

CERN-EP-2022-038
2023/05/15

CMS-SMP-21-001

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

The CMS Collaboration*

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 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ 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 $9.1 \pm 0.6 \text{ fb}$.

Published in Physics Letters B as doi:10.1016/j.physletb.2022.137495.

arXiv:2205.05711v2 [hep-ex] 12 May 2023

1 Introduction

Electroweak (EW) scattering processes of the form $VV' \rightarrow VV'$, 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].

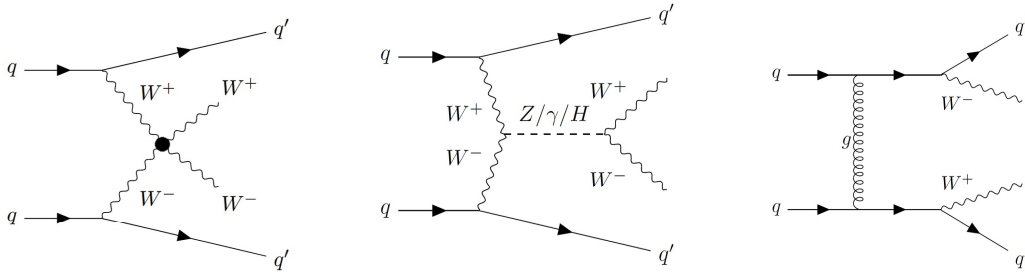


Figure 1: Examples of Feynman diagrams for the EW (left, center) and QCD-induced (right) production of W^+W^- bosons in association with two quarks.

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 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 μ 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 $m_{\ell\ell} > 50 \text{ GeV}$ and transverse momentum $p_T^{\ell\ell} > 30 \text{ GeV}$, 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 $p_T > 10 \text{ GeV}$ are rejected;
- $p_T^{\text{miss}} > 20 \text{ GeV}$;
- At least two jets with $p_T > 30 \text{ GeV}$, $m_{jj} > 300 \text{ GeV}$, 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 $m_T = \sqrt{2p_T^{\ell\ell}p_T^{\text{miss}} [1 - \cos\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{p}_T^{\text{miss}})]}$, 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 $\tau^+\tau^- \rightarrow e\mu$ 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.

Table 1: Post-fit process yields and uncertainties in each SR (ee and $\mu\mu$ final states combined).

Process	SR $e\mu$ $Z_{\ell\ell} < 1$	SR $e\mu$ $Z_{\ell\ell} > 1$	SR ee - $\mu\mu$ $Z_{\ell\ell} < 1$	SR ee - $\mu\mu$ $Z_{\ell\ell} > 1$
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	—	—

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 $p_T > 20 \text{ GeV}$ 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 $50 < m_{\ell\ell} < 80 \text{ GeV}$ window is selected.

In DY ee and $\mu\mu$ categories, the dilepton mass is chosen to be close to the Z boson mass peak, $|m_{\ell\ell} - m_Z| < 15 \text{ GeV}$. Moreover, the DY ee and $\mu\mu$ CRs are divided in two $|\Delta\eta_{jj}|$ bins, as explained in Section 5. The fraction of DY events in the DY CRs are $\approx 64\%$ and $\approx 91\%$ for the $e\mu$ and ee/ $\mu\mu$ categories, respectively. A summary of all regions included in the analysis is shown in App. A.

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 $\mu\mu$ 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 ($\approx 50\%$) 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 $\tau\tau$ events, and its normalization is determined from the $e\mu$ 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 $W + \text{jets}$ events. This background is directly estimated from data by applying a transfer function to events entering a $W + \text{jets}$ 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 $p_T^{\text{miss}} < 20 \text{ GeV}$. 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 $e\mu$ 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 App. A, and they agree with SM predictions within post-fit uncertainties. These distributions are also shown in the ee and $\mu\mu$ combined top CRs, where the data is in excellent agreement with the simulation. The DNN output is illustrated in the $e\mu$ 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^j1	p_T of the highest p_T jet
$ \Delta\eta_{jj} $	Pseudorapidity separation between the two tagging jets
p_T^j2	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 $(p_T^{\ell_1}, p_T^{\text{miss}})$ system

The signal strength modifier of EW W^+W^- production, $\mu_{EW} = \sigma^{\text{obs}}/\sigma^{\text{SM}}$, 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 $e\mu$ 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 spectrum. In the ee and $\mu\mu$ SRs, different discriminating variables are chosen as a function of m_{jj} and $|\Delta\eta_{jj}|$. For $m_{jj} > 500$ 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:

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

tion. 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 $e\mu$ 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 reasonably agreed with data at $\text{DNN} > 0.88$. 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.

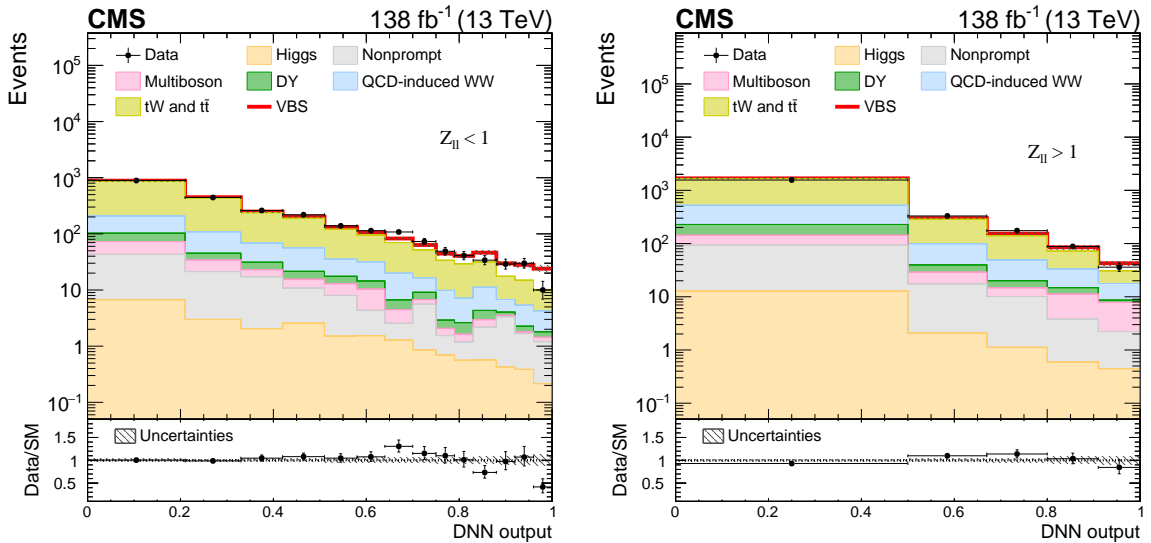


Figure 2: Post-fit DNN output distribution in different-flavor SRs for $Z_{\ell\ell} < 1$ (left) and $Z_{\ell\ell} > 1$ (right) categories. This variable quantifies how likely each event is signal. The contributions from background and signal (red line) processes are shown as stacked histograms; systematic 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.

6 Systematic uncertainties

Uncertainties in the integrated luminosity, lepton reconstruction and identification efficiency [51, 59], 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

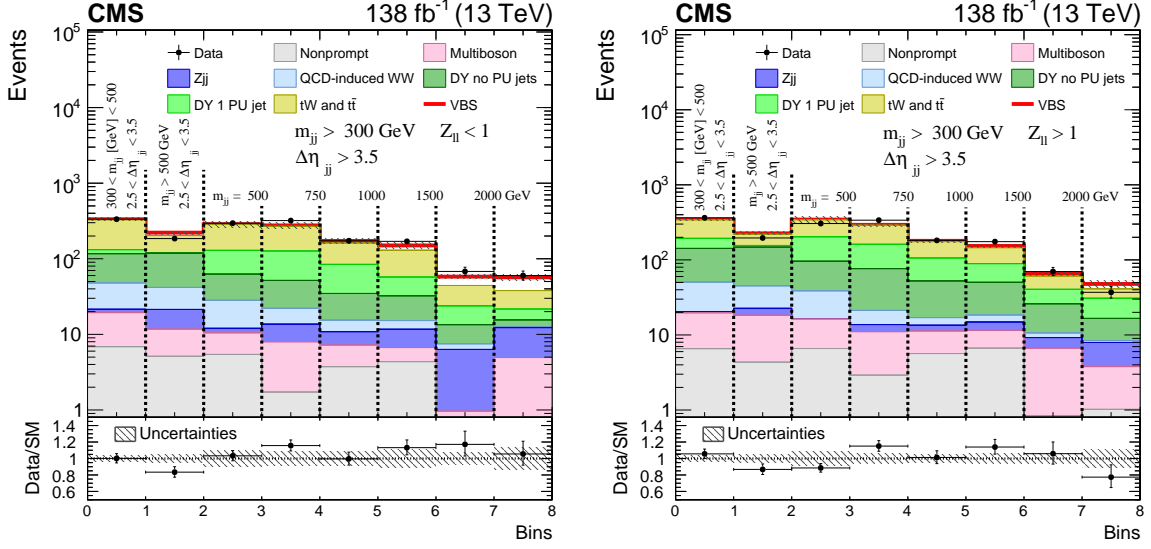


Figure 3: Post-fit m_{jj} distribution and number of events in same-flavor (ee and $\mu\mu$ combined) SRs for $Z_{\ell\ell} < 1$ (left) and $Z_{\ell\ell} > 1$ (right) categories. The first two bins contain the number of events in the selected region (as reported in the plots themselves). The third bin 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.

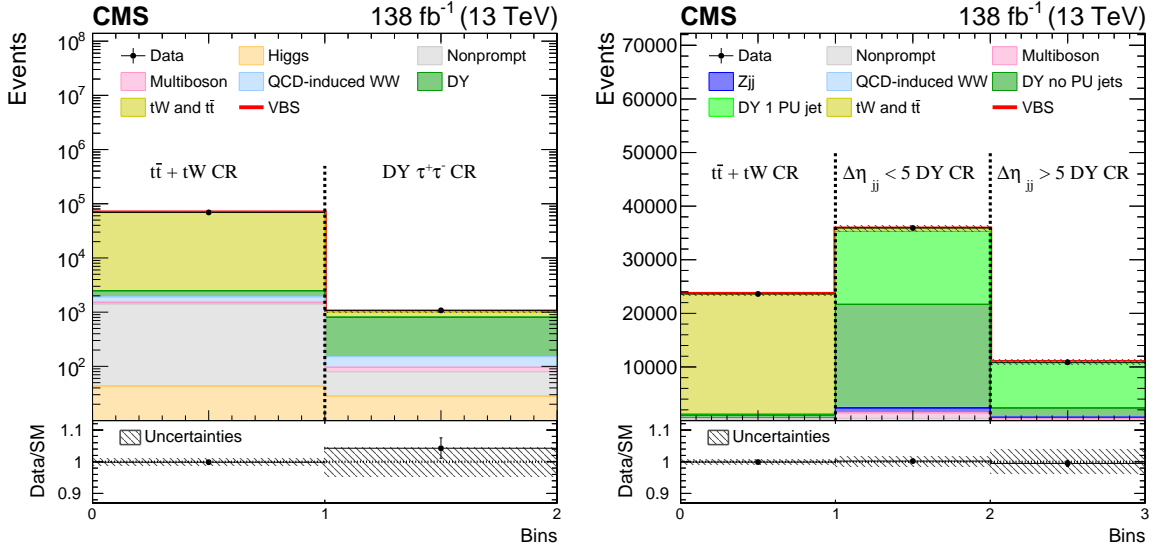


Figure 4: Post-fit number of events in different-flavor (left) and same-flavor (right, with ee and $\mu\mu$ combined) CRs. In the left plot, the first bin contains the number of events in the $t\bar{t} + tW$ different-flavor CR, and the second bin those in the $DY \tau\tau$ CR. In the right plot, the 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.

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 the former one, parton-level requirements define the phase space of interest, in particular the two outgoing partons (qq') are required to have $p_T > 10$ GeV and an invariant mass $m_{qq'} > 100$ 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 ± 20 fb, compared with the LO prediction of 89 ± 5 (scale) 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

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%

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 ± 2.0 fb, while the LO theoretical prediction is 9.1 ± 0.6 (scale) 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 fb^{-1} collected with the CMS detector at the CERN LHC in proton-proton collisions at $\sqrt{s} = 13$ 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 ± 20 fb (89 ± 5 fb expected), whereas in that comparable with the experimental phase space the measured cross section is 10.2 ± 2.0 fb (9.1 ± 0.6 fb expected). These results are compatible

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

Objects	Requirements
	$e\mu, ee, \mu\mu$ (not from τ decay), opposite charge
Leptons	$p_T^{\text{dressed } \ell} = p_T^\ell + \sum_i p_T^{\gamma_i}$ if $\Delta R(\ell, \gamma_i) < 0.1$
	$p_T^{\ell_1} > 25 \text{ GeV}, p_T^{\ell_2} > 13 \text{ GeV}, p_T^{\ell_3} < 10 \text{ GeV}$
	$ \eta < 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
	$ \eta < 4.7$
	$m_{jj} > 300 \text{ GeV}, \Delta\eta_{jj} > 2.5$
p_T^{miss}	$p_T^{\text{miss}} > 20 \text{ GeV}$

with standard model predictions within one standard deviation.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHEI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA). If acknowledgements for individuals are required for a short letter because some of the principal authors are funded through individual grants, it should be OK to add the lines below concerning individuals even for a short letter, but please first consult with the PubComm chair.

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710,

824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NK-FIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] D. Espriu and B. Yencho, "Longitudinal WW scattering in light of the "Higgs boson" discovery", *Phys. Rev. D* **87** (2013) 055017, doi:10.1103/PhysRevD.87.055017, arXiv:1212.4158.
- [2] J. Chang, K. Cheung, C.-T. Lu, and T.-C. Yuan, "Ww scattering in the era of post-higgs-boson discovery", *Phys. Rev. D* **87** (2013) 093005, doi:10.1103/PhysRevD.87.093005, arXiv:1303.6335.
- [3] ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.
- [4] CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
- [5] CMS Collaboration, "Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV", *JHEP* **06** (2013) 081, doi:10.1007/JHEP06(2013)081, arXiv:1303.4571.

-
- [6] B. W. Lee, C. Quigg, and H. B. Thacker, “Weak interactions at very high energies: The role of the Higgs-boson mass”, *Phys. Rev. D* **16** (1977) 1519, doi:10.1103/PhysRevD.16.1519.
- [7] ATLAS Collaboration, “Evidence for Electroweak Production of $W^\pm W^\pm jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector”, *Phys. Rev. Lett.* **113** (2014) 141803, doi:10.1103/PhysRevLett.113.141803, arXiv:1405.6241.
- [8] CMS Collaboration, “Study of vector boson scattering and search for new physics in events with two same-sign leptons and two jets”, *Phys. Rev. Lett.* **114** (2014) 051801, doi:10.1103/PhysRevLett.114.051801, arXiv:1410.6315.
- [9] ATLAS Collaboration, “Observation of electroweak production of a same-sign W boson pair in association with two jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Rev. Lett.* **123** (2019) 161801, doi:10.1103/PhysRevLett.123.161801, arXiv:1906.03203.
- [10] CMS Collaboration, “Observation of electroweak production of same-sign W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. Lett.* **120** (2018) 081801, doi:10.1103/PhysRevLett.120.081801, arXiv:1709.05822.
- [11] CMS Collaboration, “Measurements of production cross sections of WZ and same-sign WW boson pairs in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **809** (2020) 135710, doi:10.1016/j.physletb.2020.135710, arXiv:2005.01173.
- [12] CMS Collaboration, “Measurements of production cross sections of polarized same-sign W boson pairs in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **812** (2021) 136018, doi:10.1016/j.physletb.2020.136018, arXiv:2009.09429.
- [13] R. Bellan et al., “A sensitivity study of VBS and diboson WW to dimension-6 EFT operators at the LHC”, *JHEP* **05** (2022) 039, doi:10.1007/JHEP05(2022)039, arXiv:2108.03199.
- [14] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [15] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [16] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [17] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [18] CMS Collaboration, “Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid”, CMS Technical Proposal CERN-LHCC-2015-010, CMS-TDR-15-02, 2015.
- [19] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

- [20] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [21] CMS Collaboration, “Pileup mitigation at CMS in 13 TeV data”, *JINST* **15** (2020) P09018, doi:10.1088/1748-0221/15/09/p09018, arXiv:2003.00503.
- [22] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [23] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
- [24] D. Bertolini, P. Harris, M. Low, and N. Tran, “Pileup per particle identification”, *JHEP* **10** (2014) 059, doi:10.1007/JHEP10(2014)059, arXiv:1407.6013.
- [25] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [26] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2017.
- [27] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.
- [28] CMS Collaboration, “Measurements of inclusive W and Z cross sections in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **01** (2011) 080, doi:10.1007/jhep01(2011)080, arXiv:1012.2466.
- [29] E. Bols et al., “Jet flavour classification using DeepJet”, *JINST* **15** (2020) P12012, doi:10.1088/1748-0221/15/12/p12012, arXiv:2008.10519.
- [30] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [31] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [32] B. Cabouat and T. Sjöstrand, “Some dipole shower studies”, *Eur. Phys. J. C* **78** (2018) 226, doi:10.1140/epjc/s10052-018-5645-z, arXiv:1710.00391.
- [33] B. Jager et al., “Parton-shower effects in Higgs production via vector-boson fusion”, *Eur. Phys. J. C* **80** (2020), no. 8, 756, doi:10.1140/epjc/s10052-020-8326-7, arXiv:2003.12435.
- [34] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [35] E. Re, M. Wiesemann, and G. Zanderighi, “NNLOPS accurate predictions for W^+W^- production”, *JHEP* **12** (2018) 121, doi:10.1007/jhep12(2018)121, arXiv:1805.09857.

-
- [36] K. Hamilton, P. Nason, and G. Zanderighi, “Finite quark-mass effects in the NNLOPS POWHEG+MiNLO Higgs generator”, *JHEP* **05** (2015) 140, doi:10.1007/JHEP05(2015)140, arXiv:1501.04637.
- [37] S. Bolognesi et al., “Spin and parity of a single-produced resonance at the LHC”, *Phys. Rev. D* **86** (Nov, 2012) 095031, doi:10.1103/PhysRevD.86.095031.
- [38] CMS Collaboration, “Measurements of properties of the Higgs boson in the W boson pair decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-HIG-20-013, 2022.
- [39] J. M. Campbell and R. K. Ellis, “An update on vector boson pair production at hadron colliders”, *Phys. Rev. D* **60** (1999) 113006, doi:10.1103/PhysRevD.60.113006, arXiv:hep-ph/9905386.
- [40] J. M. Campbell, R. K. Ellis, and C. Williams, “Vector boson pair production at the LHC”, *JHEP* **07** (2011) 017, doi:10.1007/jhep07(2011)018, arXiv:1105.0020.
- [41] J. M. Campbell, R. K. Ellis, and W. T. Giele, “A multi-threaded version of MCFM”, *Eur. Phys. J. C* **75** (2015) 246, doi:10.1140/epjc/s10052-015-3461-2, arXiv:1503.06182.
- [42] CMS Collaboration, “Measurement of differential cross sections for top quark pair production using the lepton+jets final state in proton-proton collisions at 13 TeV”, *Phys. Rev. D* **95** (2017) 092001, doi:10.1103/PhysRevD.95.092001, arXiv:1610.04191.
- [43] CMS Collaboration, “Measurements of differential Z boson production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **12** (2019) 061, doi:10.1007/JHEP12(2019)061, arXiv:1909.04133.
- [44] NNPDF Collaboration, “Parton distributions with QED corrections”, *Nucl. Phys. B* **877** (2013) 290, doi:10.1016/j.nuclphysb.2013.10.010, arXiv:1308.0598.
- [45] NNPDF Collaboration, “Unbiased global determination of parton distributions and their uncertainties at NNLO and at LO”, *Nucl. Phys. B* **855** (2012) 153, doi:10.1016/j.nuclphysb.2011.09.024, arXiv:1107.2652.
- [46] NNPDF Collaboration, “Parton distributions from high-precision collider data”, *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
- [47] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [48] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [49] GEANT4 Collaboration, “GEANT4 – a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [50] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/p05014, arXiv:2012.06888.

- [51] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [52] D. L. Rainwater, R. Szalapski, and D. Zeppenfeld, “Probing color singlet exchange in Z + two jet events at the CERN LHC”, *Phys. Rev. D* **54** (1996) 6680, doi:10.1103/PhysRevD.54.6680, arXiv:hep-ph/9605444.
- [53] CMS Collaboration, “Measurements of properties of the Higgs boson decaying to a W boson pair in pp collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **791** (2019) 96, doi:10.1016/j.physletb.2018.12.073, arXiv:1806.05246.
- [54] D. P. Kingma and J. Ba, “Adam: A method for stochastic optimization”, in *3rd International Conference on Learning Representations, ICLR 2015, San Diego, CA, USA, May 7-9, 2015, Conference Track Proceedings*. 2015. arXiv:1412.6980.
- [55] D. R. Cox, “The regression analysis of binary sequences”, *J R Stat Soc Series B* **20** (1958) 215, doi:10.1111/j.2517-6161.1958.tb00292.x.
- [56] I. Goodfellow, Y. Bengio, and A. Courville, “Deep learning”. MIT Press, 2016. <http://www.deeplearningbook.org>.
- [57] S. M. Lundberg and S.-I. Lee, “A unified approach to interpreting model predictions”, in *Proceedings of the 31st International Conference on Neural Information Processing Systems, NIPS’17*, p. 4768. Curran Associates Inc., Red Hook, NY, USA, 2017. arXiv:1705.07874.
- [58] L. S. Shapley, “A value for n-person games”, *Contributions to the Theory of Games* **2.28** (1953) 303, doi:10.1515/9781400881970-018.
- [59] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
- [60] S. Catani, D. de Florian, M. Grazzini, and P. Nason, “Soft gluon resummation for Higgs boson production at hadron colliders”, *JHEP* **07** (2003) 028, doi:10.1088/1126-6708/2003/07/028, arXiv:hep-ph/0306211.
- [61] M. Cacciari et al., “The $t\bar{t}$ cross-section at 1.8 TeV and 1.96 TeV: a study of the systematics due to parton densities and scale dependence”, *JHEP* **04** (2004) 068, doi:10.1088/1126-6708/2004/04/068, arXiv:hep-ph/0303085.
- [62] J. Rojo, “PDF4LHC recommendations for Run II”, *PoS DIS2016* (2016) 018, doi:10.22323/1.265.0018, arXiv:1606.08243.
- [63] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].
- [64] E. Gross and O. Vitells, “Trial factors for the look elsewhere effect in high energy physics”, *Eur. Phys. J. C* **70** (2010) 525, doi:10.1140/epjc/s10052-010-1470-8, arXiv:1005.1891.
- [65] HEPData record for this analysis, 2022. doi:10.17182/hepdata.127763.

A Supplementary material for SMP-21-001

Table 5: Summary of the event categorization on top of signal candidates preselection. In each region, same-flavor final states share the same kinematic requirements.

Region	Final state	Requirements	Subregion
SR	$e\mu/\mu e$	$m_T > 60 \text{ GeV}$	$Z_{\ell\ell} < 1$
		$m_{\ell\ell} > 50 \text{ GeV}$	$Z_{\ell\ell} > 1$
		no b jet with $p_T > 20 \text{ GeV}$	
	ee	$m_{\ell\ell} > 120 \text{ GeV}$	$Z_{\ell\ell} < 1$
		$p_T^{\text{miss}} > 60 \text{ GeV}$	$Z_{\ell\ell} > 1$
		no b jet with $p_T > 20 \text{ GeV}$	
$\mu\mu$		$Z_{\ell\ell} < 1$	
		$Z_{\ell\ell} > 1$	
$t\bar{t} + tW \text{ CR}$	$e\mu/\mu e$	$m_{\ell\ell} > 50 \text{ GeV}$	
		at least one b jet with $p_T > 20 \text{ GeV}$	
	ee	$m_{\ell\ell} > 120 \text{ GeV}$	
		$p_T^{\text{miss}} > 60 \text{ GeV}$	
$\mu\mu$		at least one b jet with $p_T > 20 \text{ GeV}$	
DY CR	$e\mu/\mu e$	$m_T < 60 \text{ GeV}$	
		$50 \text{ GeV} < m_{\ell\ell} < 80 \text{ GeV}$	
		no b jet with $p_T > 20 \text{ GeV}$	
	ee	$ m_{\ell\ell} - m_Z < 15 \text{ GeV}$	$ \Delta\eta_{jj} < 5$
		$p_T^{\text{miss}} > 60 \text{ GeV}$	$ \Delta\eta_{jj} > 5$
		no b jet with $p_T > 20 \text{ GeV}$	
$\mu\mu$		$ \Delta\eta_{jj} < 5$	
		$ \Delta\eta_{jj} > 5$	

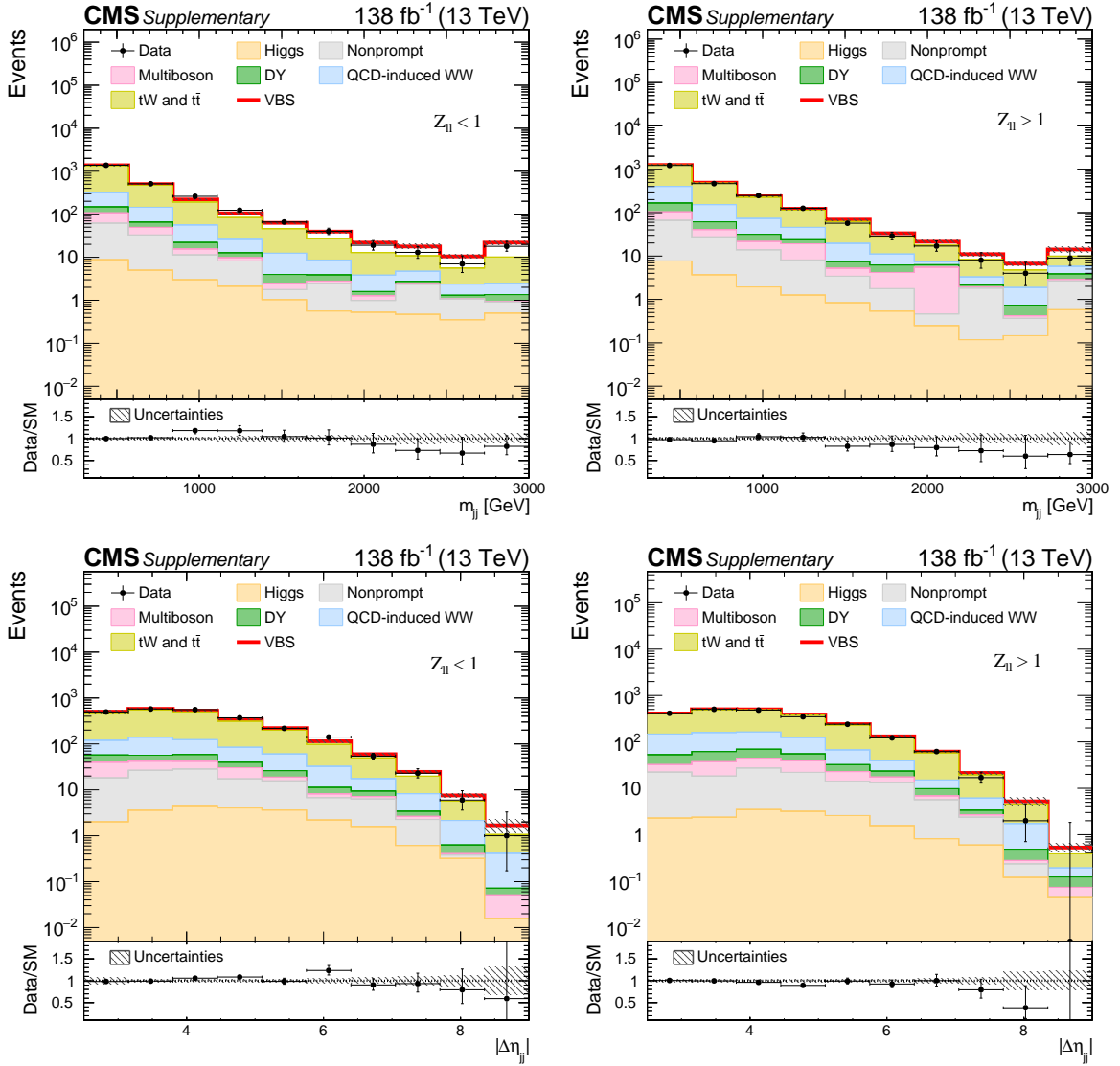


Figure 5: Post-fit distributions of m_{jj} (upper row) and $|\Delta\eta_{jj}|$ (lower row) variables in different-flavor SRs for $Z_{\ell\ell} < 1$ (left column) and $Z_{\ell\ell} > 1$ (right column) categories. These variables are among the nine observables used as inputs for the DNN, as listed in Table 2. 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.

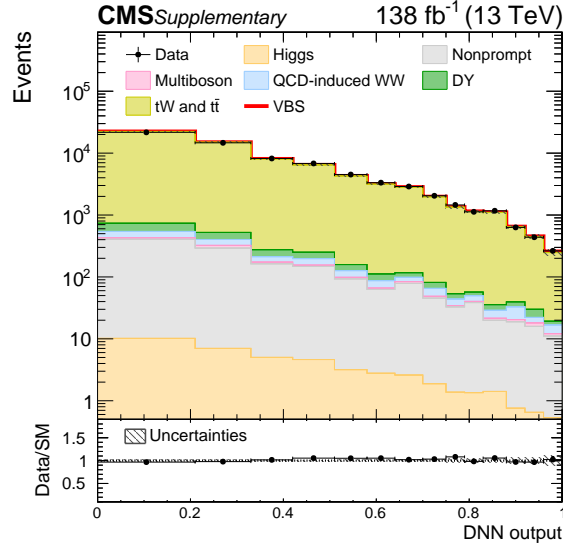


Figure 6: Post-fit distribution of the DNN output in different-flavor top CR. Data to SM expectation ratio has some residual shape dependence (less than 5% across the full spectrum), which however was found to not affect the analysis. The contributions from background and signal (red line) processes 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.

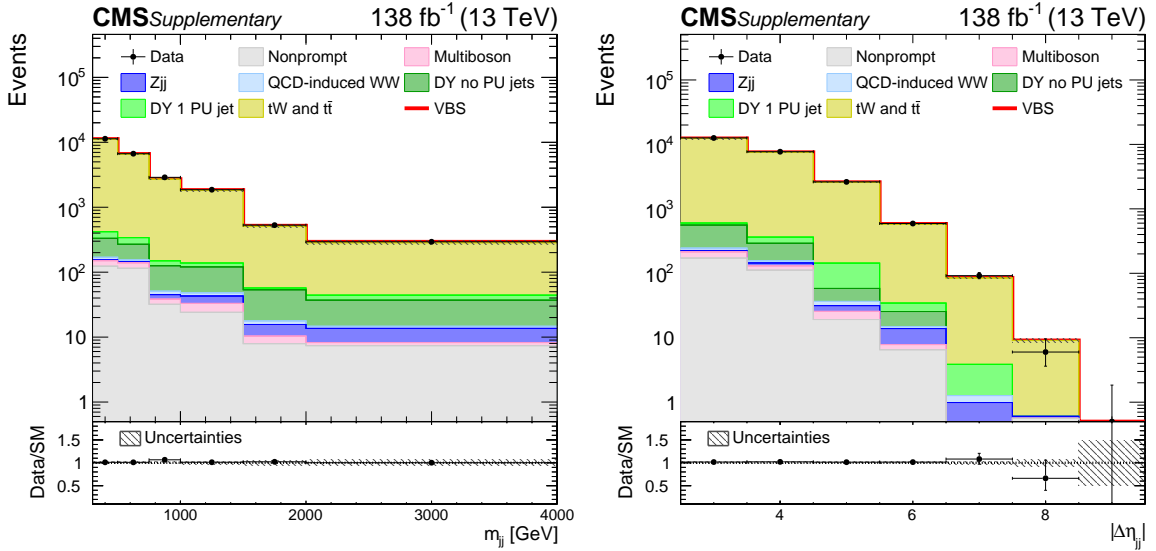





















Figure 7: Post-fit distributions of m_{jj} (left) and $|\Delta\eta_{jj}|$ (right) variables in same-flavor top CR (ee and $\mu\mu$ final states combined). The ratio between data and SM expectation is in excellent agreement with 1 within post-fit uncertainties in both spectra. The contributions from background 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.

B The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan¹ 











Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , A. Escalante Del Valle , R. Frühwirth² , M. Jeitler² , N. Krammer , L. Lechner , D. Liko , I. Mikulec , P. Paulitsch, F.M. Pitters, J. Schieck² , R. Schöfbeck , D. Schwarz , S. Templ , W. Waltenberger , C.-E. Wulz² 














Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , E.A. De Wolf, T. Janssen , T. Kello⁴, A. Lelek , H. Rejeb Sfar, P. Van Mechelen , S. Van Putte , N. Van Remortel 











Vrije Universiteit Brussel, Brussel, 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 

















Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, 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 






















Université Catholique de Louvain, Louvain-la-Neuve, 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 

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁵, E.M. Da Costa , G.G. Da Silveira⁶ , D. De Jesus Damiao , V. Dos Santos Sousa , S. Fonseca De Souza , J. Martins⁷ , 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 Araujo⁸ , A. Vilela Pereira 

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

C.A. Bernardes⁶ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , D. S. Lemos , P.G. Mercadante , S.F. Novaes , Sandra S. Padula 




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

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




University of Sofia, Sofia, Bulgaria

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


Beihang University, Beijing, China

T. Cheng , T. Javaid⁹, M. Mittal , L. Yuan 









Department of Physics, Tsinghua University, Beijing, China

M. Ahmad , G. Bauer, C. Dozen , Z. Hu , Y. Wang, K. Yi^{10,11}

Institute of High Energy Physics, Beijing, China

E. Chapon , G.M. Chen⁹ , H.S. Chen⁹ , M. Chen , F. Iemmi , A. Kapoor , H. Liao , Z.-A. Liu¹² , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker , J. Wang , H. Zhang , J. Zhao 




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

Sun Yat-Sen University, Guangzhou, China

M. Lu , Z. You 

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

X. Gao⁴ , D. Leggat, H. Okawa , Y. Zhang 




Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin , M. Xiao 

Universidad de Los Andes, Bogota, Colombia

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



Universidad de Antioquia, Medellin, Colombia

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

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

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










University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac , T. Sculac 




Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic , D. Ferencek , D. Majumder , M. Roguljic , A. Starodumov¹³ , T. Susa 

University of Cyprus, Nicosia, Cyprus

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


Charles University, Prague, Czech Republic

M. Finger¹³ , M. Finger Jr.¹³ , A. Kveton 





















































































Escuela Politecnica Nacional, Quito, Ecuador






















E. Ayala 

Universidad San Francisco de Quito, Quito, Ecuador




E. Carrera Jarrin 

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian

Network of High Energy Physics, Cairo, EgyptH. Abdalla¹⁴ , E. Salama^{15,16} **Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**M.A. Mahmoud , Y. Mohammed **National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**S. Bhowmik , R.K. Dewanjee , K. Ehataht , M. Kadastik, S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken **Department of Physics, University of Helsinki, Helsinki, Finland**P. Eerola , H. Kirschenmann , K. Osterberg , M. Voutilainen **Helsinki Institute of Physics, Helsinki, Finland**S. Bharthuar , E. Brücken , F. Garcia , J. Havukainen , M.S. Kim , R. Kinnunen, T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Lotti, L. Martikainen , M. Myllymäki , J. Ott , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi **Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**P. Luukka , H. Petrow , T. Tuuva**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**C. Amendola , M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , P. Jarry , B. Lenzi , V. Lohezic , J. Malcles , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro¹⁷ , P. Simkina , M. Titov , G.B. Yu **Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, 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 **Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**J.-L. Agram¹⁸ , J. Andrea, D. Apparù , D. Bloch , G. Bourgatte, J.-M. Brom , E.C. Chabert , C. Collard , D. Darej, J.-C. Fontaine¹⁸, U. Goerlach , C. Grimault, A.-C. Le Bihan , E. Nibigira , P. Van Hove **Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France**E. Asilar , S. Beauceron , C. Bernet , G. Boudoul , C. Camen, A. Carle, N. Chanon , D. Contardo , P. Depasse , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, K. Shchablo, V. Sordini , L. Torterotot , M. Vander Donckt , S. Viret**Georgian Technical University, Tbilisi, Georgia**I. Bagaturia¹⁹ , I. Lomidze , Z. Tsamalaidze¹³ **RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**V. Botta , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , N. Röwert , J. Schulz, M. Teroerde **RWTH Aachen University, III. Physikalisches Institut A, 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 B, Aachen, Germany

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























Deutsches Elektronen-Synchrotron, Hamburg, 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. Blekman²² , K. Borrás²³ , 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. Gallo²² , A. Geiser , A. Giraldi , G. Greau, A. Grohsjean , V. Guglielmi , M. Guthoff , A. Jafari²⁴ , N.Z. Jomhari , B. Kaech , A. Kasem²³ , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , D. Krücker , W. Lange, K. Lipka , W. Lohmann²⁵ , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally, A.B. Meyer , M. Meyer , M. Mormile , A. Mussgiller , A. Nürnberg , Y. Otariid, D. Pérez Adán , D. Pitzl, A. Raspereza, B. Ribeiro Lopes , J. Rübenach, A. Saggio , A. Saibel , M. Savitskyi , M. Scham²⁶ , V. Scheurer, S. Schnake , P. Schütze , C. Schwanenberger²² , 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. Zimmermann Castro Santos

University of Hamburg, 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










Karlsruher Institut fuer Technologie, Karlsruhe, 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. Hartmann²¹ , 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. Savoie , M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis , R. Ulrich , J. Van Der Linden , R.F. Von Cube , M. Wassmer , M. Weber , S. Wieland , R. Wolf , S. Wozniowski , S. Wunsch




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

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

National and Kapodistrian University of Athens, Athens, 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 Technical University of Athens, Athens, Greece

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






University of Ioánnina, Ioánnina, Greece

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




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

M. Csanád , K. Farkas , M.M.A. Gadallah²⁷ , S. Lökös²⁸ , P. Major , K. Mandal , G. Pásztor , A.J. Rádl , O. Surányi , G.I. Veres 



Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók²⁹ , G. Bencze, C. Hajdu , D. Horvath^{30,31} , F. Sikler , V. Veszpremi 




Institute of Nuclear Research ATOMKI, Debrecen, Hungary

S. Czellar, D. Fasanella , F. Fienga , J. Karancsi²⁹ , J. Molnar, Z. Szillasi, D. Teyssier 














Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi³² , B. Ujvari³³ 

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

T. Csorgo³⁴ , F. Nemes³⁴ , T. Novak 









Panjab University, Chandigarh, India

S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁵ , R. Gupta, A. Kaur , H. Kaur , M. Kaur , P. Kumari , M. Meena , K. Sandeep , J.B. Singh³⁶ , A. K. Viridi 













University of Delhi, Delhi, India

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


Saha Institute of Nuclear Physics, HBNI, Kolkata, India

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



Indian Institute of Technology Madras, Madras, India

P.K. Behera , S.C. Behera , P. Kalbhor , J.R. Komaragiri³⁹ , D. Kumar³⁹ , A. Muhammad , L. Panwar³⁹ , R. Pradhan , P.R. Pujahari , A. Sharma , A.K. Sikdar , P.C. Tiwari³⁹ 



Bhabha Atomic Research Centre, Mumbai, India

K. Naskar⁴⁰ 










Tata Institute of Fundamental Research-A, Mumbai, India

































































































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

Tata Institute of Fundamental Research-B, Mumbai, India























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

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











S. Bahinipati⁴¹ , C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴² , A. Nayak⁴² , P. Saha , N. Sur , S.K. Swain, D. Vats⁴² 

Indian Institute of Science Education and Research (IISER), Pune, IndiaA. Alpana , S. Dube , B. Kansal , A. Laha , S. Pandey , A. Rastogi , S. Sharma **Isfahan University of Technology, Isfahan, Iran**H. Bakhshiansohi⁴³ , A. Gholami⁴⁴ , E. Khazaie **Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**S. Chenarani⁴⁵ , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi **University College Dublin, Dublin, Ireland**M. Grunewald **INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy**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 **INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy**G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borgonovi^a , 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. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , P. Giacomelli^a , L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,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} **INFN Sezione di Catania^a, Università di Catania^b, Catania, 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} **INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, 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 **INFN Laboratori Nazionali di Frascati, Frascati, Italy**L. Benussi , S. Bianco , D. Piccolo **INFN Sezione di Genova^a, Università di Genova^b, Genova, Italy**M. Bozzo^{a,b} , F. Ferro^a , R. Mulargia^a , E. Robutti^a , S. Tosi^{a,b} **INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milano, Italy**A. Benaglia^a , G. Boldrini^a , 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} **INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Università G. Marconi^d, Roma, Italy**S. Buontempo^a , F. Carnevali^{a,b} , N. Cavallo^{a,c} , A. De Iorio^{a,b} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,49} , S. Meola^{a,d,21} , P. Paolucci^{a,21} , B. Rossi^a , C. Sciacca^{a,b} 















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

P. Azzi^a , N. Bacchetta^a , D. Bisello^{a,b} , P. Bortignon^a , A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , U. Dosselli^a , F. Gasparini^{a,b} , U. Gasparini^{a,b} , 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}























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



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























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

P. Azzurri^a , G. Bagliesi^a , V. Bertacchi^{a,c} , L. Bianchini^a , T. Boccali^a , E. Bossini^{a,b} , 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








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













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

N. Amapane^{a,b} , R. Arcidiacono^{a,c} , S. Argiro^{a,b} , M. Arneodo^{a,c} , N. Bartosik^a , R. Bellan^{a,b} , A. Bellora^{a,b} , J. Berenguer Antequera^{a,b} , C. Biino^a , N. Cartiglia^a , M. Costa^{a,b} , R. Covarelli^{a,b} , N. Demaria^a , M. Grippone^{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}

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

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




Kyungpook National University, Daegu, Korea

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





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

H. Kim , D.H. Moon 

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

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

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh , A. Gurtu 


Sejong University, Seoul, Korea

H. S. Kim , Y. Kim

Seoul National University, Seoul, Korea

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




University of Seoul, Seoul, Korea

W. Jang , D.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, Watson, I.J. , S. Yang 


Yonsei University, Department of Physics, Seoul, Korea

S. Ha , H.D. Yoo 

Sungkyunkwan University, Suwon, Korea

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

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

T. Beyrouthy, Y. Maghrbi 

Riga Technical University, Riga, Latvia

K. Dreimanis , V. Veckalns 

Vilnius University, Vilnius, Lithuania

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









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

N. Bin Norjoharuddeen , S.Y. Hoh⁵² , Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

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

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

G. Ayala , H. Castilla-Valdez , E. De La Cruz-Burelo , I. Heredia-De La Cruz⁵³ , R. Lopez-Fernandez , C.A. Mondragon Herrera, D.A. Perez Navarro , R. Reyes-Almanza , A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , F. Vazquez Valencia 

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

University of Montenegro, Podgorica, Montenegro

I. Bubanja, J. Mijuskovic⁵⁴, N. Raicevic 








University of Auckland, Auckland, New Zealand

D. Krofcheck 

University of Canterbury, Christchurch, New Zealand

P.H. Butler 








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

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






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

V. Avati, L. Grzanka , M. Malawski 

National Centre for Nuclear Research, Swierk, Poland

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

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

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


























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

M. Araujo , P. Bargassa , D. Bastos , A. Boletti , P. Faccioli , M. Gallinaro , J. Hollar ,
N. Leonardo , T. Niknejad , M. Pisano , J. Seixas , O. Toldaiev , J. Varela 


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

P. Adzic⁵⁵ , M. Dordevic , P. Milenovic , J. Milosevic 














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

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













Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz 

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





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

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

J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. 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 

University of Colombo, Colombo, Sri Lanka

M.K. Jayananda , B. Kailasapathy⁵⁶ , D.U.J. Sonnadara , D.D.C. Wickramarathna 

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

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

































CERN, European Organization for Nuclear Research, Geneva, Switzerland

T.K. Aarrestad , D. Abbaneo , J. Alimena , E. Auffray , G. Auzinger , J. Baechler, P. Baillon[†], D. Barney , J. Bendavid , M. Bianco , 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. Dünsen , N. Dupont, A. Elliott-Peisert, F. Fallavollita⁵⁷, 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. Sphicas⁵⁸ , A.G. Stahl Leitner , S. Summers , K. Tatar , V.R. Tavolaro , D. Treille , P. Tropea , A. Tsirou, J. Wanczyk⁵⁹ , K.A. Wozniak , W.D. Zeuner
























Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁶⁰ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , M. Missiroli⁶⁰ , L. Noehte⁶⁰ , T. Rohe 




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

K. Androsov⁵⁹ , 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. Reitspiess , B. Ristic , D. Ruini, D.A. Sanz Becerra , J. Steggemann⁵⁹ , R. Wallny 











Universität Zürich, Zurich, Switzerland

C. Amsler⁶¹ , P. Bäertschi , 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. Liechi , A. Macchiolo , P. Meiring , V.M. Mikuni , U. Molinatti , I. Neutelings , A. Reimers , P. Robmann, S. Sanchez Cruz , K. Schweiger , M. Senger , Y. Takahashi 




National Central University, Chung-Li, Taiwan

C. Adloff⁶², C.M. Kuo, W. Lin, A. Roy , T. Sarkar³⁸ , S.S. Yu 



















National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, Y. Chao , K.F. Chen , P.H. Chen , 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

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

B. Asavapibhop , C. Asawatangtrakuldee , N. Srimanobhas 

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

F. Boran , S. Damarseekin⁶³ , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶⁴ , E. Eskut, Y. Guler⁶⁵ , E. Gurpinar Guler⁶⁵ , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir⁶⁶ , A. Polatoz , A.E. Simsek , B. Tali⁶⁷ , U.G. Tok , S. Turkcapar , I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar, K. Ocalan⁶⁸ , M. Yalvac⁶⁹ 

Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁷⁰ , O. Kaya⁷¹ , Ö. Özçelik , S. Tekten⁷² , E.A. Yetkin⁷³ 


Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak⁶⁴ , Y. Komurcu , S. Sen⁷⁴ 

Istanbul University, Istanbul, Turkey

S. Cerci⁶⁷ , I. Hos⁷⁵ , B. Isildak⁷⁶ , B. Kaynak , S. Ozkorucuklu , H. Sert , C. Simsek , D. Sunar Cerci⁶⁷ , C. Zorbilmez 
















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

B. Grynyov 
















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

L. Levchuk 






























University of Bristol, Bristol, United Kingdom

D. Anthony , E. Bhal , S. Bologna, J.J. Brooke , A. Bundock , E. Clement , D. Cussans , H. Flacher , 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. Stylianou⁷⁷ , K. Walkingshaw Pass, R. White 





Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell , A. Belyaev⁷⁸ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg⁷⁹ , J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , T. Schuh, C.H. Shepherd-Themistocleous , I.R. Tomalin, T. Williams 

Imperial College, London, United Kingdom







R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , S. Breeze, O. Buchmuller, V. Cepaitis , G.S. Chahal⁸⁰ , 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. Nash⁸¹ , M. Pesaresi, B.C. Radburn-Smith , D.M. Raymond, A. Richards, A. Rose , E. Scott , C. Seez , A. Shtipliyski, A. Tapper , K. Uchida , T. Virdee²¹ , M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , B. Caraway , J. Dittmann , K. Hatakeyama , A.R. Kanu-

ganti , B. McMaster , M. Saunders , S. Sawant , C. Sutantawibul , J. Wilson 

















Catholic University of America, Washington, DC, USA

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

















The University of Alabama, Tuscaloosa, Alabama, USA

A. Buccilli , S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio⁸² , C. West 



















Boston University, Boston, Massachusetts, USA

A. Akpınar , 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














Brown University, Providence, Rhode Island, USA

G. Benelli , B. Burkle , X. Coubez²³, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸³ , T. Kwon , G. Landsberg , K.T. Lau , D. Li, M. Lukasik, J. Luo , M. Narain, N. Pervan , S. Sagir⁸⁴ , F. Simpson , E. Usai , W.Y. Wong, X. Yan , D. Yu , W. Zhang








University of California, Davis, Davis, California, USA

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





















University of California, Los Angeles, California, USA

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


















University of California, Riverside, Riverside, California, USA

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














University of California, San Diego, La Jolla, California, 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, Santa Barbara - Department of Physics, Santa Barbara, California, 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 

California Institute of Technology, Pasadena, California, 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 

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA



















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

University of Colorado Boulder, Boulder, Colorado, 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 
























Cornell University, Ithaca, New York, 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 














Fermi National Accelerator Laboratory, Batavia, Illinois, 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. Gece , 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. Klijsma , 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. Pena⁸⁵ , F. Ravera , A. Reinsvold Hall⁸⁶ , 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 









University of Florida, Gainesville, Florida, 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 


















Florida State University, Tallahassee, Florida, USA

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














Florida Institute of Technology, Melbourne, Florida, USA

M.M. Baarmand , S. Butalla , T. Elkafrawy¹⁶ , M. Hohlmann , R. Kumar Verma , D. Noonan , M. Rahmani , F. Yumiceva 

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

M.R. Adams , H. Becerril Gonzalez , R. Cavanaugh , 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 




























The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini , K. Dilsiz⁸⁷ , L. Emediato , R.P. Gandrajula , O.K. Köseyan , J.-P. Merlo , A. Mestvirishvili⁸⁸ , J. Nachtman , H. Ogul⁸⁹ , Y. Onel , A. Penzo , C. Snyder , E. Tiras⁹⁰ 




Johns Hopkins University, Baltimore, Maryland, USA

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

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , J. Anguiano , 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 


















Kansas State University, Manhattan, Kansas, USA

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























Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo , D. Wright 














University of Maryland, College Park, Maryland, USA

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















Massachusetts Institute of Technology, Cambridge, Massachusetts, 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 

University of Minnesota, Minneapolis, Minnesota, 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 Nebraska-Lincoln, Lincoln, Nebraska, 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 









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

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






















Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , Y. Haddad , 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 








Northwestern University, Evanston, Illinois, USA

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







University of Notre Dame, Notre Dame, Indiana, USA













R. Band , R. Bucci, 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. Musienko¹³ , R. Ruchti , A. Townsend , M. Wayne , M. Zarucki , L. Zygala 

The Ohio State University, Columbus, Ohio, USA

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

Princeton University, Princeton, New Jersey, USA




















F.M. Addesa , B. Bonham , P. Das , G. Dezoort , P. Elmer , A. Frankenthal 

B. Greenberg , N. Haubrich , S. Higginbotham , A. Kalogeropoulos , G. Kopp , S. Kwan , D. Lange , D. Marlow , K. Mei , I. Ojalvo , J. Olsen , D. Stickland , C. Tully 



University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik , S. Norberg














Purdue University, West Lafayette, Indiana, USA

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












Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar 

Rice University, Houston, Texas, 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. Zhang⁹¹, Y. Zhang 















University of Rochester, Rochester, New York, USA

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





The Rockefeller University, New York, New York, USA

K. Goulianos 














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

B. Chiarito, J.P. Chou , Y. Gershtein , E. Halkiadakis , A. Hart , M. Heindl , O. Karacheban²⁵ , I. Laflotte , A. Lath , R. Montalvo, K. Nash, M. Osherson , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, H. Wang 

University of Tennessee, Knoxville, Tennessee, USA

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









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

O. Bouhali⁹² , M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang , T. Kamon⁹³ , H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens , A. Safonov 














Texas Tech University, Lubbock, Texas, USA

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

Vanderbilt University, Nashville, Tennessee, USA

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









University of Virginia, Charlottesville, Virginia, 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 

Wayne State University, Detroit, Michigan, USA

N. Poudyal 

University of Wisconsin - Madison, Madison, Wisconsin, 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

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

S. Afanasiev, V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev , A. Belyaev , V. Blinov⁹⁴, E. Boos , V. Borshch , D. Budkouski , O. Bychkova, V. Chekhovsky, R. Chistov⁹⁴ , M. Danilov⁹⁴ , A. Dermenev , T. Dimova⁹⁴ , I. Dremin , M. Dubinin⁸⁵ , L. Dudko , V. Epshteyn , A. Ershov , G. Gavrillov , V. Gavrillov , S. Gninenko , V. Golovtcov , N. Golubev , I. Golutvin, I. Gorbunov , A. Gribushin , V. Ivanchenko , Y. Ivanov , V. Kachanov , L. Kardapoltsev⁹⁴ , V. Karjavine , A. Karneyeu , V. Kim⁹⁴ , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova⁹⁵ , D. Konstantinov , V. Korenkov , A. Kozyrev⁹⁴ , N. Krasnikov , E. Kuznetsova⁹⁶, A. Lanev , A. Litomin, O. Lukina , N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev⁹⁴ , V. Murzin , A. Nikitenko⁹⁷ , S. Obraztsov , V. Okhotnikov , V. Oreshkin , A. Oskin, I. Ovtin⁹⁴ , V. Palichik , P. Parygin , A. Pashenkov, V. Perelygin , G. Pivovarov , S. Polikarpov⁹⁴ , V. Popov, O. Radchenko⁹⁴ , M. Savina , V. Savrin , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁹⁴ , S. Slabospitskii , I. Smirnov, V. Smirnov , A. Snigirev , D. Sosnov , A. Stepenov , 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. Yuldashev⁹⁸, A. Zarubin , I. Zhizhin , A. Zhokin

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

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

⁴Also at Université Libre de Bruxelles, Bruxelles, Belgium

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁷Also at UFMS, Nova Andradina, Brazil

⁸Also at The University of the State of Amazonas, Manaus, Brazil

⁹Also at University of Chinese Academy of Sciences, Beijing, China

¹⁰Also at Nanjing Normal University Department of Physics, Nanjing, China

¹¹Now at The University of Iowa, Iowa City, Iowa, USA

¹²Also at University of Chinese Academy of Sciences, Beijing, China

¹³Also at an institute or an international laboratory covered by a cooperation agreement with CERN

¹⁴Also at Cairo University, Cairo, Egypt

¹⁵Also at British University in Egypt, Cairo, Egypt

¹⁶Now at Ain Shams University, Cairo, Egypt

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

¹⁸Also at Université de Haute Alsace, Mulhouse, France

¹⁹Also at Ilia State University, Tbilisi, Georgia

²⁰Also at Erzincan Binali Yildirim University, Erzincan, Turkey

-
- ²¹Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ²²Also at University of Hamburg, Hamburg, Germany
- ²³Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ²⁴Also at Isfahan University of Technology, Isfahan, Iran
- ²⁵Also at Brandenburg University of Technology, Cottbus, Germany
- ²⁶Also at Forschungszentrum Jülich, Juelich, Germany
- ²⁷Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ²⁸Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- ²⁹Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- ³⁰Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ³¹Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- ³²Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- ³³Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
- ³⁴Also at Wigner Research Centre for Physics, Budapest, Hungary
- ³⁵Also at Punjab Agricultural University, Ludhiana, India
- ³⁶Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- ³⁷Also at University of Hyderabad, Hyderabad, India
- ³⁸Also at University of Visva-Bharati, Santiniketan, India
- ³⁹Also at Indian Institute of Science (IISc), Bangalore, India
- ⁴⁰Also at Indian Institute of Technology (IIT), Mumbai, India
- ⁴¹Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴²Also at Institute of Physics, Bhubaneswar, India
- ⁴³Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴⁴Also at Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran
- ⁴⁵Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁶Also at Helwan University, Cairo, Egypt
- ⁴⁷Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁸Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁴⁹Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵⁰Also at Università di Napoli 'Federico II', Napoli, Italy
- ⁵¹Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵²Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵³Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁴Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ⁵⁵Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- ⁵⁶Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁷Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- ⁵⁸Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁵⁹Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶⁰Also at Universität Zürich, Zurich, Switzerland
- ⁶¹Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶²Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶³Also at Şirnak University, Şirnak, Turkey

- ⁶⁴Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁵Also at Konya Technical University, Konya, Turkey
- ⁶⁶Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁷Also at Adiyaman University, Adiyaman, Turkey
- ⁶⁸Also at Necmettin Erbakan University, Konya, Turkey
- ⁶⁹Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- ⁷⁰Also at Marmara University, Istanbul, Turkey
- ⁷¹Also at Milli Savunma University, Istanbul, Turkey
- ⁷²Also at Kafkas University, Kars, Turkey
- ⁷³Also at Istanbul Bilgi University, Istanbul, Turkey
- ⁷⁴Also at Hacettepe University, Ankara, Turkey
- ⁷⁵Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁶Also at Yildiz Technical University, Istanbul, Turkey
- ⁷⁷Also at Vrije Universiteit Brussel, Brussel, Belgium
- ⁷⁸Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁷⁹Also at University of Bristol, Bristol, United Kingdom
- ⁸⁰Also at IPPP Durham University, Durham, United Kingdom
- ⁸¹Also at Monash University, Faculty of Science, Clayton, Australia
- ⁸²Also at Università di Torino, Torino, Italy
- ⁸³Also at Bethel University, St. Paul, Minnesota, USA
- ⁸⁴Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ⁸⁵Also at California Institute of Technology, Pasadena, California, USA
- ⁸⁶Also at United States Naval Academy, Annapolis, Maryland, USA
- ⁸⁷Also at Bingol University, Bingol, Turkey
- ⁸⁸Also at Georgian Technical University, Tbilisi, Georgia
- ⁸⁹Also at Sinop University, Sinop, Turkey
- ⁹⁰Also at Erciyes University, Kayseri, Turkey
- ⁹¹Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
- ⁹²Also at Texas A&M University at Qatar, Doha, Qatar
- ⁹³Also at Kyungpook National University, Daegu, Korea
- ⁹⁴Also at another institute or international laboratory covered by a cooperation agreement with CERN
- ⁹⁵Also at Yerevan Physics Institute, Yerevan, Armenia
- ⁹⁶Also at University of Florida, Gainesville, Florida, USA
- ⁹⁷Also at Imperial College, London, United Kingdom
- ⁹⁸Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan