Eur. Phys. J. C (2020) 80:41
https://doi.org/10.1140/epjc/s10052-019-7541-6

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Evidence for WW production from double-parton interactions in proton–proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration*

CERN, 1211 Geneva 23, Switzerland

Received: 13 September 2019 / Accepted: 9 December 2019 / Published online: 17 January 2020
© CERN for the benefit of the CMS collaboration 2020

Abstract A search for WW production from double-parton scattering processes using same-charge electron-muon and dimuon events is reported, based on proton-proton collision data collected at a center-of-mass energy of 13 TeV. The analyzed data set corresponds to an integrated luminosity of 77.4 fb^{-1}, collected using the CMS detector at the LHC in 2016 and 2017. Multivariate classifiers are used to discriminate between the signal and the dominant background processes. A maximum likelihood fit is performed to extract the signal cross section. This leads to the first evidence for WW production via double-parton scattering, with a significance of 3.9 standard deviations. The measured inclusive cross section is $1.41 \pm 0.28\,(\text{stat}) \pm 0.28\,(\text{syst})$ pb.

1 Introduction

Events in which two hard parton-parton interactions occur within a single proton–proton (pp) collision – referred to as double-parton scattering (DPS) processes – have been discussed theoretically since the introduction of the parton model [1–8]. Experimentally, such processes have been studied at hadron colliders at different center-of-mass energies using multiple final states [9–22].

The cross section for a single hard scattering (SHS) can be factorized into a term containing the parton distribution functions (PDFs) and the partonic cross section of the process at hand, but this approach becomes nontrivial for DPS processes. Although the factorized partonic cross sections remain unchanged, the PDF term in the DPS case contains elements from two distinct partons in each proton. This term includes a distance parameter between the partons in the plane transverse to the direction of motion of each proton. Precise calculations of the involved dynamics have been carried out for such a case [7]. Assuming that both the partonic cross sections and the transverse and longitudinal parts of the PDF terms factorize, the DPS cross section can be written in a simplified model as

$$\sigma_{\text{AB}}^{\text{DPS}} = \frac{n}{2}\frac{\sigma_{\text{A}}\sigma_{\text{B}}}{\sigma_{\text{eff}}}, \tag{1}$$

where "A" and "B" denote the SHS processes, and σ_{A} and σ_{B} are their respective production cross sections. The factor n is equal to unity if processes A and B are the same, and is equal to two otherwise. The parameter σ_{eff}, the effective cross section of DPS processes, is related to the extent of the parton distribution in the plane orthogonal to the direction of motion of the protons. It was measured at different hadron colliders and center-of-mass energies in a variety of final-state processes with comparatively large uncertainties ($\approx 30\%$). Its value ranges between 15 and 26 mb for processes involving a vector boson [13–18,21,23]. Significantly lower values, down to 2.2 mb, are measured for processes involving heavy-flavor production [22].

One of the most promising processes to study DPS is the case in which both hard scatterings lead to the production of a W boson, and, in particular, the final state with two same-charge W bosons [24]. The SHS $\text{W}^{\pm}\text{W}^{\pm}$ production includes two additional partons and its cross section is therefore suppressed at the matrix-element level. Figure 1 illustrates the production of $\text{W}^{\pm}\text{W}^{\pm}$ via the DPS process (left) and via SHS processes (middle and right) at leading order (LO) in perturbative quantum chromodynamics (QCD). The absence of jets in the $\text{W}^{\pm}\text{W}^{\pm}$ production via DPS at LO in perturbation theory provides an additional handle to reduce the contributions from the SHS backgrounds by introducing an upper limit on the number of jets. Moreover, when both W bosons decay leptonically, this event exhibits a clean final state in the detector, and the excellent reconstruction and resolution of leptons in the CMS detector provides an accurate measurement of the WW DPS cross section.

However, DPS WW production has not been observed experimentally. An observation of this process would permit the validation of the factorization approach, which is prevalent in current Monte Carlo (MC) event generators. In addition, it is proposed that angular observables in the DPS $\text{W}^{\pm}\text{W}^{\pm}$ process are sensitive to nontrivial longitudinal momentum correlations among the partons [25–27].

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

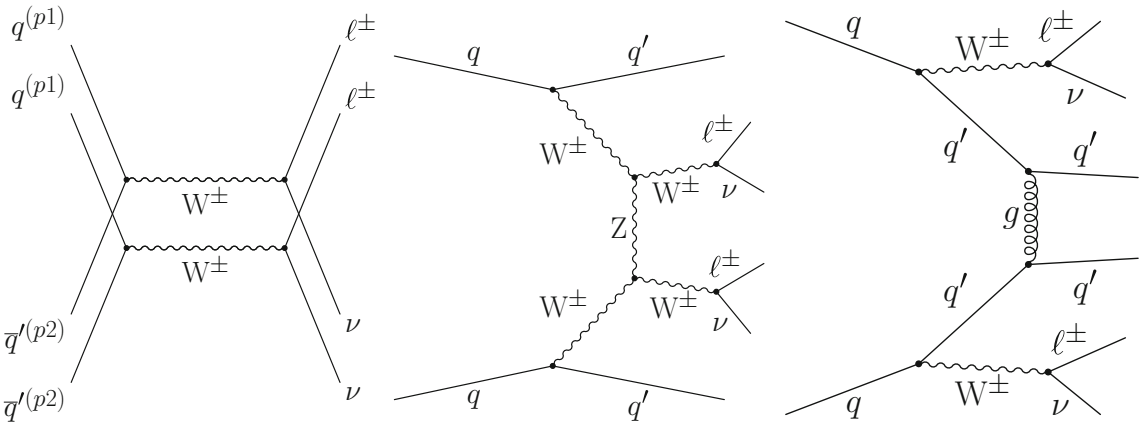


Fig. 1 Schematic diagrams corresponding to the production of $W^{\pm}W^{\pm}$ via the DPS process (left) and via SHS processes (middle and right), with both W bosons further decaying leptonically

The DPS $W^{\pm}W^{\pm}$ process also constitutes a background in searches for new physics at the CERN LHC, e.g., in searches for the electroweak production of supersymmetric particles [28]. A measurement of the DPS WW production cross section ($\sigma_{\mathrm{DPS\,WW}}$) would improve the reach of such searches.

A search for the production of $W^{\pm}W^{\pm}$ via DPS was reported in the past by the CMS Collaboration using pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$, and an upper limit of 0.32 pb was set on its production cross section at 95% confidence level [19]. An increased production cross section at $\sqrt{s} = 13\,\mathrm{TeV}$ and a larger data set collected using the CMS detector allow a more detailed study of this rare and interesting physics process. This paper presents a measurement of this process performed with pp collision data, recorded using the CMS experiment at a center-of-mass energy of 13 TeV in 2016 and 2017. The analyzed data sample corresponds to an integrated luminosity of 77.4 fb^{-1}.

The analysis focuses on the leptonic decay of the W bosons in final states consisting of a same-charge electron-muon ($e^{\pm}\mu^{\pm}$) or dimuon ($\mu^{\pm}\mu^{\pm}$) pair, which include small contributions from leptonic τ decays. The dielectron final state is not considered because of the relatively higher level of backgrounds.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. The bore of the solenoid is outfitted with various particle detection systems. Charged-particle trajectories are measured in the silicon pixel and strip trackers, covering $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, with θ being the polar angle of the trajectory of the particle with respect to the counterclockwise direction. A crystal electromagnetic calorimeter (ECAL), and a brass/scintillator hadron calorimeter surround the tracking volume. In this analysis, the calorimetry provides high resolution energy and direction measurements of electrons and hadronic jets. A preshower detector consisting of two planes of silicon sensors interleaved with lead is located in front of the ECAL at $|\eta| > 1.479$. Muons are measured in gas detectors embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, allowing energy balance measurements in the plane transverse to the beam directions. A two-tier trigger system selects the most interesting pp collision events for use in physics analysis [29]. A more detailed description of the CMS detector can be found in Ref. [30].

3 Event selection criteria

A particle-flow (PF) technique is used to reconstruct and identify particles in the event [31]. It combines subdetector-level information to reconstruct individual particles and identify them as charged and neutral hadrons, photons, and leptons. Electron and muon candidates are reconstructed by associating a charged-particle track reconstructed in the silicon detectors with a cluster of energy in the ECAL [32] or a track in the muon system [33]. These PF candidates are used to reconstruct higher-level objects, such as jets, hadronically decaying τ leptons (τ_{h}), and missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$). The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is computed as the negative vector p_{T} sum of all the PF candidates in an event, and its magnitude is denoted as $p_{\mathrm{T}}^{\mathrm{miss}}$ [34]. The τ_{h} candidates are reconstructed via the "hadrons plus strips" algorithm [35] and are further selected using a multivariate (MVA) classifier to reduce the misidentification rate of light-quark and gluon jets.

The reconstructed vertex with the largest value of summed physics-object p_{T}^2 is the primary pp interaction vertex. Jets are reconstructed from charged and neutral PF candidates

clustered using the anti-k_T clustering algorithm [36,37] with a distance parameter of 0.4, as implemented in the FastJet package [37,38].

Two b tagging algorithms, which depend on the year of data taking [39,40], are used to identify jets originating from b quarks. They are based on neural networks and combine information on tracks and secondary vertices. The chosen working points correspond to a b tagging efficiency in the range of 80–90% and a mistagging rate around 10%. Reconstructed jets must not overlap with identified electrons, muons, or τ_h within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$. To suppress jets originating from instrumental background or from additional pp interactions in the same and nearby bunch crossings (pileup), a jet quality requirement based on the energy fraction of neutral hadrons and charged hadrons associated with the primary vertex is applied [41]. The energy scale of jets is corrected for the nonlinear energy response of the calorimeters and the residual differences between the jet energy scale in the data and in the simulation, separately in the different data taking periods. The jet energy scale corrections are propagated to p_T^{miss}.

Leptons are required to originate from the primary vertex of the event to mitigate pileup effects. An MVA classifier is used to distinguish between "prompt" electrons and muons coming from W, Z, or τ lepton decays and "nonprompt" leptons originating from heavy-quark decays or quark and gluon jets incorrectly reconstructed as leptons. This MVA classifier is trained using a set of observables related to the lepton kinematics, isolation, and identification, as well as variables relating the lepton to the nearest reconstructed PF jet, as described in Ref. [42]. The requirement of this lepton MVA classifier, referred to as the "tight" selection, corresponds to a selection efficiency for prompt leptons of about 90%, and has an efficiency for nonprompt leptons at the percent level. Further selection criteria are applied to ensure the correct assignment of the electric charge in the reconstruction. These selection criteria include requirements on the number of hits in the pixel system for electrons and on the agreement in the charge assignments of multiple reconstruction algorithms for muons.

Events are selected using a combination of dilepton and single-lepton triggers with different lepton p_T thresholds. The minimum p_T threshold requirements on the leading (subleading) lepton for the electron-muon and dimuon triggers are 23 (8) and 17 (8) GeV, respectively. The single-lepton triggers, used to increase the trigger efficiency, employ lepton p_T thresholds of 32 or 35 GeV for electrons and 24 or 27 GeV for muons.

The signal process is characterized by the presence of a pair of leptons of the same electric charge, along with a moderate amount of p_T^{miss} originating from the neutrinos in the W boson decays.

Table 1 Event selection criteria

Two leptons: $e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$
$p_T^{\ell_1} > 25\,\text{GeV}$, $p_T^{\ell_2} > 20\,\text{GeV}$
$\lvert\eta_e\rvert < 2.5$, $\lvert\eta_\mu\rvert < 2.4$
$p_T^{miss} > 15\,\text{GeV}$
$N_{jets} < 2$ ($p_T^{jet} > 30\,\text{GeV}$ and $\lvert\eta_{jet}\rvert < 2.5$)
$N_{b-tagged\,jets} = 0$ ($p_T^{b\,jet} > 25\,\text{GeV}$ and $\lvert\eta_{b\,jet}\rvert < 2.4$)
Veto on additional e, μ, and τ_h candidates

A "loose" set of requirements is imposed to retain a large set of events for training the boosted decision trees (BDT) that separate the signal from the main backgrounds [43]. Events are selected by requiring exactly two leptons of the same charge, $e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$, with p_T greater than 25 (20) GeV for the leading (subleading) lepton, and $|\eta| < 2.5$ (2.4) for electrons (muons). Events are vetoed if there are additional leptons fulfilling looser identification and isolation requirements. The p_T thresholds for these additional leptons are 7 GeV for electrons, 5 GeV for muons, and 20 GeV for τ_h candidates. A lower threshold of 15 GeV is applied to p_T^{miss}, which retains most of the signal events, while significantly reducing the contributions from QCD multijet production, i.e., events from heavy- and light-flavor jets produced via strong interactions. The signal process involves no jet activity at LO although around 25% of signal events contain at least one reconstructed jet with $p_T^{jet} > 30\,\text{GeV}$ within $|\eta_{jet}| < 2.5$. To ensure high signal efficiency, a requirement of at most one such jet is imposed. Processes with b quark jets, such as $t\bar{t}$, are further suppressed by rejecting events with at least one b-tagged jet having $p_T^{b\,jet} > 25\,\text{GeV}$ and $|\eta_{b\,jet}| < 2.4$. The event selection criteria are summarized in Table 1.

4 Simulated samples

A set of simulated samples is used to estimate the signal and some of the backgrounds, whereas other backgrounds are estimated using the data control regions, as described below.

The signal process is simulated at LO in perturbation theory using the pythia 8.226 [44] event generator with the underlying tune CUETP8M1 [23] for 2016, and pythia 8.230 with the tune CP5 [45] for 2017 conditions. The resulting values for σ_{eff} of the two pythia tunes are 29.9 mb for CUETP8M1 and 19.5 mb for CP5. The large difference between these values and the resulting tune dependence of $\sigma_{DPS\,WW}$ underline the importance of measuring $\sigma_{DPS\,WW}$ experimentally. For the interpretation of the results a production cross section of 1.92 pb, obtained with the CP5 tune, is used.

Another set of signal events is simulated using the MC event generator herwig++ [46] with tune CUETHppS1 [23]

and the CTEQ6L1 [47] PDF set. The kinematic observables are described consistently with the PYTHIA and HERWIG++ event generators. Neither the underlying generator tune, nor the different PDF sets used to generate the samples, impact the kinematic observables relevant to the analysis.

The WZ process is simulated at next-to-LO (NLO) with POWHEG version 2.0 [48,49] and MADGRAPH5_aMC@NLO 2.3.3 [50]. The former is used for the central prediction of this background, while the latter is used for the study of systematic differences in kinematic distributions. The $W\gamma$ and $Z\gamma$ samples, relevant to the $e^{\pm}\mu^{\pm}$ final state, are generated with the MADGRAPH5_aMC@NLO event generator at NLO and LO, respectively. To account correctly for parton multiplicities larger than one in the matrix element calculations, the FxFx jet merging scheme [51] is used for the NLO samples, while the MLM jet merging scheme [52] is used for the LO samples. The background contributions arising from $W\gamma^*$ and ZZ production processes are simulated at NLO with the POWHEG event generator, while MADGRAPH5_aMC@NLO is used to simulate the SHS WW process.

The generators are interfaced with PYTHIA to model parton showering and hadronization with the same underlying tunes used for the signal generation. The NNPDF PDF sets with version 3.0 [53] are used for 2016, while NNPDF v3.1 [54] PDF sets are used for 2017 conditions in the simulation of all processes. The CMS detector response is modeled in the simulated events using GEANT4 [55], and are reconstructed with the same algorithms used for the data. Simulated events are weighted to reproduce the pileup distribution measured in the data. The average pileup in data was 23 in 2016 and 32 in 2017. The simulated MC events are scaled to correspond to the respective theoretical cross sections using the highest order prediction available in each case [56,57].

5 Background estimation

Background processes can be separated into two categories. The first category consists of processes with genuine same-charge lepton pairs from leptonic decays of bosons produced in the hard scattering. These processes include first and foremost the WZ process, in which both bosons decay leptonically and one of the leptons from the Z boson decay is either out of detector acceptance or does not pass the identification criteria. Other such processes include $W\gamma^*$, $W\gamma$, $Z\gamma$, and ZZ production, as well as – to a lesser extent – the SHS $W^{\pm}W^{\pm}$ and WWW processes. Processes involving associated production of W/Z bosons and photons contribute via asymmetric conversions of the photons into lepton pairs inside the detector. All these background components are estimated from MC simulation after applying scale factors to correct for residual differences between simulation and data in the selection, reconstruction, and the modeling of the trigger. These scale factors are measured using a "tag-and-probe" method [42].

The second category consists of two types of experimental backgrounds that resemble the production of prompt, same-charge lepton pairs. The first type includes nonprompt lepton backgrounds in which one or two of the selected leptons do not originate from the decay of a massive boson from the hard scattering. This background component is dominated by W+jets and QCD multijet events, with smaller contributions from $t\bar{t}$ production. The second type of experimental background arises from the misassignment of the charge of an electron in the reconstruction and is dominated by $Z \to \tau\tau$ when both τ leptons decay leptonically to form an electron-muon pair.

Nonprompt leptons arise largely from leptonic heavy-flavor decays and from jets misidentified as leptons. The main difference between a nonprompt and a prompt lepton is the presence of larger hadronic activity around the lepton direction for the former. This hadronic activity influences the lepton isolation and identification variables, and consequently the lepton MVA classifier used for the selection of leptons. The selection criterion on this lepton MVA variable is relaxed to define loose lepton selection criteria, and the leptons selected with this relaxed MVA threshold are called "loose" leptons.

The lepton misidentification rate, which is defined as the probability of a "loose" nonprompt lepton to pass the "tight" lepton selection criteria, is estimated directly from the data in a sample dominated by nonprompt leptons from QCD multijet and W+jets processes [42]. This control sample is constructed by requiring exactly one "loose" lepton and at least one jet with $\Delta R(\text{jet}, \ell) > 1.0$ away from the lepton. To suppress contributions of prompt leptons from electroweak processes, an upper limit of 40 GeV is imposed on both $p_{\mathrm{T}}^{\mathrm{miss}}$ and the transverse mass of the lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$. The transverse mass of two objects is defined as

$$m_{\mathrm{T}}(1,\,2) = \sqrt{2 p_{\mathrm{T}}^{(1)} p_{\mathrm{T}}^{(2)} [1 - \cos \Delta\phi(1,\,2)]}, \tag{2}$$

where $\Delta\phi(1,\,2)$ corresponds to the azimuthal angular difference between the momenta of the two objects.

The residual contamination of prompt leptons in this control sample is subtracted using simulation. The lepton misidentification rate is measured separately for electrons and muons as a function of the lepton p_{T} and $|\eta|$.

To estimate the contribution of events with nonprompt leptons to the signal region, another control sample of events is defined in the data. It is composed of events in which either one or both leptons fail the lepton MVA selection criteria but pass the "loose" selection, resulting in a sample of "tight-loose" and "loose-loose" lepton pairs. These events are reweighted as a function of the lepton misidentification rates

to obtain the estimated contribution from this background in the signal region.

Similar to the nonprompt lepton background, the probability for the charge of a lepton to be incorrectly reconstructed is calculated and applied to the selected opposite-charge dilepton events in data. This lepton p_{T}-$|\eta|$ dependent charge misidentification rate is measured in $\mathrm{Z} \to \mathrm{ee}$ events as the ratio of same-charge to opposite-charge dilepton events. Its value ranges from 0.02 (0.01)% for electrons in the barrel to 0.40 (0.16)% for electrons in the endcaps for 2016 (2017) data. The charge misidentification rate for muons is negligible.

6 Multivariate classifier training

The major background contributions arise from WZ production and processes with nonprompt leptons. To separate the signal from these two background components, two separate MVA classifiers are trained using a set of kinematic variables.

The WZ background is kinematically very similar to the signal, because they both have two prompt leptons with moderate $p_{\mathrm{T}}^{\mathrm{miss}}$. Neither the signal nor the WZ process feature any hadronic activity in the form of high-p_{T} jets at LO, and the masses of the bosons decaying to leptons are very similar, resulting in similar p_{T} spectra for the leptons. The main difference between the signal and WZ production is that in WZ production the bosons share a Lorentz boost along the z-axis, whereas the bosons in the signal process are approximately uncorrelated.

In the case of nonprompt lepton production, dominated by W+jets and QCD multijet processes, the kinematic differences with respect to the signal are larger. However, these processes have production cross sections that are orders of magnitude larger than that for the signal process. Therefore, even with a low probability of passing the event selection criteria, the impact of these background processes is considerable.

A BDT-based framework combines this information to discriminate between the signal and the background events. The BDT training against the WZ sample is done using its simulated sample, whereas the training against nonprompt leptons is carried out using a "tight-loose" control sample in data.

The following set of eleven input variables based on the lepton and event kinematics are used to train the BDTs:

- $p_{\mathrm{T}}^{\ell_1}$ and $p_{\mathrm{T}}^{\ell_2}$: transverse momenta of the two leptons;
- $p_{\mathrm{T}}^{\mathrm{miss}}$;
- $\eta_{\ell_1}\eta_{\ell_2}$: product of pseudorapidities of the two leptons;
- $|\eta_{\ell_1}+\eta_{\ell_2}|$: absolute sum of η of the two leptons;
- $m_{\mathrm{T}}(\ell_1,\ p_{\mathrm{T}}^{\mathrm{miss}})$: transverse mass of the leading lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$;
- $m_{\mathrm{T}}(\ell_1,\ \ell_2)$: transverse mass of the two leptons;
- $|\Delta\phi(\ell_1,\ \ell_2)|$: azimuthal angular separation between the leptons;
- $|\Delta\phi(\ell_2,\ p_{\mathrm{T}}^{\mathrm{miss}})|$: azimuthal angular separation between the subleading lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$;
- $|\Delta\phi(\ell_1\ell_2,\ \ell_2)|$: azimuthal angular separation between the dilepton system and the subleading lepton;
- $m_{\mathrm{T2}}(\ell_1,\ \ell_2)$: the so-called "stransverse mass" of the dilepton and $p_{\mathrm{T}}^{\mathrm{miss}}$ system [58,59].

The stransverse mass is defined as

$$m_{\mathrm{T2}}(\ell_1,\ \ell_2) = \min_{\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}\,(1)}+\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}\,(2)}=\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left[\max\left(m_{\mathrm{T}}^{(1)}, m_{\mathrm{T}}^{(2)}\right)\right], \tag{3}$$

in which $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is divided into two missing momentum vectors, $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}\,(1)}$ and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}\,(2)}$, to produce the transverse masses $m_{\mathrm{T}}^{(1/2)}$ with the leptons in the event. In the case where both leptons and both neutrinos originate from mother particles of equal mass, the $m_{\mathrm{T2}}(\ell_1,\ \ell_2)$ variable exhibits an end point at the mother particle mass. All these variables show significant discrimination between the signal and background processes. The background estimations describe the data well for these variables.

The two classifiers are mapped into a single two-dimensional (2D) classifier by combining contiguous regions in the 2D plane of the two separate classifiers. These regions are chosen to optimize the constraining power of the maximum likelihood fit. Namely, bins are chosen so that some exhibit large signal-to-background ratio, while others are chosen to have small signal contribution, but large contributions of either of the two main backgrounds. In total, the 2D plane is split into 15 such bins, on which the final fit is performed. Several different choices of mapping the 2D plane into a one-dimensional (1D) classifier are tested according to these criteria, and the one exhibiting the largest expected significance for the signal is chosen.

Events are analyzed separately in the two distinct lepton flavor channels and the two – positive and negative – charge configurations. Because the signal process is expected to be enhanced in the $\ell^+\ell^+$ configuration, while the background processes exhibit more symmetry between the two charges, the classification into the two charge configurations increases the sensitivity of the analysis.

7 Systematic uncertainties

Various sources of systematic uncertainties, experimental and theoretical, can be grouped into two categories. The first type changes the overall normalization of one or more processes, whereas the second one can change both the normal-

ization and the shape of the final 1D classifier distribution. Their values and their correlation structure among the different data-taking periods and processes are described below.

The uncertainty in the integrated luminosity is 2.5 (2.3)% for the 2016 (2017) data-taking period [60,61]. The two values are considered uncorrelated between the 2 years and are applied to all background processes estimated from simulation, as well as the signal.

The dominant source of experimental systematic uncertainty is associated with the method adopted for the estimation of nonprompt lepton contributions. A normalization uncertainty of 40 (25)% for the $e^{\pm}\mu^{\pm}$ ($\mu^{\pm}\mu^{\pm}$) final state is applied to account for the observed variations in the performance of the background estimation method when applied to MC simulations. Variations in the misidentification rate as a function of p_T and η of the leptons are included in addition to the uncertainties stemming from the kinematics of the event sample used to measure the lepton misidentification rate. These kinematic variations are estimated by varying the p_T of the jets in this sample, leading to shape variations of the order of 5–10% for the final classifier. The overall normalization uncertainty is considered correlated between the years, but uncorrelated between the two flavor channels, whereas the shape uncertainties are considered fully uncorrelated between the years and flavor channels.

A 30% normalization uncertainty is applied to the "charge misid." background in the $e^{\pm}\mu^{\pm}$ final state, covering the differences in the measurement of the charge misidentification rate in data and simulation. This uncertainty is treated as fully correlated between the years.

Normalization uncertainties for the main backgrounds estimated from simulation are derived in dedicated 3 (4) lepton control regions for the WZ (ZZ) processes. The scale factors for the WZ and ZZ processes are measured to be 1.01 ± 0.16 and 0.97 ± 0.06, respectively. The normalization uncertainties are estimated from the statistical uncertainty and purity of these control samples and their scale factors, and take values of 16 (6)% for the WZ (ZZ) process. A 50% normalization uncertainty is applied to all other simulated backgrounds, accounting for the theoretical uncertainties in the predicted cross sections and the lack of proper control samples in the data. The shape of the WZ process is allowed to vary between the shapes coming from the two event generators, POWHEG and MADGRAPH5_aMC@NLO, and the corresponding uncertainty is considered correlated between 2016 and 2017. The shape agreement in the kinematic observables between the prediction and observation is of the order of 5% in the WZ and ZZ control regions. It is assumed that the shape agreement is similar in all remaining simulation-derived backgrounds. Therefore a 5% shape uncertainty is applied to these components, which allows the shape of the final classifier to vary by up to 5% linearly and quadratically along the classifier distribution. The effect of variations in the renormalization and factorization scales is negligible for the most important background component, WZ, and is therefore neglected. Uncertainties in the PDF sets are expected to play a small role compared to the uncertainties described above. Both the relevant generator level distributions such as the rapidity of the W boson and the observable kinematic variables used in the analysis are consistent between NNPDF sets v3.0 and v3.1. An additional complication in the estimation of the uncertainty in the PDFs arises because the standard procedures for evaluating such uncertainties are ill-defined in the case of the signal process. For instance, varying a PDF set by any number of replicas is an inadequate estimation of the modeling uncertainty that emerges because the two PDF terms of the separate hard scatters are factorized when simulating signal events. Therefore, such uncertainties are not considered. Rather, future measurements with larger data sets will allow the study of the production cross section differentially in observables that are sensitive to such nonfactorization effects.

The uncertainty in the pileup modeling is 1% in the total yield for all simulated backgrounds and the signal, and is assumed correlated among all flavors, charges, and years. No significant differences in the kinematics are observed because of the pileup modeling. The uncertainty in the b tagging is considerably smaller than the statistical uncertainty in the simulated samples and is therefore neglected. The acceptance effect of the uncertainty in the jet energy scale is 2% in the signal and the simulated background samples and is considered fully correlated among all channels.

The trigger efficiency uncertainty associated with the combination of single-lepton and dilepton triggers is 1–2%, whereas the uncertainty in the data-to-simulation scale factors for the "loose" lepton selection is 2%. These uncertainties are considered correlated among the flavor channels but uncorrelated between the years. The uncertainty in the "tight" lepton selection is 2–3%, and is considered correlated between the 2 years.

Any residual model dependence of the signal process is estimated by allowing the shape of the DPS WW process to vary between the PYTHIA and HERWIG++ simulations. The corresponding variations in the final BDT classifier are small.

Finally, the statistical uncertainty arising from the limited number of events in the simulated samples is included independently for each bin of the final discriminant distribution for each final state and the two data-taking periods, and is treated as fully uncorrelated [62].

8 Statistical analysis and results

Results are obtained after combining all the background and signal processes in the two separate flavor configurations, $e\mu$ and $\mu\mu$, and two separate charge configurations, $\ell^+\ell^+$

Table 2 Postfit background and signal yields and their uncertainties, and the observed event counts in the four charge and flavor combinations. The uncertainties include both statistical and systematic components. The SHS $W^{\pm}W^{\pm}$ and WWW contributions are grouped as the "Rare" background

	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$
Nonprompt	462 ± 71	411 ± 62	142 ± 31	118 ± 26
WZ	834 ± 74	543 ± 50	537 ± 49	329 ± 31
ZZ	71 ± 6	66 ± 6	44 ± 4	38 ± 4
$W\gamma^*$	256 ± 73	227 ± 65	133 ± 38	118 ± 34
Rare	48 ± 17	23 ± 8	35 ± 13	14 ± 5
Charge misid.	17 ± 5	17 ± 5	–	–
$W/Z\gamma$	131 ± 36	104 ± 28	–	–
Total background	1819 ± 132	1391 ± 107	891 ± 71	617 ± 53
DPS $W^{\pm}W^{\pm}$	77 ± 22	40 ± 12	57 ± 16	29 ± 9
Data	1840	1480	926	675

and $\ell^-\ell^-$, resulting in four independent distributions of the final BDT classifier. The final maximum likelihood fit is performed simultaneously in these four distinct flavor and charge categories [63–65]. The classification of events into the two charge configurations increases the sensitivity of the analysis by 10%.

Systematic uncertainties are represented in the likelihood by individual nuisance parameters, and are profiled in the fit as described in Ref. [66]. The number of events in each bin of the final classifier distribution used to extract the signal is modeled as a Poisson random variable, with a mean value that is equal to the sum of signal and background contributions.

In total, 4921 events are observed in the four lepton-charge and flavor combinations. Table 2 summarizes the yields of the various background and signal components along with their associated total uncertainties after the ML fit (postfit).

Figure 2 shows the distribution of the final BDT classifier in the two charge configurations in the eμ channel in the upper row, and the two charge configurations in the μμ channel in the lower row, under the same scenario as in Table 2, i.e., postfit background and signal yields, together with the postfit total uncertainties.

Although the fit is performed with all the kinematic requirements applied, the following cross sections are quoted as inclusive production cross sections for DPS WW. The kinematic acceptance, defined as the ratio of events having a same-charge electron-muon or dimuon pair from the W boson decays and passing the analysis-level kinematic selection to the total number of generated events, is measured using the PYTHIA generator. In this definition, the leptons are used at the "dressed" level where the momentum of a lepton is defined by combining its pre-final-state radiation four-momentum with that of photons radiated within a cone defined by $\Delta R = 0.1$ around the lepton. The kinematic acceptance is measured to be $4.70 \pm 0.02\,(\text{stat}) \pm 0.94\,(\text{model})\,\%$. The model uncertainty accounts for the differences in acceptance measured using different PDF sets (NNPDF v3.0 and NNPDF v3.1), different PYTHIA generator tunes (CUETP8M1 and CP5), and with different event generators (PYTHIA and HERWIG++). This uncertainty is dominated by the differences seen between the PYTHIA and HERWIG++ event generators.

The prediction of any DPS WW cross section suffers from large uncertainties. For the factorization approach from Eq. (1), the largest uncertainty comes from the imprecise knowledge of σ_{eff}, which differs substantially between different measurements in different final states [17]. Any predicted cross section from an MC simulation, such as the one obtained from PYTHIA also suffers from large uncertainties because of the tuning of generator parameters sensitive to the modeling of the underlying event. Although the kinematic observables are tested to be unaffected by these tuning parameters, the predicted cross section varies by as much as 50%. It is therefore essential to interpret any "predicted" number in the following, either from the factorization approach or from PYTHIA, only as a rough estimate rather than a precisely derived quantity. Conversely, any observed cross section and the corresponding significance do not depend on the predicted cross section, but only on the kinematics of the MC generator. These limitations emphasize the importance of measuring the cross section of the DPS WW process from data.

For this analysis, two predicted cross sections are used. The PYTHIA event generator with the CP5 tune gives a cross section of 1.92 pb. Alternatively, using Eq. (1) with the highest order cross section for inclusive W boson production and decay at next-to-NLO accuracy in QCD and NLO in electroweak corrections [67,68], 189 ± 7 nb, along with $\sigma_{\text{eff}} = 20.7 \pm 6.6$ mb [17], results in an expected cross section for the inclusive DPS WW process of 0.87 ± 0.28 pb. The value for σ_{eff} is chosen as a representative number from a DPS cross section measurement based on a final state containing a W boson. A different choice of σ_{eff} would alter the prediction of the cross section from the factorization approach accordingly.

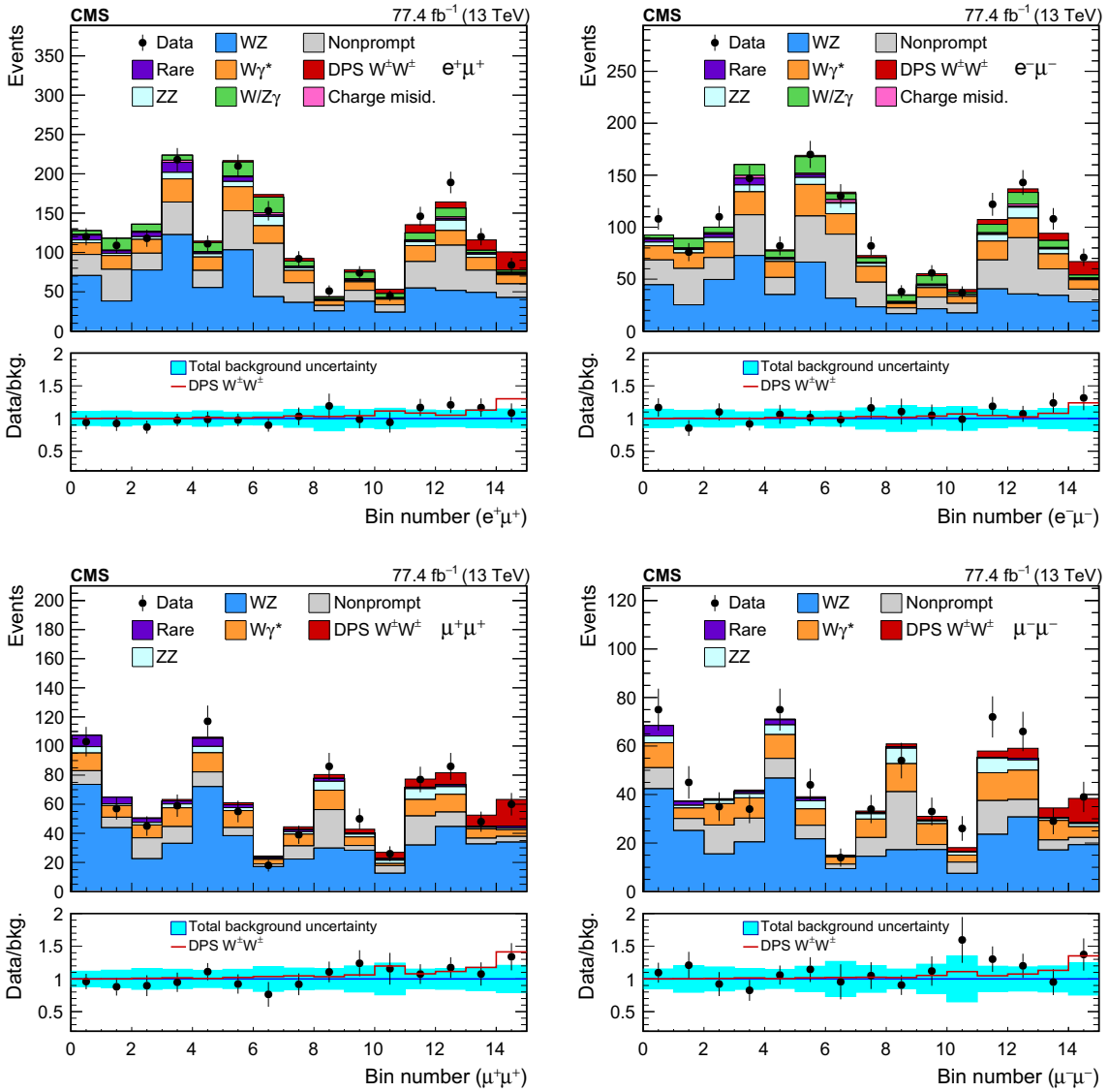


Fig. 2 Distribution of the final BDT classifier output for eμ (upper) and μμ (lower) final states, in the positive (left) and negative (right) charge configurations. Observed data are shown in black markers while the backgrounds and signal are shown in colored histograms with their postfit yields. The SHS $W^{\pm}W^{\pm}$ and WWW contributions are grouped in the "Rare" background category. The bottom panels show the ratio of data to the sum of all background contributions in the black markers along with the signal shown using a red line. The band represents the postfit background uncertainty, which includes both the statistical and systematic components

The following quantities are obtained from the simultaneous fit to the final BDT classifier in the four lepton charge and flavor combinations:

- the expected significance assuming the signal process follows the PYTHIA kinematics with the input cross section as $\sigma^{\text{PYTHIA}}_{\text{DPS WW, exp}}$;
- the expected significance assuming the signal process exhibits PYTHIA-like kinematics with a production cross section, $\sigma^{\text{factorized}}_{\text{DPS WW, exp}}$, extracted based on the factorization approach using the inclusive W production cross section and value of σ_{eff} mentioned above;
- the observed cross section $\sigma_{\text{DPS WW, obs}}$ and the corresponding significance, assuming PYTHIA-like kinematics, independent of the assumed cross section;
- σ_{eff} using the inclusive W production cross section and $\sigma_{\text{DPS WW, obs}}$.

A maximum likelihood fit is performed separately for different lepton charge configurations and their combination. The values obtained for the DPS $W^{\pm}W^{\pm}$ cross section are then extrapolated to the inclusive WW phase space. Table 3 summarizes the numbers extracted from the maximum likeli-

Table 3 Results obtained from the maximum likelihood fit to the final classifier distribution

	Value	Significance (standard deviations)
$\sigma^{\text{PYTHIA}}_{\text{DPS WW, exp}}$	1.92 pb	5.4
$\sigma^{\text{factorized}}_{\text{DPS WW, exp}}$	0.87 pb	2.5
$\sigma_{\text{DPS WW, obs}}$	$1.41 \pm 0.28\,(\text{stat}) \pm 0.28\,(\text{syst})$ pb	3.9
σ_{eff}	$12.7^{+5.0}_{-2.9}$ mb	—

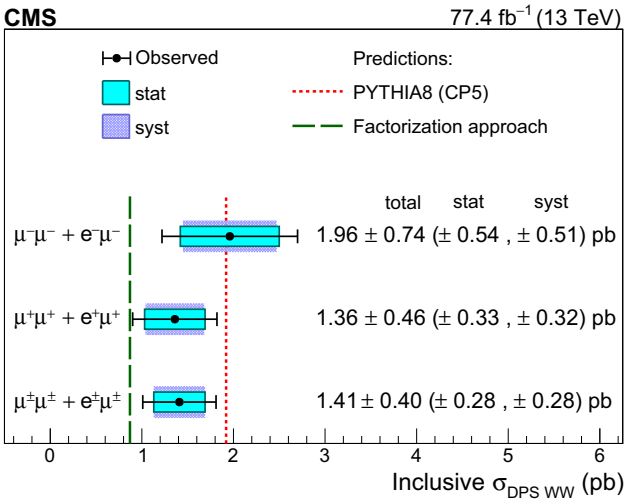


Fig. 3 Observed cross section values for inclusive DPS WW production from the two lepton charge configurations and their combination. These values are obtained from the extrapolation of the observed DPS $W^{\pm}W^{\pm}$ cross section to the inclusive WW case. The statistical and systematic uncertainties are shown using shaded bands. The predictions from PYTHIA and from the factorization approach are represented with the red dotted and green dashed lines, respectively

hood fit to the final classifier distribution for the combination of the $\ell^+\ell^+$ and $\ell^-\ell^-$ final states.

The observed inclusive DPS WW production cross section is $1.41 \pm 0.28\,(\text{stat}) \pm 0.28\,(\text{syst})$ pb with an observed significance of 3.9 standard deviations with respect to the background-only hypothesis. This value lies between the prediction from PYTHIA, which gives a cross section of 1.92 pb with an expected significance of 5.4 standard deviations, and the one of the factorization approach, which predicts a cross section of 0.87 pb with an expected significance of 2.5 standard deviations.

The values of the inclusive DPS WW production cross sections, obtained from the positive and negative lepton charge configurations, along with their combination, are shown in Fig. 3. The expected values for $\sigma_{\text{DPS WW}}$, taken from PYTHIA and the factorization approach, are also shown. The positive charge configuration results in a measured inclusive cross section of $1.36 \pm 0.33\,(\text{stat}) \pm 0.32\,(\text{syst})$ pb, whereas for the negative charge configuration the value is $1.96 \pm 0.54\,(\text{stat}) \pm 0.51\,(\text{syst})$ pb.

A value of σ_{eff} is extracted from Eq. (1) in the following way. The SHS cross sections for inclusive W boson production are taken from theoretical calculations at next-to-NLO in QCD and NLO in electroweak corrections, as described before. These cross sections are then combined with the measured DPS $W^{\pm}W^{\pm}$ cross section, extrapolated to the full WW phase space, to extract a value for σ_{eff}. This procedure results in a value for σ_{eff} of $12.7^{+5.0}_{-2.9}$ mb, consistent with previous measurements of this quantity from other final states [20]. This hybrid approach employed for calculating σ_{eff} using, on the one hand, a theoretical prediction and, on the other hand, the measured DPS WW cross section results from the following consideration. Because the statistical uncertainty dominates the measured $\sigma_{\text{DPS WW}}$ and the leading systematic uncertainties are specific to the $\ell^{\pm}\ell^{\pm}$ final state, these would not cancel with the uncertainties in a measurement of the single W boson production cross section. Therefore, the benefit of measuring the single W boson production cross section to extract a fully experimental value for σ_{eff} is negligible.

9 Summary

A study of WW production from double-parton scattering (DPS) processes in proton-proton collisions at $\sqrt{s} = 13$ TeV has been reported. The analyzed data set corresponds to an integrated luminosity of 77.4 fb^{-1}, collected using the CMS detector in 2016 and 2017 at the LHC. The WW candidates are selected in same-charge electron-muon or dimuon events with moderate missing transverse momentum and low jet multiplicity. Multivariate classifiers based on boosted decision trees are used to discriminate between the signal and the dominant background processes. A maximum likelihood fit is performed to extract the signal cross section, which is compared to the predictions from simulation and from an approximate factorization approach. A measurement of the DPS WW cross section is achieved for the first time, and a cross section of $1.41 \pm 0.28\,(\text{stat}) \pm 0.28\,(\text{syst})$ pb is extracted with an observed significance of 3.9 standard deviations. This cross section leads to an effective cross section parameter of $\sigma_{\text{eff}} = 12.7^{+5.0}_{-2.9}$ mb. The results in this paper constitute the first evidence for WW production from DPS.

Acknowledgements 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 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 and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium);

CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (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); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (UK); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the A.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 (FRIA-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. Z181100004218003; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Education, grant no. 3.2989.2017 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Nvidia Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS policy as written in its document "CMS data preservation, re-use and open access policy" (https://cmsdocdb.cern.ch/cgibin/PublicDocDB/RetrieveFile?docid=6032&filename=CMSDataPolicyV1.2.pdf&version=2).]

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

Funded by SCOAP[3].

References

1. C. Goebel, F. Halzen, D.M. Scott, Double Drell-Yan annihilations in hadron collisions: novel tests of the constituent picture. Phys. Rev. D **22**, 2789 (1980). https://doi.org/10.1103/PhysRevD.22.2789
2. V.P. Shelest, A.M. Snigirev, G.M. Zinovev, Gazing into the multiparton distribution equations in QCD. Phys. Lett. B **113**, 325 (1982). https://doi.org/10.1016/0370-2693(82)90049-1
3. T. Sjöstrand, M. van Zijl, A multiple interaction model for the event structure in hadron collisions. Phys. Rev. D **36**, 2019 (1987). https://doi.org/10.1103/PhysRevD.36.2019
4. G. Calucci, D. Treleani, Disentangling correlations in multiple parton interactions. Phys. Rev. D **83**, 016012 (2011). https://doi.org/10.1103/PhysRevD.83.016012. arXiv:1009.5881
5. M. Diehl, D. Ostermeier, A. Schafer, Elements of a theory for multiparton interactions in QCD. JHEP **03**, 089 (2012). https://doi.org/10.1007/JHEP03(2012)089. arXiv:1111.0910
6. B. Blok, Yu. Dokshitzer, L. Frankfurt, M. Strikman, Perturbative QCD correlations in multi-parton collisions. Eur. Phys. J. C **74**, 2926 (2014). https://doi.org/10.1140/epjc/s10052-014-2926-z. arXiv:1306.3763
7. M. Diehl, J.R. Gaunt, Double parton scattering theory overview. Adv. Ser. Direct. High Energy Phys. **29**, 7 (2018). https://doi.org/10.1142/9789813227767_0002. arXiv:1710.04408
8. P. Bartalini, J.R. Gaunt, Multiple parton interactions at the LHC. Adv. Ser. Direct. High Energy Phys. (2018). https://doi.org/10.1142/10646
9. AFS Collaboration, Double parton scattering in pp collisions at $\sqrt{s} = 63$ GeV. Z. Phys. C **34**, 163 (1987). https://doi.org/10.1007/BF01566757
10. UA2 Collaboration, A study of multi-jet events at the CERN $\bar{p}p$ collider and a search for double parton scattering. Phys. Lett. B **268** (1991). https://doi.org/10.1016/0370-2693(91)90937-L
11. CDF Collaboration, Study of four-jet events and evidence for double parton interactions in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. Phys. Rev. D **47**, 4857 (1993). https://doi.org/10.1103/PhysRevD.47.4857
12. CDF Collaboration, Double parton scattering in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. Phys. Rev. D **56**, 3811 (1997). https://doi.org/10.1103/PhysRevD.56.3811
13. CDF Collaboration, Measurement of double parton scattering in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. Phys. Rev. Lett. **79**, 584 (1997). https://doi.org/10.1103/PhysRevLett.79.584
14. D0 Collaboration, Double parton interactions in $\gamma + 3$ jet events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. Phys. Rev. D **81**, 052012 (2010). https://doi.org/10.1103/PhysRevD.81.052012. arXiv:0912.5104
15. LHCb Collaboration, Observation of double charm production involving open charm in pp collisions at $\sqrt{s} = 7$ TeV. JHEP **06**, 141 (2012), https://doi.org/10.1007/JHEP06(2012)141. arXiv:1205.0975. [Addendum: https://doi.org/10.1007/JHEP03(2014)108]
16. ATLAS Collaboration, Measurement of hard double-parton interactions in $W(\rightarrow l\nu) + 2$ jet events at $\sqrt{s} = 7$ TeV with the ATLAS detector. New J. Phys. **15**, 033038 (2013). https://doi.org/10.1088/1367-2630/15/3/033038. arXiv:1301.6872

17. CMS Collaboration, Study of double parton scattering using W +2-jet events in proton-proton collisions at $\sqrt{s} = 7$ TeV. JHEP **03**, 032 (2014). https://doi.org/10.1007/JHEP03(2014)032. arXiv:1312.5729
18. LHCb Collaboration, Production of associated Υ and open charm hadrons in pp collisions at $\sqrt{s} = 7$ and 8 TeV via double parton scattering. JHEP **07**, 052 (2016). https://doi.org/10.1007/JHEP07(2016)052. arXiv:1510.05949
19. CMS Collaboration, Constraints on the double-parton scattering cross section from same-sign W boson pair production in proton-proton collisions at $\sqrt{s} = 8$ TeV. JHEP **02**, 032 (2018). https://doi.org/10.1007/JHEP02(2018)032. arXiv:1712.02280
20. ATLAS Collaboration, Study of the hard double-parton scattering contribution to inclusive four-lepton production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector. Phys. Lett. B **790**, 595 (2019). https://doi.org/10.1016/j.physletb.2019.01.062. arXiv:1811.11094
21. ATLAS Collaboration, Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector. Eur. Phys. J. C **75**, 229 (2015). https://doi.org/10.1140/epjc/s10052-015-3406-9. arXiv:1412.6428
22. D0 Collaboration, Evidence for simultaneous production of J/ψ and Υ mesons. Phys. Rev. Lett. **116**, 082002 (2016). https://doi.org/10.1103/PhysRevLett.116.082002. arXiv:1511.02428
23. CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements. Eur. Phys. J. C **76**, 155 (2016). https://doi.org/10.1140/epjc/s10052-016-3988-x. arXiv:1512.00815
24. A. Kulesza, W.J. Stirling, Like sign W boson production at the LHC as a probe of double parton scattering. Phys. Lett. B **475**, 168 (2000). https://doi.org/10.1016/S0370-2693(99)01512-9. arXiv:hep-ph/9912232
25. J.R. Gaunt, C.-H. Kom, A. Kulesza, W.J. Stirling, Same-sign W pair production as a probe of double parton scattering at the LHC. Eur. Phys. J. C **69**, 53 (2010). https://doi.org/10.1140/epjc/s10052-010-1362-y. arXiv:1003.3953
26. F.A. Ceccopieri, M. Rinaldi, S. Scopetta, Parton correlations in same-sign W pair production via double parton scattering at the LHC. Phys. Rev. D **95**, 114030 (2017). https://doi.org/10.1103/PhysRevD.95.114030. arXiv:1702.05363
27. S. Cotogno, T. Kasemets, M. Myska, Spin on same-sign W-boson pair production. Phys. Rev. D **100**, 011503 (2019). https://doi.org/10.1103/PhysRevD.100.011503. arXiv:1809.09024
28. CMS Collaboration, Searches for electroweak production of charginos, neutralinos, and sleptons decaying to leptons and W, Z, and Higgs bosons in pp collisions at 8 TeV. Eur. Phys. J. C **74**, 3036 (2014). https://doi.org/10.1140/epjc/s10052-014-3036-7. arXiv:1405.7570
29. CMS Collaboration, The CMS trigger system. JINST **12**, P01020 (2017). https://doi.org/10.1088/1748-0221/12/01/P01020. arXiv:1609.02366
30. CMS Collaboration, The CMS experiment at the CERN LHC. JINST **3**, S08004 (2008). https://doi.org/10.1088/1748-0221/3/08/S08004
31. CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector. JINST **12**, P10003 (2017). https://doi.org/10.1088/1748-0221/12/10/P10003. arXiv:1706.04965
32. CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV. JINST **10**, P06005 (2015). https://doi.org/10.1088/1748-0221/10/06/P06005. arXiv:1502.02701
33. CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV. JINST **13**, P06015 (2018). https://doi.org/10.1088/1748-0221/13/06/P06015. arXiv:1804.04528
34. CMS Collaboration, Performance of missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV using the CMS detector, CMS Physics Analysis Summary CMS-PAS-JME-17-001 (2018). https://cds.cern.ch/record/2628600
35. CMS Collaboration, Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV. JINST **13**, P10005 (2018). https://doi.org/10.1088/1748-0221/13/10/P10005. arXiv:1809.02816
36. M. Cacciari, G.P. Salam, G. Soyez, The anti-k_T jet clustering algorithm. JHEP **04**, 063 (2008). https://doi.org/10.1088/1126-6708/2008/04/063. arXiv:0802.1189
37. M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual. Eur. Phys. J. C **72**, 1896 (2012). https://doi.org/10.1140/epjc/s10052-012-1896-2. arXiv:1111.6097
38. M. Cacciari, G.P. Salam, Dispelling the N^3 myth for the k_T jet-finder. Phys. Lett. B **641**, 57 (2006). https://doi.org/10.1016/j.physletb.2006.08.037. arXiv:hep-ph/0512210
39. CMS Collaboration, Identification of b quark jets with the CMS experiment. JINST **8**, P04013 (2013). https://doi.org/10.1088/1748-0221/8/04/P04013. arXiv:1211.4462
40. CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV. JINST **13**, P05011 (2018). https://doi.org/10.1088/1748-0221/13/05/P05011. arXiv:1712.07158
41. CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV. JINST **12**, P02014 (2017). https://doi.org/10.1088/1748-0221/12/02/P02014. arXiv:1607.03663
42. CMS Collaboration, Evidence for associated production of a Higgs boson with a top quark pair in final states with electrons, muons, and hadronically decaying τ leptons at $\sqrt{s} = 13$ TeV. JHEP **08**, 066 (2018). https://doi.org/10.1007/JHEP08(2018)066. arXiv:1803.05485
43. H. Voss, A. Höcker, J. Stelzer, F. Tegenfeldt, TMVA, the toolkit for multivariate data analysis with ROOT. in *XIth International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT)*, p. 40 (2007). arXiv:physics/0703039
44. T. Sjöstrand et al., An introduction to PYTHIA 8.2. Comput. Phys. Commun. **191**, 159 (2015). https://doi.org/10.1016/j.cpc.2015.01.024. arXiv:1410.3012
45. CMS Collaboration, Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements (2019). arXiv:1903.12179. **(Submitted to Eur. Phys. J. C)**
46. M. Bahr et al., Herwig++ physics and manual. Eur. Phys. J. C **58**, 639 (2008). https://doi.org/10.1140/epjc/s10052-008-0798-9. arXiv:0803.0883
47. J. Pumplin et al., New generation of parton distributions with uncertainties from global QCD analysis. JHEP **07**, 012 (2002). https://doi.org/10.1088/1126-6708/2002/07/012. arXiv:hep-ph/0201195
48. S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method. JHEP **11**, 070 (2007). https://doi.org/10.1088/1126-6708/2007/11/070. arXiv:0709.2092
49. S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX. JHEP **06**, 043 (2010). https://doi.org/10.1007/JHEP06(2010)043. arXiv:1002.2581
50. 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**, 079 (2014). https://doi.org/10.1007/JHEP07(2014)079. arXiv:1405.0301
51. R. Frederix, S. Frixione, Merging meets matching in MC@NLO. JHEP **12**, 061 (2012). https://doi.org/10.1007/JHEP12(2012)061. arXiv:1209.6215

52. J. Alwall et al., Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions. Eur. Phys. J. C **53**, 473 (2008). https://doi.org/10.1140/epjc/s10052-007-0490-5. arXiv:0706.2569
53. NNPDF Collaboration, Parton distributions for the LHC Run II. JHEP **04**, 040 (2015). https://doi.org/10.1007/JHEP04(2015)040. arXiv:1410.8849
54. NNPDF Collaboration, Parton distributions from high-precision collider data. Eur. Phys. J. C **77**, 663 (2017). https://doi.org/10.1140/epjc/s10052-017-5199-5. arXiv:1706.00428
55. GEANT4 Collaboration, GEANT4—simulation toolkit. Nucl. Instrum. Meth. A **506**, 250 (2003). https://doi.org/10.1016/S0168-9002(03)01368-8
56. J.M. Campbell, R.K. Ellis, C. Williams, Vector boson pair production at the LHC. JHEP **07**, 018 (2011). https://doi.org/10.1007/JHEP07(2011)018. arXiv:1105.0020
57. T. Binoth, G. Ossola, C.G. Papadopoulos, R. Pittau, NLO QCD corrections to tri-boson production. JHEP **06**, 082 (2008). https://doi.org/10.1088/1126-6708/2008/06/082. arXiv:0804.0350
58. C.G. Lester, D.J. Summers, Measuring masses of semi-invisibly decaying particles pair produced at hadron colliders. Phys. Lett. B **463**, 99 (1999). https://doi.org/10.1016/S0370-2693(99)00945-4. arXiv:hep-ph/9906349
59. A. Barr, C. Lester, P. Stephens, m_{T2}: the truth behind the glamour. J. Phys. G **29**, 2343 (2003). https://doi.org/10.1088/0954-3899/29/10/304. arXiv:hep-ph/0304226
60. CMS Collaboration, CMS luminosity measurements for the 2016 data-taking period, CMS Physics Analysis Summary CMS-PAS-LUM-17-001 (2017). https://cds.cern.ch/record/2257069
61. 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 (2018). http://cds.cern.ch/record/2621960
62. R.J. Barlow, C. Beeston, Fitting using finite Monte Carlo samples. Comput. Phys. Commun. **77**, 219 (1993). https://doi.org/10.1016/0010-4655(93)90005-W
63. CMS Collaboration, Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV. Eur. Phys. J. C **75**, 212 (2015). https://doi.org/10.1140/epjc/s10052-015-3351-7. arXiv:1412.8662
64. G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics. Eur. Phys. J. C **71**, 1554 (2011). https://doi.org/10.1140/epjc/s10052-011-1554-0. arXiv:1007.1727. [Erratum: https://doi.org/10.1140/epjc/s10052-013-2501-z]
65. A.L. Read, Presentation of search results: The CL_s technique. J. Phys. G **28**, 2693 (2002). https://doi.org/10.1088/0954-3899/28/10/313
66. ATLAS and CMS Collaborations, LHC Higgs Combination Group, Procedure for the LHC Higgs boson search combination in Summer 2011, Technical Report CMS-NOTE-2011-005. ATL-PHYS-PUB-2011-11 (2011). https://cds.cern.ch/record/1379837
67. C. Anastasiou, L.J. Dixon, K. Melnikov, F. Petriello, High precision QCD at hadron colliders: electroweak gauge boson rapidity distributions at NNLO. Phys. Rev. D **69**, 094008 (2004). https://doi.org/10.1103/PhysRevD.69.094008. arXiv:hep-ph/0312266
68. R. Gavin, Y. Li, F. Petriello, S. Quackenbush, W physics at the LHC with FEWZ 2.1. Comput. Phys. Commun. **184**, 208 (2013). https://doi.org/10.1016/j.cpc.2012.09.005. arXiv:1201.5896

CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. M. Sirunyan†, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth[1], M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerp, Belgium
M. R. Darwish, E. A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussels, Belgium
F. Blekman, E. S. Bols, S. S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Brussels, Belgium
D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A. K. Kalsi, J. Luetic, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, I. Khvastunov[2], C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, A. Magitteri, J. Prisciandaro, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F. L. Alves, G. A. Alves, G. Correia Silva, C. Hensel, A. Moraes, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[3], E. Coelho, E. M. Da Costa, G. G. Da Silveira[4], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L. M. Huertas Guativa, H. Malbouisson, J. Martins[5], D. Matos Figueiredo, M. Medina Jaime[6], M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W. L. Prado Da Silva, L. J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E. J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista[a], Universidade Federal do ABC[b], São Paulo, Brazil
S. Ahuja[a], C. A. Bernardes[a], L. Calligaris[a], T. R. Fernandez Perez Tomei[a], E. M. Gregores[b], D. S. Lemos, P. G. Mercadante[b], S. F. Novaes[a], Sandra S. Padula[a]

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang[7], X. Gao[7], L. Yuan

Institute of High Energy Physics, Beijing, China
M. Ahmad, G. M. Chen, H. S. Chen, M. Chen, C. H. Jiang, D. Leggat, H. Liao, Z. Liu, S. M. Shaheen[8], A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang[8], J. Zhao, V. Krutelyov[1]

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S. J. Qian, D. Wang, Q. Wang

Tsinghua University, Beijing, China
Z. Hu, Y. Wang

Universidad de Los Andes, Bogotá, Colombia
C. Avila, A. Cabrera, L. F. Chaparro Sierra, C. Florez, C. F. González Hernández, M. A. Segura Delgado

Universidad de Antioquia, Medellín, Colombia
J. Mejia Guisao, J. D. Ruiz Alvarez, C. A. Salazar González, N. Vanegas Arbelaez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Ceci, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov[9], T. Susa

University of Cyprus, Nicosia, Cyprus
M. W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P. A. Razis, H. Rykaczewski, D. Tsiakkouri

Charles University, Prague, Czech Republic
M. Finger[10], M. Finger Jr.[10], A. Kveton, J. Tomsa

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[11,12], S. Elgammal[12]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R. K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
F. Garcia, J. Havukainen, J. K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J. L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M. Ö. Sahin, A. Savoy-Navarro[13], M. Titov

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
C. Amendola, F. Beaudette, P. Busson, C. Charlot, B. Diab, G. Falmagne, R. Granier de Cassagnac, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J. B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[14], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E. C. Chabert, C. Collard, E. Conte[14], J.-C. Fontaine[14], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, C. Camen, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, F. Lagarde, I. B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili[15]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[10]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M. K. Kiesel, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M. P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, M. Erdmann, S. Erdweg, T. Esch, B. Fischer, R. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, M. Rieger, J. Roemer, A. Schmidt, S. C. Schuler, A. Sharma, S. Thüer, S. Wiedenbeck

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, W. Haj Ahmad[16], O. Hlushchenko, T. Kress, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[17]

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A. A. Bin Anuar, K. Borras[18], V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M. M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo[19], A. Geiser, J. M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N. Z. Jomhari, H. Jung, A. Kasem[18], M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, J. Lidrych, K. Lipka, W. Lohmann[20], R. Mankel, I.-A. Melzer-Pellmann, A. B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S. K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G. P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebcik

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, D. Marconi, J. Multhaup, M. Niedziela, C. E. N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F. M. Stober, M. Stöver, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
M. Akbiyik, C. Barth, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, P. Goldenzweig, A. Gottmann, M. A. Harrendorf, F. Hartmann[17], U. Husemann, I. Katkov[14], S. Kudella, S. Mitra, M. U. Mozer, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H. J. Simonis, R. Ulrich, M. Weber, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, A. Stakia, K. Theofilatos, K. Vellidis

National Technical University of Athens, Athens, Greece
G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioannina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitara, N. Manthos, I. Papadopoulos, J. Strologas, F. A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Bartók[21], M. Csanad, P. Major, K. Mandal, A. Mehta, M. I. Nagy, G. Pasztor, O. Surányi, G. I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[22], F. Sikler, T. Vámi, V. Veszpremi, G. Vesztergombi†

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[21], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, D. Teyssier, Z. L. Trocsanyi, B. Ujvari

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
T. Csorgo, W. J. Metzger, F. Nemes, T. Novak

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J. R. Komaragiri, P. C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[24], C. Kar, G. Kole, P. Mal, V. K. Muraleedharan Nair Bindhu, A. Nayak[25], D. K. Sahoo[24], S. K. Swain

Panjab University, Chandigarh, India
S. Bansal, S. B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J. B. Singh, A. K. Virdi, G. Walia

University of Delhi, Delhi, India
A. Bhardwaj, B. C. Choudhary, R. B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj[26], M. Bharti[26], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[26], D. Bhowmik, S. Dey, S. Dutta, S. Ghosh, M. Maity[27], K. Mondal, S. Nandan, A. Purohit, P. K. Rout, G. Saha, S. Sarkar, T. Sarkar[27], M. Sharan, B. Singh[26], S. Thakur[26]

Indian Institute of Technology Madras, Madras, India
P. K. Behera, P. Kalbhor, A. Muhammad, P. R. Pujahari, A. Sharma, A. K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, D. K. Mishra, P. K. Netrakanti, L. M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M. A. Bhat, S. Dugad, G. B. Mohanty, N. Sur, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[28], E. Eskandari Tadavani, S. M. Etesami[28], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,b,29], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[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,b], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F. R. Cavallo[a], C. Ciocca[a], G. Codispoti[a,b], M. Cuffiani[a,b], G. M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi, P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], F. Iemmi[a,b], S. Lo Meo[a,30], 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], N. Tosi[a]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Albergo[a,b,31], S. Costa[a,b], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,31], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Florence, Italy
G. Barbagli[a], R. Ceccarelli, K. Chatterjee[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino, P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], D. Strom[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], Genoa, Italy
M. Bozzo[a,b], F. Ferro[a], R. Mulargia[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milan, Italy
A. Benaglia[a], A. Beschi[a,b], F. Brivio[a,b], V. Ciriolo[a,b,17], S. Di Guida[a,b,17], M. E. Dinardo[a,b], P. Dini[a], S. Fiorendi[a,b], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M. Malberti[a], S. Malvezzi[a], D. Menasce[a], F. Monti[a,b], L. Moroni[a], G. Ortona[a,b], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], 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], Rome, Italy
S. Buontempo[a], N. Cavallo[a,c], A. De Iorio[a,b], A. Di Crescenzo[a,b], F. Fabozzi[a,c], F. Fienga[a], G. Galati[a], A. O. M. Iorio[a,b], L. Lista[a,b], S. Meola[a,d,17], P. Paolucci[a,17], B. Rossi[a], C. Sciacca[a,b], E. Voevodina[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], A. Boletti[a,b], A. Bragagnolo, R. Carlin[a,b], P. Checchia[a], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Y. Hoh, P. Lujan, M. Margoni[a,b], A. T. Meneguzzo[a,b], J. Pazzini[a,b], N. Pozzobon[a,b], M. Presilla[b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko, M. Tosi[a,b], M. Zanetti[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
A. Braghieri[a], P. Montagna[a,b], S. P. Ratti[a,b], V. Re[a], M. Ressegotti[a,b], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
M. Biasini[a,b], G. M. Bilei[a], C. Cecchi[a,b], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], E. Manoni[a], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy
K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], R. Castaldi[a], M. A. Ciocci[a,b], R. Dell'Orso[a], G. Fedi[a], L. Giannini[a,c], A. Giassi[a], M. T. Grippo[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[32], S. Roy Chowdhury, A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini, A. Venturi[a], P. G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Rome, Italy
F. Cavallari[a], M. Cipriani[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], E. Longo[a,b], B. Marzocchi[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,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], C. Biino[a], A. Cappati[a,b], N. Cartiglia[a], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M. M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G. L. Pinna Angioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], R. Salvatico[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a]

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], F. Vazzoler[a,b], A. Zanetti[a]

Kyungpook National University, Daegu, Korea
B. Kim, D. H. Kim, G. N. Kim, M. S. Kim, J. Lee, S. W. Lee, C. S. Moon, Y. D. Oh, S. I. Pak, S. Sekmen, D. C. Son, Y. C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D. H. Moon, G. Oh

Hanyang University, Seoul, Korea
B. Francois, T. J. Kim, J. Park

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, K. Lee, K. S. Lee, J. Lim, J. Park, S. K. Park, Y. Roh

Department of Physics, Kyung Hee University, Seoul, Korea
J. Goh

Sejong University, Seoul, Korea
H. S. Kim

Seoul National University, Seoul, Korea
J. Almond, J. H. Bhyun, J. Choi, S. Jeon, J. Kim, J. S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, M. Oh, S. B. Oh, B. C. Radburn-Smith, U. K. Yang, H. D. Yoo, I. Yoon, G. B. Yu

University of Seoul, Seoul, Korea
D. Jeon, H. Kim, J. H. Kim, J. S. H. Lee, I. C. Park, I. Watson

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

Riga Technical University, Riga, Latvia
V. Veckalns[33]

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, G. Tamulaitis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
Z. A. Ibrahim, F. Mohamad Idris[34], W. A. T. Wan Abdullah, M. N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J. F. Benitez, A. Castaneda Hernandez, J. A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[35], R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H. A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro
N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P. H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, 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, Kraków, 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, A. Byszuk[36], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, K. Shchelina, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
Y. Ershov, M. Gavrilenko, I. Golutvin, N. Gorbounov, I. Gorbunov, V. Karjavine, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev[37,38], P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, V. Trofimov, B. S. Yuldashev[39], A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim[40], E. Kuznetsova[41], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[42], V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
R. Chistov[43], M. Danilov[43], P. Parygin, S. Polikarpov[43], E. Zhemchugov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[44], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
A. Barnyakov[45], V. Blinov[45], T. Dimova[45], L. Kardapoltsev[45], Y. Skovpen[45]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, A. Iuzhakov, V. Okhotnikov

Tomsk State University, Tomsk, Russia
V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Beograde, Serbia
P. Adzic[46], P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. lvarez Fernández, I. Bachiller, M. Barrio Luna, J. A. Brochero Cifuentes, C. A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J. P. Fernández Ramos, J. Flix, M. C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J. M. Hernandez, M. I. Josa, D. Moran,

Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M. S. Soares, A. Triossi, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J. F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J. R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I. J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P. J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Russo[47], L. Scodellaro, N. Trevisani, I. Vila, J. M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
K. Malagalage

Department of Physics, University of Ruhuna, Matara, Sri Lanka
W. G. D. Dharmaratna, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A. H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, E. Bossini, C. Botta, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, O. Davignon, A. De Roeck, N. Deelen, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita[48], D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, P. Janot, O. Karacheban[20], J. Kaspar, J. Kieseler, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J. A. Merlin, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo[17], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F. M. Pitters, D. Rabady, A. Racz, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[49], J. Steggemann, V. R. Tavolaro, D. Treille, A. Tsirou, A. Vartak, M. Verzetti, W. D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[50], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S. A. Wiederkehr

ETH Zurich-Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R. A. Manzoni, M. Marionneau, M. T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Reichmann, C. Reissel, T. Reitenspiess, D. Ruini, D. A. Sanz Becerra, M. Schönenberger, L. Shchutska, M. L. Vesterbacka Olsson, R. Wallny, D. H. Zhu

Universität Zürich, Zurich, Switzerland
T. K. Aarrestad, C. Amsler[51], D. Brzhechko, M. F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, B. Kilminster, S. Leontsinis, V. M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, S. Wertz, A. Zucchetta

National Central University, Chung-Li, Taiwan
T. H. Doan, C. M. Kuo, W. Lin, A. Roy, S. S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Chang, Y. Chao, K. F. Chen, P. H. Chen, W.-S. Hou, Y. y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

ukuroa University, Physics Department, Science and Art Faculty, Adana, Turkey
A. Bat, F. Boran, S. Cerci[52], S. Damarseckin[53], Z. S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, G. Gokbulut, EmineGurpinar Guler[54], Y. Guler, I. Hos[55], C. Isik, E. E. Kangal[56], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir[57], S. Ozturk[58], A. E. Simsek, D. Sunar Cerci[52], U. G. Tok, S. Turkcapar, I. S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[59], G. Karapinar[60], M. Yalvac

Bogazici University, Istanbul, Turkey
I. O. Atakisi, E. Gülmez, M. Kaya[61], O. Kaya[62], B. Kaynak, Ö. Özçelik, S. Tekten, E. A. Yetkin[63]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, Y. Komurcu, S. Sen[64]

Istanbul University, Istanbul, Turkey
S. Ozkorucuklu

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, UK
F. Ball, E. Bhal, S. Bologna, J. J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G. P. Heath, H. F. Heath, L. Kreczko, S. Paramesvaran, B. Penning, T. Sakuma, S. Seif El Nasr-Storey, D. Smith, V. J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, UK
K. W. Bell, A. Belyaev[65], C. Brew, R. M. Brown, D. Cieri, D. J. A. Cockerill, J. A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D. M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C. H. Shepherd-Themistocleous, A. Thea, I. R. Tomalin, T. Williams, W. J. Womersley

Imperial College, London, UK
R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, GurpreetSingh CHAHAL[66], D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash[67], V. Palladino, M. Pesaresi, D. M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee[17], N. Wardle, D. Winterbottom, J. Wright, A. G. Zecchinelli, S. C. Zenz

Brunel University, Uxbridge, UK
J. E. Cole, P. R. Hobson, A. Khan, P. Kyberd, C. K. Mackay, A. Morton, I. D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA
K. Call, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA
R. Bartek, A. Dominguez, R. Uniyal

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S. I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, T. Bose, Z. Demiragli, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, B. Burkle, X. Coubez, D. Cutts, Y. t. Duh, M. Hadley, J. Hakala, U. Heintz, J. M. Hogan[68], K. H. M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir[69], R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, USA
R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P. T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, W. A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Riverside, Riverside, USA
K. Burt, R. Clare, J. W. Gary, S. M. A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, O. R. Long, M. Olmedo Negrete, M. I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B. R. Yates, Y. Zhang

University of California, San Diego, La Jolla, USA
J. G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara-Department of Physics, Santa Barbara, USA
N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J. M. Lawhorn, N. Lu, J. Mao, H. B. Newman, T. Q. Nguyen, J. Pata, M. Spiropulu, J. R. Vlimant, S. Xie, Z. Zhang, R. Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M. B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J. P. Cumalat, W. T. Ford, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K. A. Ulmer, S. R. Wagner

Cornell University, Ithaca, USA
J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, N. Mirman, J. R. Patterson, D. Quach, A. Rinkevicius[70], A. Ryd, S. M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L. A. T. Bauerdick, A. Beretvas, J. Berryhill, P. C. Bhat, K. Burkett, J. N. Butler, A. Canepa, G. B. Cerati, H. W. K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V. D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, AllisonReinsvold Hall, J. Hanlon, R. M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M. J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J. M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena, G. Rakness, F. Ravera, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W. J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H. A. Weber

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, V. Cherepanov, D. Curry, F. Errico, R. D. Field, S. V. Gleyzer, B. M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K. H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, USA
Y. R. Joshi

Florida State University, Tallahassee, USA
T. Adams, A. Askew, S. Hagopian, V. Hagopian, K. F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, USA
M. M. Baarmand, V. Bhopatkar, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M. R. Adams, L. Apanasevich, D. Berry, R. R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C. E. Gerber, D. A. Hangal, D. J. Hofman, K. Jung, C. Mills, T. Roy, M. B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu

The University of Iowa, Iowa City, USA
M. Alhusseini, B. Bilki[54], W. Clarida, K. Dilsiz[71], S. Durgut, R. P. Gandrajula, M. Haytmyradov, V. Khristenko, O. K. Köseyan, J.-P. Merlo, A. Mestvirishvili[72], A. Moeller, J. Nachtman, H. Ogul[73], Y. Onel, F. Ozok[74], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A. V. Gritsan, W. T. Hung, P. Maksimovic, J. Roskes, M. Swartz, M. Xiao

The University of Kansas, Lawrence, USA
C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, D. Majumder, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J. D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D. R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
A. Baden, O. Baron, A. Belloni, S. C. Eno, Y. Feng, N. J. Hadley, S. Jabeen, G. Y. Jeng, R. G. Kellogg, J. Kunkle, A. C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y. H. Shin, A. Skuja, S. C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, A. Baty, R. Bi, S. Brandt, W. Busza, I. A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P. D. Luckey, B. Maier, A. C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G. S. F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T. W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA
A. C. Benvenuti[†], R. M. Chatterjee, A. Evans, S. Guts, P. Hansen, J. Hiltbrand, Sh. Jain, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M. A. Wadud

University of Mississippi, Oxford, USA
J. G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, D. R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. E. Siado, G. R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D. M. Morse, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, J. Bueghly, T. Gunter, K. A. Hahn, N. Odell, M. H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D. J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, C. Mueller, Y. Musienko[37], M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, B. Bylsma, L. S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, A. Lefeld, T. Y. Ling, B. L. Winer

Princeton University, Princeton, USA
S. Cooperstein, G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M. T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully, Z. Wang

University of Puerto Rico, Mayagüez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
A. Barker, V. E. Barnes, S. Das, L. Gutay, M. Jones, A. W. Jung, A. Khatiwada, B. Mahakud, D. H. Miller, G. Negro, N. Neumeister, C. C. Peng, S. Piperov, H. Qiu, J. F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA
K. M. Ecklund, S. Freed, F. J. M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B. P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A. G. Stahl Leiton, Z. Tu, A. Zhang

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

Rutgers, The State University of New Jersey, Piscataway, USA
B. Chiarito, J. P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

University of Tennessee, Knoxville, USA
H. Acharya, A. G. Delannoy, J. Heideman, G. Riley, S. Spanier

Texas A & M University, College Station, USA
O. Bouhali[75], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[76], S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, S. Kunori, K. Lamichhane, S. W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

University of Virginia, Charlottesville, USA
M. W. Arenton, P. Barria, B. Cox, G. Cummings, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P. E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin-Madison, Madison, WI, USA
J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, F. Fiori, C. Galloni, B. Gomber[77], M. Grothe,

M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Loeliger, K. Long, R. Loveless, J. Madhusudanan Sreekala, T. Ruggles, A. Savin, V. Sharma, W. H. Smith, D. Teague, S. Trembath-reichert, N. Woods

† **Deceased**

1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at UFMS, Nova Andradina, Brazil
6: Also at Universidade Federal de Pelotas, Pelotas, Brazil
7: Also at Université Libre de Bruxelles, Bruxelles, Belgium
8: Also at University of Chinese Academy of Sciences, Beijing, China
9: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Suez University, Suez, Egypt
12: Now at British University in Egypt, Cairo, Egypt
13: Also at Purdue University, West Lafayette, USA
14: Also at Université de Haute Alsace, Mulhouse, France
15: Also at Tbilisi State University, Tbilisi, Georgia
16: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
17: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
19: Also at University of Hamburg, Hamburg, Germany
20: Also at Brandenburg University of Technology, Cottbus, Germany
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
22: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
23: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
24: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
25: Also at Institute of Physics, Bhubaneswar, India
26: Also at Shoolini University, Solan, India
27: Also at University of Visva-Bharati, Santiniketan, India
28: Also at Isfahan University of Technology, Isfahan, Iran
29: Now at INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
30: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
31: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
32: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
33: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
39: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
40: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
41: Also at University of Florida, Gainesville, USA
42: Also at Imperial College, London, UK
43: Also at P.N. Lebedev Physical Institute, Moscow, Russia
44: Also at California Institute of Technology, Pasadena, USA
45: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
46: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
47: Also at Università degli Studi di Siena, Siena, Italy

48: Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy, Pavia, Italy
49: Also at National and Kapodistrian University of Athens, Athens, Greece
50: Also at Universität Zürich, Zurich, Switzerland
51: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
52: Also at Adiyaman University, Adiyaman, Turkey
53: Also at Şırnak University, Sirnak, Turkey
54: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
55: Also at Istanbul Aydin University, Istanbul, Turkey
56: Also at Mersin University, Mersin, Turkey
57: Also at Piri Reis University, Istanbul, Turkey
58: Also at Gaziosmanpasa University, Tokat, Turkey
59: Also at Ozyegin University, Istanbul, Turkey
60: Also at Izmir Institute of Technology, Izmir, Turkey
61: Also at Marmara University, Istanbul, Turkey
62: Also at Kafkas University, Kars, Turkey
63: Also at Istanbul Bilgi University, Istanbul, Turkey
64: Also at Hacettepe University, Ankara, Turkey
65: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
66: Also at IPPP Durham University, Durham, UK
67: Also at Monash University, Faculty of Science, Clayton, Australia
68: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
69: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
70: Also at Vilnius University, Vilnius, Lithuania
71: Also at Bingol University, Bingol, Turkey
72: Also at Georgian Technical University, Tbilisi, Georgia
73: Also at Sinop University, Sinop, Turkey
74: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
75: Also at Texas A&M University at Qatar, Doha, Qatar
76: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea
77: Also at University of Hyderabad, Hyderabad, India