



Observation of nuclear modifications in $W^\pm$ boson production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

The CMS Collaboration*

CERN, Switzerland

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ABSTRACT

The production of $W^\pm$ bosons is studied in proton-lead (pPb) collisions at a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 8.16$ TeV. Measurements are performed in the $W^\pm \rightarrow \mu^\pm \nu_\mu$ channel using a data sample corresponding to an integrated luminosity of 173.4 ± 6.1 nb $^{-1}$, collected by the CMS Collaboration at the LHC. The number of positively and negatively charged W bosons is determined separately in the muon pseudorapidity region in the laboratory frame $|\eta_{lab}^\mu| < 2.4$ and transverse momentum $p_T^\mu > 25$ GeV/c. The $W^\pm$ boson differential cross sections, muon charge asymmetry, and the ratios of $W^\pm$ boson yields for the proton-going over the Pb-going beam directions are reported as a function of the muon pseudorapidity in the nucleon-nucleon centre-of-mass frame. The measurements are compared to the predictions from theoretical calculations based on parton distribution functions (PDFs) at next-to-leading-order. The results favour PDF calculations that include nuclear modifications and provide constraints on the nuclear PDF global fits.

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1. Introduction

The production of electroweak (EW) gauge bosons is considered to be a powerful probe of the parton distribution functions (PDFs) of the proton [1]. Most recent proton PDF sets include W and Z boson production data from the Tevatron and the CERN Large Hadron Collider (LHC) in their global fit analyses [2–4]. Similarly, the measurements of EW boson production in proton-nucleus and nucleus-nucleus collisions, available for the first time at centre-of-mass energies of the TeV scale, provide constraints on nuclear modifications of the PDFs [5–8]. The presence of a nuclear environment modifies the parton densities in the nucleus as compared to those in a free nucleon. The nuclear PDFs (nPDFs) are expected to be enhanced for partons carrying a momentum fraction in the range $5 \times 10^{-2} \lesssim x \lesssim 10^{-1}$ in the so-called *antishadowing* region, and suppressed for $x \lesssim 10^{-2}$ in the *shadowing* region [9], with the modifications depending on the scale Q^2 . Because of the limited amount and type of experimental data sets available for nuclear collisions, the determination of the nuclear parton densities is less precise than for the free-proton case. As a consequence, the nPDF uncertainties are one of the main limitations of the precision

of quantum chromodynamics (QCD) calculations describing hard-scattering processes in nuclear collisions at high energies [7].

Since W bosons are predominantly produced via $q\bar{q}$ annihilation through $u\bar{d} \rightarrow W^+$ and $d\bar{u} \rightarrow W^-$ processes, W boson production can be used to probe the light quark PDFs, both for the proton and nuclei. In addition, the asymmetries of the separate yields of W^+ and W^- bosons are known to be sensitive probes of the down-to-up quark PDF ratio [10–12]. Consequently, their measurement may allow for the flavour decomposition of u and d quark distributions in nuclei [13]. Among the possible decay channels of the W boson, the leptonic decays are less affected by background processes than hadronic decays. Another advantage of the leptonic decays is that any possible effect due to the QCD medium produced in nuclear collisions should be negligible, since leptons are not subject to medium-induced energy loss through the strong interaction [14,15].

Studies of the W and Z boson production in PbPb collisions at a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV, performed by the ATLAS [16–18] and CMS [19–21] Collaborations, have shown that the W and Z boson cross sections are consistent with no modification by the nuclear medium formed in these collisions. In pPb collisions, measurements of W production at $\sqrt{s_{NN}} = 5.02$ TeV have been performed by ALICE [22] and CMS [13]. The comparison with next-to-leading-order (NLO) perturbative QCD predictions favours the calculations that include

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

nPDF effects. A similar observation is made from the analysis of the Z boson production in pPb collisions at the same energy [23, 24]. These EW boson measurements have been used for the first time in a global fit analysis of nPDF sets (EPPS16 [25]). Nevertheless, a modest enhancement of the W^- boson production cross section in the most backward region (Pb-going direction) showed some difference with theoretical calculations (with and without nPDF effects), possibly pointing to different nuclear modifications of the up and down quark PDFs [13]. More precise measurements are thus needed in order to clarify the origin of this discrepancy.

This letter reports the results of measurements of $W^\pm$ boson production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. The measurements are performed in the $W^\pm \rightarrow \mu^\pm \nu_\mu$ decay channel using pPb data recorded with the CMS detector in 2016, corresponding to a total integrated luminosity of 173.4 ± 6.1 nb $^{-1}$. This data set is roughly five times larger than the one available for the previous measurement at $\sqrt{s_{NN}} = 5.02$ TeV [13, 26, 27]. The $W^\pm$ boson differential cross sections are presented as functions of the muon pseudorapidity in the nucleon-nucleon centre-of-mass (CM) frame, η_{CM} . In order to fully exploit the information provided by the data, two additional sets of observables are also measured as functions of η_{CM} : the muon charge asymmetry and the muon forward-backward ratios (R_{FB}). The measurement of asymmetries has a couple of advantages as compared to that of the cross sections. First, asymmetries are more sensitive to modifications of the quark PDFs [7]. Second, uncertainties in the integrated luminosity and the theoretical scale dependence cancel in the measurement of these asymmetries. The results of the $W^\pm$ boson differential cross sections and asymmetries are compared to perturbative QCD calculations based on NLO PDFs with and without nuclear modifications. The theoretical predictions for free protons are obtained using the CT14 [2] proton PDF set, while those including nuclear effects are derived using two different nPDF sets for lead ions: nCTEQ15 [28] and EPPS16 [25].

2. Experimental methods

2.1. Data-taking conditions and the CMS detector

During the data-taking period, the directions of the proton and lead beams were swapped after an integrated luminosity of 62.6 nb $^{-1}$ was collected. The beam energies were 6.5 TeV for the protons and 2.56 TeV per nucleon for the lead nuclei. By convention, the proton-(Pb-)going side defines the positive (negative) η region, labelled as the forward (backward) direction. Because of the asymmetric collision system, massless particles produced in the nucleon-nucleon centre-of-mass frame at an η_{CM} are reconstructed at $\eta_{lab} = \eta_{CM} + 0.465$ in the laboratory frame. The $W^\pm$ boson measurements presented in this letter are expressed in terms of the muon pseudorapidity in the CM, η_{CM}^μ .

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, that provides a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the η coverage provided by the barrel and endcap detectors. The hadron forward (HF) calorimeter uses steel as an absorber and quartz fibres as the sensitive material. The two halves of the HF are located 11.2 m from the interaction region, one on each end, and together they provide coverage in the range $3.0 < |\eta| < 5.2$. They also serve as luminosity monitors. Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [29].

The particle-flow (PF) algorithm [30] aims to reconstruct and identify each individual particle in an event, with an optimised combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The charge and momentum of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker (assuming the charged-pion mass) and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

2.2. Event selection and muon reconstruction

Collision events are required to have at least one interaction vertex reconstructed using two or more tracks within a distance from the nominal collision point of 25 cm along the beam axis and 2 cm along its transverse plane. The contamination from background events not originating from inelastic hadronic collisions is further suppressed by requiring at least one tower on each side of the HF calorimeter with a total energy larger than 3 GeV. The loss of events with $W^\pm$ bosons candidates due to this pPb collision event selection has been determined to be less than 0.2%.

The main signature of the $W^\pm \rightarrow \mu^\pm \nu_\mu$ process is the presence of an isolated high- p_T muon. Events of interest for offline analysis are selected using a trigger algorithm [31] that requires the presence of at least one muon candidate of $p_T > 12$ GeV/c. Moreover, to enhance the signal purity [11, 13], the fiducial region of the analysis has been restricted to muons of $p_T > 25$ GeV/c with $|\eta_{lab}^\mu| < 2.4$. The muon candidates are reconstructed in CMS with an algorithm that combines the information from the muon detectors and the tracker [32]. Muons are selected by applying the standard tight selection criteria described in Ref. [32]. Further, muons are required to be isolated from nearby hadronic activity to reduce the jet background. The muon isolation parameter (I_μ) is defined as the p_T sum of all PF-reconstructed photons, charged and neutral hadrons, in a cone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the muon candidate, where $\Delta\eta$ and $\Delta\phi$ are the pseudorapidity and azimuthal (in radians) distances to the muon. A muon is considered isolated if I_μ is less than 15% of the muon p_T .

Background processes yielding high- p_T muons can be classified as reducible or irreducible. The reducible background includes muon decays that can be tagged and removed from the signal. These events are mainly composed of $\mu^+\mu^-$ pairs from Drell-Yan events (Z/γ^*), and high- p_T muons from jets produced via the strong interaction, referred to as QCD multijet events. To further suppress the former processes, events containing at least two isolated oppositely charged muons, each with $p_T^\mu > 15$ GeV/c, are removed. The irreducible background sources comprise muon decays that pass the analysis selection criteria and therefore cannot be tagged event-by-event, including $Z/\gamma^* \rightarrow \tau^-\tau^+$, $W \rightarrow \tau\nu_\tau$, and $t\bar{t}$ production. All backgrounds are estimated using Monte Carlo (MC) simulations, except QCD multijet, which is modelled with a data-driven technique described below.

2.3. Signal yield determination

Leptonic decays of W bosons include neutrinos, which are not detected in CMS. Their presence is inferred from the overall mo-

momentum imbalance in the transverse plane, known as the missing transverse momentum $\vec{p}_T^{\text{miss}}$; its magnitude (p_T^{miss}) is defined as the magnitude of the sum of the negative p_T vectors of all reconstructed PF objects in an event. In this analysis, the p_T^{miss} distribution is used to extract the signal yields in 24 muon η_{CM}^{μ} bins, each 0.2 units wide, except for four in the most backward ($-2.86 < \eta_{\text{CM}}^{\mu} < -2.60$, $-2.20 < \eta_{\text{CM}}^{\mu} < -1.93$, $-1.93 < \eta_{\text{CM}}^{\mu} < -1.80$), and forward ($1.80 < \eta_{\text{CM}}^{\mu} < 1.93$) regions, because of the detector geometry and the unbalanced beam energies.

The p_T^{miss} distributions of the signal and EW backgrounds are described using templates from MC simulations. The MC samples were generated using the NLO generator POWHEG v2 [33–35]. To include EW corrections, the POWHEGBOX packages $W_{\text{ew-BMNNP}}$ [36] and $Z_{\text{ew-BMNNPV}}$ [37] are used to generate the $pp \rightarrow W^{\pm} \rightarrow l^{\pm} \nu_l$ and $pp \rightarrow Z/\gamma^* \rightarrow l^+ l^-$ processes, respectively. Events from the $pp \rightarrow t\bar{t}$ process are generated using the POWHEGBOX package hvq [38], which is a heavy flavour quark generator. The simulation of pPb collisions is performed using the CT14 [2] PDF set corrected with the EPPS16 nuclear modification factors, defined as the ratios of the bound proton PDF to that of a free proton, derived for Pb ions [25]. The parton densities of protons and neutrons are scaled according to the mass and atomic number of the lead isotopes.

The parton showering is performed by hadronising the events using PYTHIA 8.212 [39] with the CUETP8M1 underlying-event (UE) tune [40,41]. To consider a more realistic distribution of the underlying environment present in pPb collisions, the POWHEG samples are embedded in simulated pPb events generated by EPOS LHC (v3400) [42], taking into account the pPb boost. The EPOS LHC simulation is tuned to reproduce the global event properties of the pPb data such as the η distributions of charged hadrons [43]. The embedding of the signal and pPb UEs is performed by requiring the same generated interaction point when simulating the detector hits. The trigger decisions are emulated and the embedded events are reconstructed with the same algorithms as used for data. The detector response is simulated with GEANT4 [44].

The agreement between the EW simulations and the data is improved by weighting the EW boson p_T distribution using a p_T -dependent function derived from the ratio of the Z boson p_T distributions in $Z \rightarrow \mu^+ \mu^-$ events in data and simulation. Furthermore, the pPb event activity is reweighted by matching the simulated total energy distribution reconstructed on both sides of the HF calorimeters to the one observed in data in a $Z/\gamma^* \rightarrow \mu^+ \mu^-$ sample.

The shape of the QCD multijet background is modelled with a functional form described by a modified Rayleigh distribution [45] defined as:

$$f(p_T^{\text{miss}}) = p_T^{\text{miss}} \exp \left[- \left(p_T^{\text{miss}} \right)^2 / 2 \left(\sigma_0 + \sigma_1 p_T^{\text{miss}} + \sigma_2 \left(p_T^{\text{miss}} \right)^2 \right)^2 \right],$$

where σ_0 , σ_1 , and σ_2 are free parameters to be determined. It is found to reproduce well the p_T^{miss} shape of data events containing nonisolated muons, with χ^2 values divided by the number of degrees of freedom (dof) close to one. The QCD shape is extracted by fitting the data in five relative muon isolation (I_{μ}/p_T^{μ}) bins with boundaries ranging from 0.4 to 0.9. The σ_0 , σ_1 , and σ_2 parameters extracted from the fits are found to linearly depend on the relative muon isolation and are extrapolated to the isolated muon signal region.

Because of momentum conservation, the production of Z and W bosons is balanced by a hadronic recoil composed of jets and particles from the pPb underlying activity. The distribution of the

hadronic recoil significantly contributes to the p_T^{miss} resolution. Because of the similarity of the production processes of the Z and W bosons, and their similar masses, we assume that the recoil distributions are the same for both species. Therefore, the correction of the simulated recoil distribution is derived in a control region of $Z \rightarrow \mu^+ \mu^-$ events using a hadronic recoil technique [46,47]. The hadronic recoil of $Z \rightarrow \mu^+ \mu^-$ events, $\vec{u}_T$, is defined as the vector p_T sum of all PF candidates, excluding the decay products of the Z boson. The distributions of the hadronic recoil components that are parallel and perpendicular to the Z boson transverse momentum $\vec{p}_T^Z$ are fitted in simulation and data using a weighted sum of two Gaussian functions. The mean and resolution values extracted from the recoil fits are used to scale the simulated hadronic recoil distributions to match the performance measured in data. The corrected p_T^{miss} distribution is then derived in the EW MC samples as the vector sum of the corrected hadronic recoil $\vec{u}_T^{\text{corr}}$ and the $\vec{p}_T$ of the reconstructed muons from the decay of Z and W bosons.

The number of $W^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$ events is extracted by performing an unbinned maximum likelihood fit of the observed p_T^{miss} distribution in each muon η_{CM}^{μ} bin. The total fit model includes six contributions: the signal $W^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$ template, the EW background $Z/\gamma^* \rightarrow \mu^+ \mu^-$, $W \rightarrow \tau \nu_{\tau}$ and $Z/\gamma^* \rightarrow \tau^+ \tau^-$ templates, the $t\bar{t}$ background template, and the QCD background functional form derived from control data samples. When fitting the data, the QCD shape parameters (σ_i) are fixed to the extrapolated values, while the ratio of the EW and $t\bar{t}$ background yields to the signal yield is fixed to the results from simulation. Only two parameters are left free in the fit, the W boson signal and QCD background normalisations. The observed numbers of muons coming from W boson decays over the entire η_{CM}^{μ} range are: $97971 \pm 332 \mu^+$ and $81147 \pm 301 \mu^-$, where the uncertainty is statistical. Examples of the resulting p_T^{miss} distributions in the midrapidity ($-0.2 < \eta_{\text{CM}}^{\mu} < 0.0$) and forward ($1.80 < \eta_{\text{CM}}^{\mu} < 1.93$) bins, are shown in Fig. 1, after applying all analysis corrections and selection criteria. The fit model is found to give a good description of the data, with χ^2/dof values close to one.

The simulated sample of $W^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$ embedded into EPOS LHC is used to derive the efficiency of the muon trigger, isolation, reconstruction, and selection criteria, as a function of η_{CM}^{μ} . These single-muon efficiencies are also directly estimated from pPb data in a $Z \rightarrow \mu^+ \mu^-$ sample using the *tag-and-probe* (TnP) technique, as described in Ref. [48]. The data and MC reconstruction efficiencies are observed to be consistent with each other, whereas the trigger efficiency is lower in the Z boson simulation by 5% than in data at $|\eta_{\text{lab}}^{\mu}| = 1.4$. The muon isolation selection is found to reject fewer muons in the simulation, because of the smaller pPb UE activity compared to data. In order to correct for the differences between data and simulation, the muon efficiency computed from the $W^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$ MC sample is multiplied by the TnP correction factors event-by-event. These correction factors are computed, in bins of muon p_T and η_{lab}^{μ} , from the ratio of the muon efficiencies measured in data to those calculated from simulations. The TnP scale factors produce changes in the muon efficiency ranging from -3% in the mid-rapidity region ($|\eta_{\text{lab}}^{\mu}| < 1.0$) to $+5\%$ at $|\eta_{\text{lab}}^{\mu}| = 1.4$. The TnP-corrected efficiencies vary with η_{CM}^{μ} , from $(81 \pm 1)\%$ to $(92 \pm 2)\%$.

2.4. Systematic uncertainties

The leading source of systematic uncertainty originates from the TnP efficiency corrections. The uncertainties on the TnP corrections are determined by propagating the uncertainties on the muon efficiencies extracted from data and simulation, derived from the fits to the invariant mass of $Z \rightarrow \mu^+ \mu^-$ candidates. These uncertainties include a statistical component due to the finite size of

the data sample available, as well as a systematic component estimated from variations in the fitting procedure (different signal

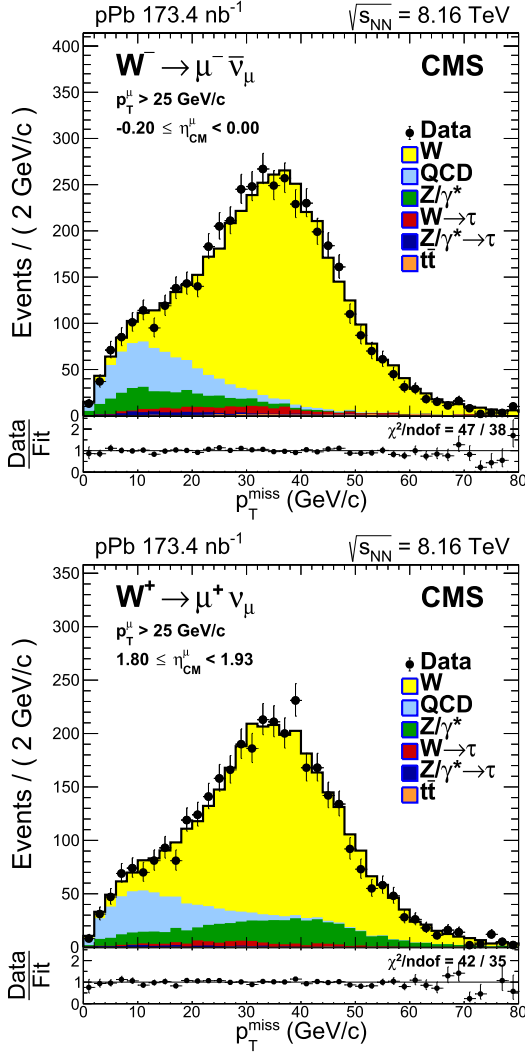


Fig. 1. The missing transverse momentum p_T^{miss} distribution for $W^- \rightarrow \mu^- \bar{\nu}_\mu$ events within the $-0.2 < \eta_{\text{CM}}^\mu < 0.0$ (top) range and for $W^+ \rightarrow \mu^+ \nu_\mu$ events within the $1.80 < \eta_{\text{CM}}^\mu < 1.93$ (bottom) range. Unbinned fits to the data (black points) are performed with six contributions, stacked from bottom to top: $t\bar{t}$ (orange), $Z/\gamma^* \rightarrow \tau^+ \tau^-$ (dark blue), $W^\pm \rightarrow \tau^\pm \nu_\tau$ (red), $Z/\gamma^* \rightarrow \mu^+ \mu^-$ (green), QCD multijet (light blue) and $W^\pm \rightarrow \mu^\pm \nu_\mu$ (yellow). The η_{CM}^μ regions are defined such that the proton is moving towards positive pseudorapidity. Error bars represent statistical uncertainties. The lower panels display the data divided by the result of the fit.

Table 1

Maximum uncertainty in the measured observables among the η_{CM}^μ bins determined for each source. The uncertainties in the cross sections are relative, whereas those for the asymmetries are absolute. The global integrated luminosity uncertainty of $\pm 3.5\%$ is not included in the total systematic uncertainty in the cross sections.

Source	$W^- \frac{d\sigma}{d\eta_{\text{CM}}^\mu} [\%]$	$W^+ \frac{d\sigma}{d\eta_{\text{CM}}^\mu} [\%]$	$W^- R_{\text{FB}}$	$W^+ R_{\text{FB}}$	WR_{FB}	$\frac{N_\mu^+ - N_\mu^-}{N_\mu^+ + N_\mu^-}$
Boson p_T reweighting	0.5	0.4	0.001	0.001	0.001	0.001
EW background	0.4	0.3	0.002	0.001	0.001	0.000
POWHEG EW correction	0.9	0.5	0.007	0.004	0.006	0.003
Efficiency	3.0	3.2	0.026	0.037	0.030	0.011
Event activity reweighting	0.6	0.4	0.002	0.002	0.001	0.002
p_T^{miss} template binning	0.1	0.1	0.002	0.001	0.001	0.001
QCD background	1.2	0.7	0.016	0.007	0.009	0.006
Hadronic recoil correction	0.2	0.3	0.002	0.004	0.002	0.002
Total systematic uncertainty	3.3	3.3	0.030	0.038	0.031	0.013
Statistical uncertainty	2.4	2.0	0.026	0.029	0.019	0.015

and background functions, and different mass range used for fitting). Additionally, uncertainties are included to account for: (1) possible differences in the reconstruction of muon tracks (0.6%), and (2) the impact of pileup and UE activity (0.3%). Another important source of systematic uncertainty arises from the modelling of the QCD multijet p_T^{miss} distribution in the signal region, which is estimated by allowing the QCD shape parameters to vary within the root-mean-square of the extrapolated values in bins of η_{CM}^μ , and by changing the p_T^{miss} model to that used in Ref. [13].

The uncertainty in the normalisation of the EW background is estimated from the nPDF uncertainty in the Z over W boson inclusive cross sections using the CT14 proton PDF and the EPPS16 nPDF for the lead ions, the uncertainty in the W and Z boson branching fractions to leptons [49], and the experimental uncertainty in the $t\bar{t}$ cross section in pPb events [50]. The uncertainty in the vector boson p_T reweighting is derived from the difference of the results obtained applying and not applying the boson p_T correction. The uncertainty in the binning of the p_T^{miss} MC templates is estimated by using a p_T^{miss} bin size of 1 GeV/c. The impact of EW corrections in POWHEG is estimated from the difference in the efficiency when computed using POWHEG without EW corrections [51]. The uncertainty in the p_T^{miss} recoil correction is determined by changing the model used to fit the hadronic recoil distribution and the profile of the recoil mean and resolution as a function of p_T^Z . Finally, the mismodelling of the UE activity in the simulation is estimated by reweighting the distribution of the track multiplicity instead of the energy deposited in the HF calorimeters. The integrated luminosity measurement uncertainty (3.5%) [27] only affects the W boson differential cross sections and cancels out in the asymmetry measurements. The maximum relative uncertainty of the differential cross sections and absolute uncertainties on the asymmetries are presented for each source of systematic uncertainty in Table 1.

3. Results

The $W^\pm$ boson differential production cross sections are computed as functions of η_{CM}^μ . The differential $W^\pm \rightarrow \mu^\pm \nu_\mu$ cross sections are determined from

$$\frac{d\sigma^{W^\pm \rightarrow \mu^\pm \nu_\mu}}{d\eta_{\text{CM}}^\mu}(\eta_{\text{CM}}^\mu) = \frac{N_\mu(\eta_{\text{CM}}^\mu)}{\mathcal{L} \Delta \eta_{\text{CM}}^\mu}, \quad (1)$$

where $N_\mu(\eta_{\text{CM}}^\mu)$ is the efficiency-corrected muon yield in bins of η_{CM}^μ , $\mathcal{L}$ is the recorded integrated luminosity, and $\Delta \eta_{\text{CM}}^\mu$ is the width of the measured bin.

The cross sections for the $W \rightarrow \mu \nu_\mu$ decays for W^+ and W^- bosons are compared in Fig. 2 with NLO perturbative QCD predictions calculated with the MC program MCFM v8.0 [52]

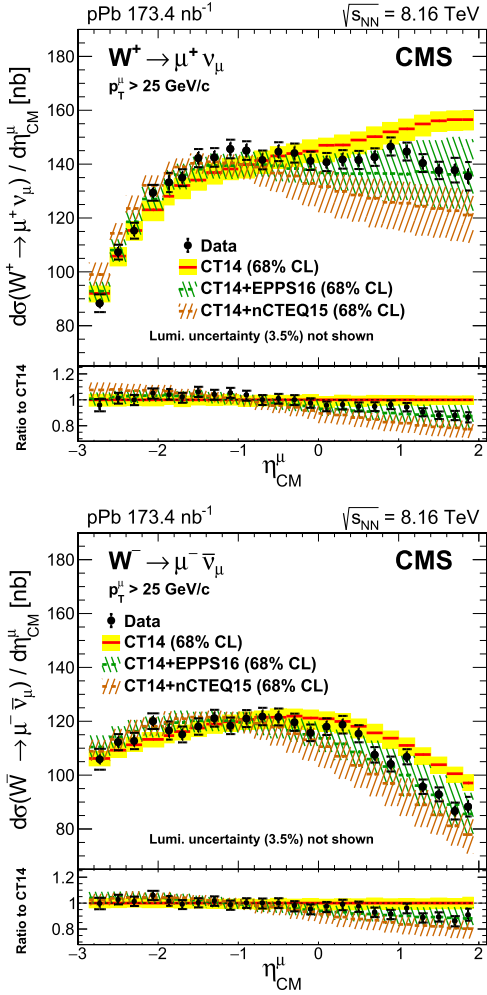


Fig. 2. Differential production cross sections for $W^+ \rightarrow \mu^+ \nu_\mu$ (top) and $W^- \rightarrow \mu^- \bar{\nu}_\mu$ (bottom), as a function of the muon pseudorapidity in the centre-of-mass frame. The small horizontal lines represent the statistical and systematic uncertainties summed in quadrature, whereas the error bars show the statistical uncertainties only. The global integrated luminosity uncertainty of $\pm 3.5\%$ is not shown. The NLO calculations with CT14 PDF, and CT14+EPPS16 and CT14+nCTEQ15 nPDFs, are also displayed, including their 68% confidence interval PDF uncertainty bands. The bottom panels show the ratio of data, CT14+EPPS16 and CT14+nCTEQ15 with respect to CT14.

using the CT14 [2] proton PDF. Also shown are two calculations that include nuclear modifications in the PDF, based on the nCTEQ15 [28] and EPPS16 [25] nPDF sets (labelled as CT14+nCTEQ15 and CT14+EPPS16, respectively). Both EPPS16 and nCTEQ15 are Hessian NLO nPDF sets, but the former includes more measurements in the fit (containing LHC EW boson [13,23,24] and dijet [53] data), as well as more free parameters (20 for EPPS16, 17 for nCTEQ15). In addition, nuclear modifications of valence and sea quarks are allowed to be different in EPPS16 for up and down quarks, while nCTEQ15 assumes flavour independence for the sea quarks. The nPDF uncertainties are propagated using the PDF4LHC recommendations for Hessian nPDF sets as prescribed in Ref. [1]. As can be seen in Fig. 2, the predicted CT14+nCTEQ15 and CT14+EPPS16 cross sections are systematically below the calculation using CT14 PDF at large positive muon rapidities because of the depletion of the antiquark PDF in nuclei at small $x = (M_W/\sqrt{s_{NN}}) \exp(-y_W) \simeq (M_W/\sqrt{s_{NN}}) \exp(-\eta_{CM}^\mu) \approx 10^{-3}$. Conversely, the predicted cross sections from calculations including nPDF modifications are above those using CT14 PDF in the negative rapidity region, because of the slight quark antishadowing at

large $x \approx 0.1$. When compared to data, all theoretical calculations reproduce the measurement at backward rapidity within uncertainties, while at forward rapidity the calculations including nPDF effects appear to be favoured.

The muon forward-backward ratios, defined as $N_\mu^\pm(+\eta_{CM}^\mu)/N_\mu^\pm(-\eta_{CM}^\mu)$ for both positive and negative muons, are compared in the upper panel of Fig. 3 to the CT14 PDF, and CT14+EPPS16 and CT14+nCTEQ15 nPDF calculations. These observables probe the ratio of the nuclear modifications of the quark PDFs in the Pb nucleus from small to large x values. The results for muons of both charges favour the predictions including nuclear modifications over the free-proton PDF calculations. Based on the precision of the experimental results, the measurements provide constraints on both the CT14+EPPS16 and CT14+nCTEQ15 nPDF sets, especially in the proton-going region (small x).

The yields of positively and negatively charged muons are further combined to measure the forward-backward ratio for all muons $N_\mu(+\eta_{CM}^\mu)/N_\mu(-\eta_{CM}^\mu)$. This observable has a couple of advantages compared to $N_\mu^\pm(+\eta_{CM}^\mu)/N_\mu^\pm(-\eta_{CM}^\mu)$: it is less sensitive to the quark content in the proton and nuclei, and it has better statistical precision. The results for this asymmetry are presented in the right panel of Fig. 3, and they strongly deviate from the CT14 PDF predictions, favouring the CT14+nCTEQ15 and CT14+EPPS16 nPDF sets. Moreover, the experimental uncertainties are significantly smaller than the theoretical nPDF uncertainties. Consequently, these measurements could constrain the quark and antiquark distributions in nuclei, and will be valuable inputs for global fits to the data.

The muon charge asymmetry, defined as $\mathcal{A} \equiv (N_\mu^+ - N_\mu^-)/(N_\mu^+ + N_\mu^-)$, reflects the differences in the production of W^+ and W^- bosons. Fig. 4 shows the measurement of the muon charge asymmetry as a function of η_{CM}^μ compared to the MCFM [52] predictions calculated using CT14 PDF alone and including nuclear modifications described by the EPPS16 and nCTEQ15 nPDFs. All calculations reproduce the present measurements within uncertainties in the entire muon η range, including when the CT14 proton PDF set is used, because nuclear modifications of the PDFs mostly cancel in this quantity.

The tension between data and theoretical calculations reported at negative muon η in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [13] is not observed in the present measurements. The present use of the CT14 proton PDF set decreases the value of the charge asymmetry compared to the predictions based on CT10 in Ref. [13]. Moreover, the theoretical uncertainties are also enlarged in the EPPS16 nPDF sets and the theoretical calculations using the CT14+EPPS16 nPDF sets agree better with the measurements at $\sqrt{s_{NN}} = 5.02$ TeV, as compared to the EPS09 nPDF sets used in the analysis at $\sqrt{s_{NN}} = 5.02$ TeV. It has been shown in Ref. [54] that the measurements of the lepton charge asymmetry at different collision energies ($\sqrt{s'}$) are simply related by a shift in the lepton pseudorapidity, $\mathcal{A}(\eta_l, \sqrt{s'}) = \mathcal{A}(\eta_{ref}, \sqrt{s})$, where $\eta_{ref} = \eta_l + \ln(\sqrt{s}/\sqrt{s'})$ if $\eta_l > 0$ and $\eta_{ref} = \eta_l - \ln(\sqrt{s}/\sqrt{s'})$ if $\eta_l < 0$. The result of this shift is shown in Fig. 5, demonstrating that the present results and the measurements performed at $\sqrt{s_{NN}} = 5.02$ TeV [13] obey this scaling property.

The agreement between data and theoretical calculations is quantified through a χ^2 test performed for each observable taking into account both experimental (including luminosity) and theoretical uncertainties and their bin-to-bin correlations, obtained following the prescription for Hessian PDF sets [55] and rescaled to 68% confidence intervals. The results of the χ^2 test and the dof of each observable are shown in Table 2. The CT14+EPPS16 and CT14+nCTEQ15 nPDF predictions prove compatible with the data, while the CT14 PDF calculations do not describe the measurements well. These experimental results thus provide for the first time

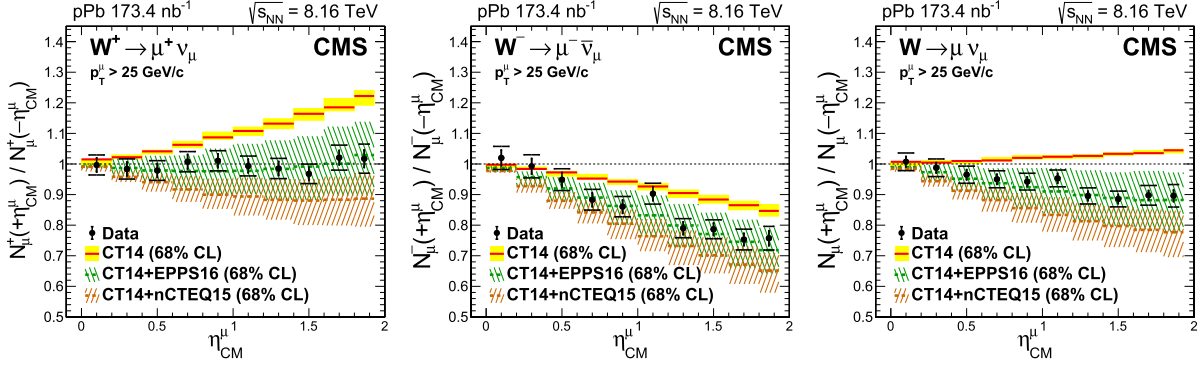


Fig. 3. Forward-backward ratios, $N_{\mu}^{\pm}(+\eta_{\text{CM}}^{\mu})/N_{\mu}^{\pm}(-\eta_{\text{CM}}^{\mu})$, for the positively (left) and negatively (middle) charged muons, and the forward-backward ratio for muons of both signs, $N_{\mu}(+\eta_{\text{CM}}^{\mu})/N_{\mu}(-\eta_{\text{CM}}^{\mu})$ (right), as a function of η_{CM}^{μ} . The small horizontal lines represent the statistical and systematic uncertainties summed in quadrature, whereas the error bars show the statistical uncertainties only. The NLO calculations with CT14 PDF, CT14+EPPS16 nPDF, and CT14+nCTEQ15 nPDF, are also displayed, including their 68% confidence interval PDF uncertainty bands.

clear evidence of the nuclear modification of quark PDFs from the measurements of EW boson production in nuclear collisions. Bin-to-bin correlations have been found to have a large impact on the obtained χ^2 values, especially from nPDF uncertainties in the NLO calculations, which are strongly correlated inside each of the shadowing (positive η_{CM}^{μ}) and antishadowing (negative η_{CM}^{μ}) regions, and anticorrelated between these two regions.

Furthermore, the possible sources of differences between data and the (n)PDFs are investigated. In the Hessian representation, a central PDF is given along with error sets, each of which corresponds to an eigenvector of the covariance matrix in parameter space [56]. The values of χ^2/dof corresponding to the compatibility between the cross section measurements and the calculations using each of the individual sets of CT14, nCTEQ15, and EPPS16 (57, 33 and 41 error sets, respectively) have been determined. Fig. 6 shows the distribution of the χ^2/dof values for the central and error sets. The χ^2/dof values obtained are for individual sets, thus ignoring theoretical uncertainties and their correlations. While most of the EPPS16 individual sets lead to a good agreement with data (with χ^2/dof around unity), only those nCTEQ15 sets that exhibit the smaller quark shadowing at small x are more compatible with the data, yet with $\chi^2/\text{dof} \gtrsim 2$. All CT14 PDF sets lead to a narrow distribution centred around $\chi^2/\text{dof} \simeq 3$, because of the strong constraints imposed by the large experimental data sets used to extract them. The current measurements of $W^{\pm}$ boson production in pPb collisions will permit further constraints on the quark and antiquark nPDFs and the amount of quark shadowing in the nuclei.

4. Summary

A study of $W^{\pm}$ boson production in pPb collisions at a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{\text{NN}}} = 8.16$ TeV is reported, using the muon decay channel for muons with transverse momenta greater than 25 GeV/c and for absolute values of the pseudorapidity in the laboratory frame $|\eta_{\text{lab}}^{\mu}| < 2.4$. The differential production cross sections for positively and negatively charged $W \rightarrow \mu\nu_{\mu}$ decays, the muon charge asymmetry, and the muon forward-backward ratios, are measured as functions of the muon pseudorapidity in the centre-of-mass frame, in the range $-2.86 < \eta_{\text{CM}}^{\mu} < 1.93$.

The measurements are compared to theoretical predictions from both proton parton distribution functions (PDFs) (CT14) and nuclear PDF (CT14+EPPS16, CT14+nCTEQ15) sets. The cross sections and the forward-backward asymmetries exhibit significant deviations from the CT14 prediction, revealing nuclear modifications of the PDFs unambiguously for the first time in the production of electroweak bosons in nuclear collisions. Both the

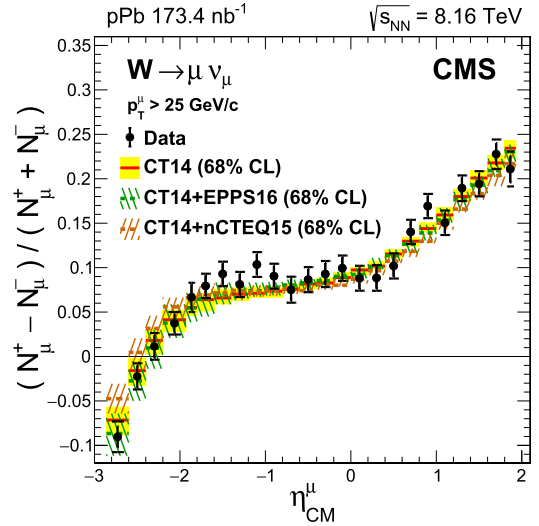


Fig. 4. Muon charge asymmetry, $(N_{\mu}^{+} - N_{\mu}^{-})/(N_{\mu}^{+} + N_{\mu}^{-})$, as a function of the muon pseudorapidity in the centre-of-mass frame. The small horizontal lines represent the statistical and systematic uncertainties summed in quadrature, whereas the error bars show the statistical uncertainties only. The NLO calculations with CT14 PDF, CT14+EPPS16 nPDF, and CT14+nCTEQ15 nPDF, are also displayed, including their 68% confidence interval PDF uncertainty bands.

CT14+EPPS16, and the CT14+nCTEQ15 calculations show a good overall agreement with the data, with the measurements favouring the former nPDF set. In the latter case, only the individual sets that exhibit the smallest nuclear PDF modifications at small values of x (in the shadowing region) turn out to be compatible with experimental measurements. The small experimental uncertainties allow for a significant reduction in the current uncertainties on the quark and antiquark nuclear PDFs in the range $10^{-3} \lesssim x \lesssim 10^{-1}$.

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Table 2

Results of the χ^2 statistical test between the measurements and the nPDF calculations from the CT14 PDF, CT14+EPPS16 nPDF, and CT14+nCTEQ15 nPDF sets. The value of the χ^2 , the number of degrees of freedom (dof) and the χ^2 probability (Prob.), are presented for the $W^\pm$ boson differential cross sections, the muon charge asymmetries, the charged muon forward-backward ratios, and the forward-backward ratios of all muons, respectively.

Observable	CT14			CT14+EPPS16			CT14+nCTEQ15		
	χ^2	dof	Prob. [%]	χ^2	dof	Prob. [%]	χ^2	dof	Prob. [%]
$d\sigma^{W^\pm \rightarrow \mu^\pm \nu_\mu}(\eta_{CM}^\mu)/d\eta_{CM}^\mu$	135	48	3×10^{-8}	32	48	96	40	48	79
$(N_\mu^+ - N_\mu^-)/(N_\mu^+ + N_\mu^-)$	23	24	54	18	24	80	29	24	23
$N_\mu^\pm(+\eta_{CM}^\mu)/N_\mu^\pm(-\eta_{CM}^\mu)$	98	20	3×10^{-10}	11	20	95	14	20	83
$N_\mu(+\eta_{CM}^\mu)/N_\mu(-\eta_{CM}^\mu)$	87	10	2×10^{-12}	3	10	99	5	10	90

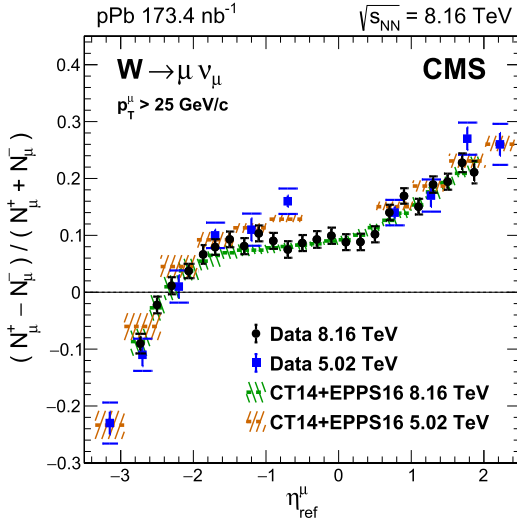


Fig. 5. Comparison of the muon charge asymmetry measured at $\sqrt{s_{NN}} = 8.16$ TeV (circles) and at $\sqrt{s_{NN}} = 5.02$ TeV [13] (squares). The muon pseudorapidity of the measurements at 5.02 TeV has been shifted (see text for details) [54]. The small horizontal lines represent the statistical and systematic uncertainties summed in quadrature, whereas the error bars show the statistical uncertainties only. The NLO calculations with CT14+EPPS16 nPDF at 8.16 TeV and at 5.02 TeV, are also displayed, including their 68% confidence interval PDF uncertainty bands.

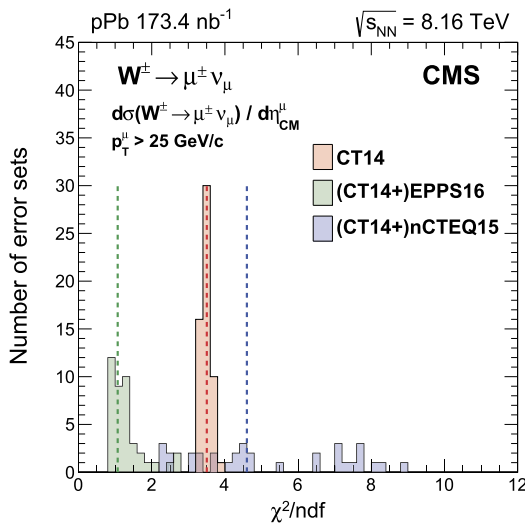


Fig. 6. Distribution of the χ^2/dof values from the comparison of data (cross section measurements) and theoretical calculations, for the CT14, nCTEQ15, and EPPS16 individual error sets. The vertical dashed lines represent the prediction corresponding to the central set of CT14, nCTEQ15, and EPPS16.

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The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambroggi, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, V.M. Ghete, J. Hrubec, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck¹, R. Schöffbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, 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

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov², D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

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

F.L. Alves, G.A. Alves, M. Correa Martins Junior, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, 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 Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

S. Ahuja^a, C.A. Bernardes^a, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a

^a *Universidade Estadual Paulista, São Paulo, Brazil*

^b *Universidade Federal do ABC, São Paulo, Brazil*

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

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

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang⁵, X. Gao⁵, L. Yuan

Beihang University, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen⁶, A. Spiezia, J. Tao, Z. Wang, E. Yazgan, H. Zhang, S. Zhang⁶, J. Zhao

Institute of High Energy Physics, Beijing, China

Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

Y. Wang

Tsinghua University, Beijing, China

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov⁷, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

University of Cyprus, Nicosia, Cyprus

M. Finger⁸, M. Finger Jr.⁸

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A. Ellithi Kamel⁹, M.A. Mahmoud^{10,11}, Y. Mohammed¹⁰

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

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

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

A. Abdulsalam¹², C. Amendola, I. Antropov, F. Arleo, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

J.-L. Agram¹³, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte¹³, J.-C. Fontaine¹³, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, A. Popov¹⁴, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

A. Khvedelidze⁸

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze⁸

Tbilisi State University, Tbilisi, Georgia

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov¹⁴

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

A. Albert, D. Duchardt, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, A. Schmidt, D. Teyssier, S. Thüer

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

G. Flügge, O. Hlushchenko, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁵

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

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras¹⁶, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁷, A. Geiser, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann¹⁸, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pflitsch, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, 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, D. Marconi, J. Multhaus, 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, A. Vanhoefer, B. Vormwald, I. Zoi

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann¹⁵, S.M. Heindl, U. Husemann, F. Kassel¹⁵, I. Katkov¹⁴, S. Kudella, S. Mitra, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, I. Topsis-Giotis

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

B. Francois, G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, E. Tziaferi, K. Vellidis

National and Kapodistrian University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

University of Ioánnina, Ioánnina, Greece

M. Bartók¹⁹, M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

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

G. Bencze, C. Hajdu, D. Horvath²⁰, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

Institute of Physics, University of Debrecen, Debrecen, Hungary

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati²², C. Kar, P. Mal, K. Mandal, A. Nayak²³, D.K. Sahoo²², S.K. Swain

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

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi, G. Walia

Panjab University, Chandigarh, 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

University of Delhi, Delhi, India

R. Bhardwaj²⁴, M. Bharti²⁴, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁴, D. Bhowmik, S. Dey, S. Dutt²⁴, S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, G. Saha, S. Sarkar, M. Sharan, B. Singh²⁴, S. Thakur²⁴

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, Ravindra Kumar Verma

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, M. Maity²⁵, G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar²⁵

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani²⁶, E. Eskandari Tadavani, S.M. Etesami²⁶, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh²⁷, M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, 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}, F. Errico^{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}, A. Sharma^a, L. Silvestris^a, R. Venditti^a, P. Verwilligen^a, G. Zito^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, 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, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b,15}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli^a, 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, L. Russo^{a,28}, G. Sguazzoni^a, D. Strom^a, L. Viliani^a

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

F. Ferro^a, F. Ravera^{a,b}, E. Robutti^a, S. Tosi^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

A. Benaglia^a, A. Beschi^b, L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b,15}, S. Di Guida^{a,b,15}, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, A. Massironi^{a,b}, D. Menasce^a, F. Monti, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}, D. Zuolo^{a,b}

^a INFN Sezione di Milano-Bicocca, Milano, Italy

^b Università di Milano-Bicocca, Milano, 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}, W.A. Khan^a, L. Lista^a, S. Meola^{a,d,15}, P. Paolucci^{a,15}, C. Sciacca^{a,b}, E. Voevodina^{a,b}

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, A. Boletti^{a,b}, A. Bragagnolo, R. Carlin^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, 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, S. Lacaprara^a, P. Lujan, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, A. Tiko, E. Torassa^a, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, Italy

A. Braghieri^a, A. Magnani^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}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, 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

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, L. Bianchini^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, F. Fiori^{a,c}, 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}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, F. Pandolfi^a, R. Paramatti^{a,b}, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

^a INFN Sezione di Roma, Rome, Italy

^b Sapienza Università di Roma, Rome, 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, N. Cartiglia^a, F. Cenna^{a,b}, 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}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

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

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon, G. Oh

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

J. Goh²⁹, T.J. Kim

Hanyang University, Seoul, Republic of Korea

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

Korea University, Seoul, Republic of Korea

H.S. Kim

Sejong University, Seoul, Republic of Korea

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

University of Seoul, Seoul, Republic of Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali³⁰, F. Mohamad Idris³¹, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

Universidad de Sonora (UNISON), Hermosillo, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz³², R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, M. Ramirez-Garcia, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

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

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

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk³³, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadrucchio, J. Varela

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev^{34,35}, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim³⁶, E. Kuznetsova³⁷, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

M. Chadeeva³⁸, P. Parygin, D. Philippov, S. Polikarpov³⁸, E. Popova, V. Rusinov

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin³⁵, M. Kirakosyan, S.V. Rusakov, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, A. Demiyanov, A. Ershov, A. Gribushin, O. Kodolova, V. Korotkikh, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Barnyakov³⁹, V. Blinov³⁹, T. Dimova³⁹, L. Kardapoltsev³⁹, Y. Skovpen³⁹

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitiukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

A. Babaev, S. Baidali, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

P. Adzic⁴⁰, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

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

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, 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, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

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

C. Albajar, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

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, P. Vischia, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

N. Wickramage

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

D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita⁴¹, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, V. Innocente, A. Jafari, P. Janot, O. Karacheban¹⁸, J. Kieseler, A. Kornmayer, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴², F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo¹⁵, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, T. Reis, G. Rolandi⁴³, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁴, A. Stakia, J. Steggemann, M. Tosi, D. Treille, A. Tsiros, V. Veckalns⁴⁵, M. Verzetti, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada⁴⁶, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, L. Bäni, 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, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Quittnat, C. Reissel, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

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

T.K. Aarrestad, C. Amsler⁴⁷, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, S. Leontsinis, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

Universität Zürich, Zurich, Switzerland

Y.H. Chang, K.y. Cheng, T.H. Doan, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Arun Kumar, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

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

A. Bat, F. Boran, S. Cerci⁴⁸, S. Damarseckin, Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos⁴⁹, C. Isik, E.E. Kangal⁵⁰, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵¹, S. Ozturk⁵², D. Sunar Cerci⁴⁸, B. Tali⁴⁸, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Isildak⁵³, G. Karapinar⁵⁴, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁵⁵, O. Kaya⁵⁶, S. Ozkorucuklu⁵⁷, S. Tekten, E.A. Yetkin⁵⁸

Bogazici University, Istanbul, Turkey

M.N. Agaras, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen⁵⁹

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold⁶⁰, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

A. Belyaev⁶¹, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash⁶², A. Nikitenko⁷, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee¹⁵, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. McMaster, N. Pastika, C. Smith

Baylor University, Waco, USA

R. Bartek, A. Dominguez

Catholic University of America, Washington, DC, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

D. Arcaro, T. Bose, D. Gastler, D. Pinna, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶³, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir⁶⁴, R. Syarif, E. Usai, D. Yu

Brown University, Providence, USA

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

University of California, Davis, Davis, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Los Angeles, USA

E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁵, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

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

D. Anderson, A. Bornheim, J.M. Lawhorn, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Cornell University, Ithaca, 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, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, 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, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro⁶⁶,

B. Schneider, E. Sexton-Kennedy, 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, A. Whitbeck

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, M. Carver, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rosenzweig, K. Shi, D. Sperka, J. Wang, S. Wang, X. Zuo

University of Florida, Gainesville, USA

Y.R. Joshi, S. Linn

Florida International University, Miami, USA

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, C. Schiber, R. Yohay

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, 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, J. Kamin, C. Mills, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

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

M. Alhusseini, B. Bilki⁶⁷, W. Clarida, K. Dilsiz⁶⁸, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁶⁹, Y. Onel, F. Ozok⁷⁰, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

The University of Iowa, Iowa City, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, V. Azzolini, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, 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, C. Roland, G. Roland, G.S.F. Stephens, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti[†], R.M. Chatterjee, A. Evans, P. Hansen, Sh. Jain, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁴, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer

The Ohio State University, Columbus, USA

S. Cooperstein, P. Elmer, J. Hardenbrook, S. Higginbotham, A. Kalogeropoulos, 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

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

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

Purdue University, West Lafayette, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

Rice University, Houston, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, P. Tan, R. Taus

University of Rochester, Rochester, USA

A. Agapitos, J.P. Chou, Y. Gershtein, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

University of Tennessee, Knoxville, USA

O. Bouhali⁷¹, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷², S. Luo, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, P.R. Duderod, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

Wayne State University, Detroit, USA

M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, V. Sharma, N. Smith, W.H. Smith, N. Woods

University of Wisconsin – Madison, Madison, WI, USA

[†] 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 Université Libre de Bruxelles, Bruxelles, Belgium.

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

⁷ Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

⁸ Also at Joint Institute for Nuclear Research, Dubna, Russia.

⁹ Now at Cairo University, Cairo, Egypt.

¹⁰ Also at Fayoum University, El-Fayoum, Egypt.

¹¹ Now at British University in Egypt, Cairo, Egypt.

¹² Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia.

¹³ Also at Université de Haute Alsace, Mulhouse, France.

¹⁴ Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

- ¹⁵ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- ¹⁶ Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
- ¹⁷ Also at University of Hamburg, Hamburg, Germany.
- ¹⁸ Also at Brandenburg University of Technology, Cottbus, Germany.
- ¹⁹ Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
- ²⁰ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ²¹ Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
- ²² Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.
- ²³ Also at Institute of Physics, Bhubaneswar, India.
- ²⁴ Also at Shoolini University, Solan, India.
- ²⁵ Also at University of Visva-Bharati, Santiniketan, India.
- ²⁶ Also at Isfahan University of Technology, Isfahan, Iran.
- ²⁷ Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- ²⁸ Also at Università degli Studi di Siena, Siena, Italy.
- ²⁹ Also at Kyung Hee University, Department of Physics, Seoul, Republic of Korea.
- ³⁰ Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- ³¹ Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- ³² Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ³³ Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- ³⁴ Also at Institute for Nuclear Research, Moscow, Russia.
- ³⁵ Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ³⁶ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ³⁷ Also at University of Florida, Gainesville, USA.
- ³⁸ Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ³⁹ Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ⁴⁰ Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ⁴¹ Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy.
- ⁴² Also at University of Belgrade, Belgrade, Serbia.
- ⁴³ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ⁴⁴ Also at National and Kapodistrian University of Athens, Athens, Greece.
- ⁴⁵ Also at Riga Technical University, Riga, Latvia.
- ⁴⁶ Also at Universität Zürich, Zurich, Switzerland.
- ⁴⁷ Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
- ⁴⁸ Also at Adiyaman University, Adiyaman, Turkey.
- ⁴⁹ Also at Istanbul Aydin University, Istanbul, Turkey.
- ⁵⁰ Also at Mersin University, Mersin, Turkey.
- ⁵¹ Also at Piri Reis University, Istanbul, Turkey.
- ⁵² Also at Gaziosmanpasa University, Tokat, Turkey.
- ⁵³ Also at Ozyegin University, Istanbul, Turkey.
- ⁵⁴ Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁵⁵ Also at Marmara University, Istanbul, Turkey.
- ⁵⁶ Also at Kafkas University, Kars, Turkey.
- ⁵⁷ Also at Istanbul University, Istanbul, Turkey.
- ⁵⁸ Also at Istanbul Bilgi University, Istanbul, Turkey.
- ⁵⁹ Also at Hacettepe University, Ankara, Turkey.
- ⁶⁰ Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ⁶¹ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁶² Also at Monash University, Faculty of Science, Clayton, Australia.
- ⁶³ Also at Bethel University, St. Paul, USA.
- ⁶⁴ Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- ⁶⁵ Also at Utah Valley University, Orem, USA.
- ⁶⁶ Also at Purdue University, West Lafayette, USA.
- ⁶⁷ Also at Beykent University, Istanbul, Turkey.
- ⁶⁸ Also at Bingöl University, Bingöl, Turkey.
- ⁶⁹ Also at Sinop University, Sinop, Turkey.
- ⁷⁰ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- ⁷¹ Also at Texas A&M University at Qatar, Doha, Qatar.
- ⁷² Also at Kyungpook National University, Daegu, Republic of Korea.