

CERN-PH-EP/2011-035
2011/04/11

CMS-EWK-10-013

Measurement of the Inclusive Z Cross Section via Decays to Tau Pairs in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

A measurement of inclusive $Z \rightarrow \tau^+\tau^-$ production in pp collisions is presented, in the final states μ +hadrons, e+hadrons, $e+\mu$, and $\mu+\mu$. The data sample corresponds to an integrated luminosity of 36 pb^{-1} collected with the CMS detector at the LHC. The measured cross section is $\sigma(\text{pp} \rightarrow ZX) \times \mathcal{B}(Z \rightarrow \tau^+\tau^-) = 1.00 \pm 0.05 \text{ (stat.)} \pm 0.08 \text{ (syst.)} \pm 0.04 \text{ (lumi.) nb}$, which is in good agreement with the next-to-next-to-leading order QCD prediction and with previous measurements in the $Z \rightarrow e^+e^-$ and $\mu^+\mu^-$ channels. The reconstruction efficiency for hadronic τ decays is determined with a precision of 7%.

Submitted to the Journal of High Energy Physics

*See Appendix A for the list of collaboration members

1 Introduction

The measurement of the production cross section for $pp \rightarrow ZX$ with $Z \rightarrow \tau^+\tau^-$ constitutes an important physics benchmark at the Large Hadron Collider (LHC). The τ lepton can decay either into purely leptonic final states ($\tau \rightarrow e\bar{\nu}_e\nu_\tau$ denoted as “ τ_e ” or $\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$ denoted as “ τ_μ ”) or into hadronic final states denoted by “ τ_{had} ” consisting of a hadronic system and a ν_τ . Constrained by the τ mass, the hadronic system is characterized by a low particle multiplicity and a highly collimated jet which allows a τ_{had} signal to be separated from the large QCD jet backgrounds. The validation of the τ_{had} signal is essential in searches for new physics based on τ leptons, such as Higgs boson decays to $\tau^+\tau^-$ [1]. The Compact Muon Solenoid (CMS) Collaboration recently reported a search for the Higgs boson in this channel [2]. Tau leptons can also be important signatures for searches of supersymmetry, extra dimensions, and extra gauge bosons [3].

The $Z \rightarrow \tau^+\tau^-$ production cross section has been previously measured in proton-antiproton collisions by the CDF and D0 Collaborations [4, 5]. In this study, $Z \rightarrow \tau^+\tau^-$ events in the $\tau_\mu\tau_{\text{had}}$, $\tau_e\tau_{\text{had}}$, $\tau_e\tau_\mu$, and $\tau_\mu\tau_\mu$ final states are selected from a sample of $\sqrt{s} = 7$ TeV proton-proton collision data recorded by the CMS experiment at the LHC. The data sample corresponds to an integrated luminosity of 36 ± 1 pb⁻¹. The results are compared to previous measurements made in the e^+e^- and $\mu^+\mu^-$ final states [6], providing a validation of τ_{had} reconstruction and identification [7–9] and a direct measurement of the tau selection efficiency.

2 CMS Detector

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke.

CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the centre of the LHC, the y axis pointing up perpendicular to the LHC plane, and the z axis along the counterclockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the xy plane. Variables used in this article are the pseudorapidity, $\eta \equiv -\ln[\tan(\theta/2)]$, and the transverse momentum, $p_T = \sqrt{p_x^2 + p_y^2}$.

The ECAL is designed to have both excellent energy resolution and high granularity, which are crucial for reconstructing electrons and photons produced in τ decays. The ECAL is constructed with projective lead tungstate crystals in two pseudorapidity regions: the barrel ($|\eta| < 1.479$) and the endcap ($1.479 < |\eta| < 3$). The transition regions between the barrel and the endcaps, $1.444 < |\eta| < 1.567$, are not used for electron reconstruction. In the barrel region, the crystals are $25.8 X_0$ long, where X_0 is the radiation length, and conform to a granularity of $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$. The endcap region is instrumented with a lead–silicon-strip preshower detector consisting of two orthogonal strip detectors with a strip pitch of 1.9 mm. One plane is at a depth of $2X_0$ and the other at $3X_0$. The ECAL has an energy resolution of better than 0.5% for unconverted photons with transverse energies above 100 GeV. The energy resolution is 3% or better for the range of electron energies relevant for this analysis. The HCAL barrel and endcap regions cover the range $|\eta| < 3$ and are subdivided into towers with a segmentation of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$, corresponding to 5×5 ECAL crystals in the barrel

region. The HCAL forward region extends the calorimetry to $|\eta| < 5$.

The inner tracker measures charged particle tracks within the range $|\eta| < 2.5$. It consists of 1 440 silicon pixel and 15 148 silicon strip detector modules and provides an impact parameter resolution of $\sim 15 \mu\text{m}$ and a transverse momentum resolution of about 1.5% for 100 GeV particles.

The muon barrel region is covered by drift tubes and the endcap regions by cathode strip chambers. In both regions resistive plate chambers provide additional coordinate and timing information. Muons can be reconstructed in the range $|\eta| < 2.4$, with a typical p_T resolution of 1% for $p_T \approx 40 \text{ GeV}$.

A more detailed description of CMS can be found in [10].

3 Lepton Reconstruction and Identification

Muons produced by τ decays in the $Z \rightarrow \tau^+ \tau^-$ process are reconstructed in the tracker and muon chambers [11]. Quality cuts, based on the minimum number of hits in the silicon tracker, pixel detector, and muon chambers, are applied to suppress backgrounds from punch-throughs and decays in flight.

Electrons are reconstructed by combining tracks produced by the Gaussian Sum Filter algorithm with ECAL clusters [12]. Requirements are imposed that distinguish prompt electrons from charged pions mimicking electron signatures, and from electrons produced by photon conversions.

The CMS particle flow (PF) algorithm [8] is used to form a mutually exclusive collection of reconstructed particles (muons, electrons, photons, and charged and neutral hadrons) by combining tracks and calorimeter clusters. These reconstructed particles are used to build composite objects such as τ 's and jets, and to measure the missing transverse energy \cancel{E}_T .

Electrons and muons from τ decays are expected to be isolated in the detector, while leptons from heavy-flavour (c and b) decays and decays in flight are expected to be found inside jets. A measure of isolation is used to discriminate the signal from the QCD multijet background, based on the charged hadrons, photons, and neutral hadrons falling within a cone $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ around the lepton momentum direction. In the $\tau_\mu \tau_\mu$ final state, a cone of $\Delta R = 0.3$ is used. A sum of the p_T for each particle type is made for charged hadrons with $p_T > 0.5 \text{ GeV}$ and for photons and neutral hadrons with $p_T > 1 \text{ GeV}$; photons and neutral hadrons are excluded from the sum if they fall within inner cones of $\Delta R = 0.05$ and $\Delta R = 0.08$, respectively. The relative isolation variable is $I_{\text{rel}}^{\text{PF}} = \Sigma \left(p_T^{\text{charged}} + p_T^{\text{photon}} + p_T^{\text{neutral}} \right) / p_T^\ell$, where p_T^{charged} , p_T^{photon} , and p_T^{neutral} refer to the charged hadrons, photons, and neutral hadrons in the sum, respectively, and p_T^ℓ refers to the p_T of the lepton $\ell = e, \mu$. For muons, it is required that $I_{\text{rel}}^{\text{PF}} < 0.1$, while for electrons it is required that $I_{\text{rel}}^{\text{PF}} < 0.08$ in the barrel and $I_{\text{rel}}^{\text{PF}} < 0.04$ in the endcaps. A similar formula is used for the $\tau_e \tau_\mu$ final state but with the isolation quantities based directly on tracker and calorimeter information, calculated in a cone of $\Delta R = 0.3$. In this case, it is required that $I_{\text{rel}} < 0.15$ for muons and $I_{\text{rel}} < 0.1$ for electrons.

The τ_{had} identification algorithm used in this measurement is known as the Hadrons Plus Strips algorithm [9], which starts from a high- p_T charged hadron and combines it with other nearby charged or neutral hadrons to reconstruct τ decay modes. The identification of π^0 mesons is enhanced by clustering electrons and photons in "strips" along the bending plane to take into account possible broadening of calorimeter signatures by photon conversions. To reduce

the contamination from QCD jets, the τ_{had} -candidate isolation is calculated in a cone of $\Delta R = 0.5$ around the reconstructed τ -momentum direction. It is requested that there be no charged hadrons with $p_T > 1.0$ GeV and no photons with $E_T > 1.5$ GeV in the isolation cone, other than the τ constituents.

4 Event Selection

The events preselected for this analysis in the $\tau_\mu \tau_{\text{had}}$, $\tau_e \tau_\mu$, and $\tau_\mu \tau_\mu$ final states are required to pass the single-muon Level-1 (L1) trigger with a p_T threshold of 7 GeV and the single muon High Level Trigger (HLT) [13], with a threshold varying from 9 GeV to 15 GeV, depending on the instantaneous luminosity. Events in the $\tau_e \tau_{\text{had}}$ final state are selected using the single-electron L1 trigger with a threshold of 8 GeV in the transverse energy, and a single-electron HLT trigger with a threshold of 12 GeV at higher instantaneous luminosity. At the end of the 2010 data taking period, a combined $e+\tau$ trigger was used in order to keep the rate low enough without a further increase of the electron threshold. The trigger has the same L1 requirements as the electron trigger, but the HLT requires the presence of an electron of transverse energy larger than 12 GeV and a hadronic tau decay with p_T larger than 15 GeV, tagged with a simplified version of the tau reconstruction algorithm with a less restrictive selection than the one used in the offline analysis.

Offline event selection starts with the requirement of a well-defined primary vertex [14]. For the $\tau_\mu \tau_{\text{had}}$ and $\tau_e \tau_{\text{had}}$ final states, one isolated muon or electron is required with $p_T > 15$ GeV and $|\eta| < 2.1$. The associated τ_{had} must be oppositely charged, with $p_T > 20$ GeV and $|\eta| < 2.3$. In order to reject events coming from the W +jets background, the transverse mass of the lepton and the \cancel{E}_T , $M_T(\ell, \cancel{E}_T) = \sqrt{2p_T^\ell \cancel{E}_T \cdot (1 - \cos \Delta\phi)}$, is required to be less than 40 GeV, where $\Delta\phi$ is the difference in azimuthal angle between the lepton and \cancel{E}_T vectors. The M_T distribution and the selection requirement applied are illustrated in Fig. 1 (left) for the $\tau_\mu \tau_{\text{had}}$ final state.

For the $\tau_e \tau_\mu$ final state, one isolated muon with $|\eta| < 2.1$ and one oppositely charged isolated electron with $|\eta| < 2.4$ are required, both with $p_T > 15$ GeV. Further background suppression is achieved by requiring $M_T(\mu, \cancel{E}_T) < 50$ GeV and $M_T(e, \cancel{E}_T) < 50$ GeV.

For the $\tau_\mu \tau_\mu$ final state, events with two oppositely charged isolated muons with $|\eta| < 2.1$ are selected if one satisfies $p_T > 19$ GeV and the other $p_T > 10$ GeV. The requirement $\cancel{E}_T < 50$ GeV suppresses $t\bar{t}$ and W +jets backgrounds, and a requirement on the azimuthal angle difference between the muons, $\Delta\phi_{\mu\mu} > 2$, rejects QCD background events, for muons originating from the same quarkonia decay or from a decay chain of heavy-flavour hadrons. Effective suppression of the Drell–Yan background is achieved with a multivariate likelihood ratio technique. For each event, the relative probabilities to belong to two event classes ($Z \rightarrow \tau^+ \tau^- \rightarrow \tau_\mu \tau_\mu$ and $Z/\gamma^* \rightarrow \mu^+ \mu^-$) are computed, exploiting the following set of discriminating variables: the ratio of the transverse momentum of the dimuon system to the scalar sum of the momenta of the two muons; the significance of the distance of closest approach (DCA) between the two muon helix tracks; the pseudorapidity of the dimuon system; and the azimuthal angle between the positive muon momentum and \cancel{E}_T . A normalized likelihood discriminant is computed and is shown in Fig. 1 (right). Events with a likelihood discriminant value larger than 0.87 are kept in the final sample.

For the plots in Fig. 1, the QCD multijet, W and diboson backgrounds were simulated with PYTHIA [15], the Drell–Yan signal and background with the next-to-leading order (NLO) Monte Carlo generator POWHEG [16–18], and the top samples with Madgraph [19]. The tau decays were performed with Tauola [20]. The samples were normalized using the cross section

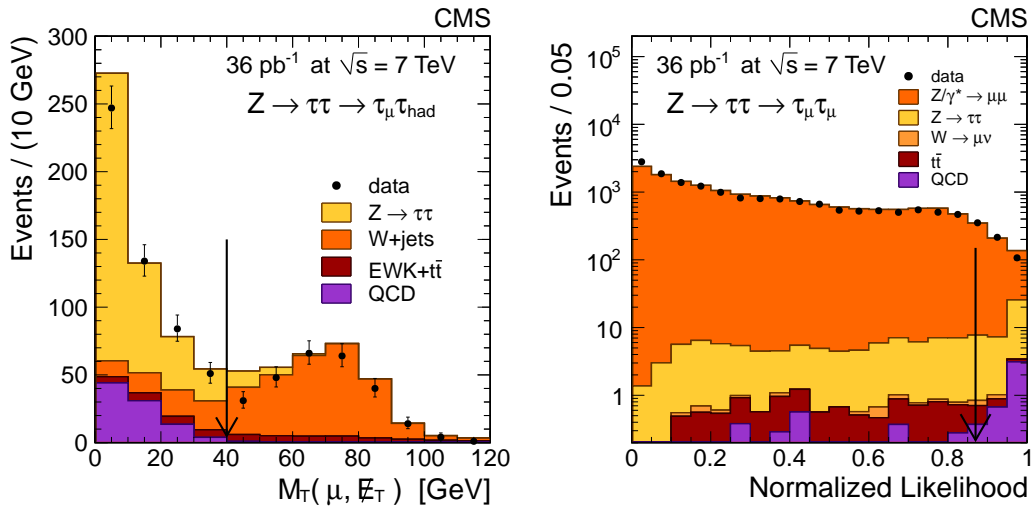


Figure 1: Muon+ E_T transverse mass (left) for the $\tau_\mu\tau_{\text{had}}$ final state. Likelihood discriminant (right) for the $\tau_\mu\tau_\mu$ final state. The arrows show the final selection criteria applied.

at next-to-next-to-leading order (NNLO) for Drell–Yan and W , at leading order (LO) for QCD, and NLO for the $t\bar{t}$ sample. The EWK label in the figure refers to the $Z \rightarrow e^+e^-, \mu^+\mu^-$, and diboson backgrounds.

5 Background Estimation

The $Z \rightarrow \tau^+\tau^-$ signal is established using the visible mass, which is the reconstructed mass of the $\ell\tau_{\text{had}}$ system in the $\tau_\ell\tau_{\text{had}}$ final states, and the dilepton invariant mass for the $\tau_e\tau_\mu$ and $\tau_\mu\tau_\mu$ final states. Due to the presence of neutrinos in the final state, the $Z \rightarrow \tau^+\tau^-$ visible mass peak extends across the range 30–100 GeV, which is considerably broader than the Z resonance itself. The backgrounds generally span the same mass range, so an accurate determination of the signal yield requires effective background estimation techniques. The main background sources are QCD multijet processes, W +jets, and $Z \rightarrow \ell^+\ell^-$, with small contributions from top-quark decays and dibosons. All backgrounds are measured in control regions where their contributions are enhanced and extrapolated to the signal selection region using selection efficiencies determined either from data or the Monte Carlo simulation. In the $\tau_\ell\tau_{\text{had}}$ final state, the QCD multijet background is estimated using samples of same-sign (SS) and opposite-sign (OS) events from data, for which the electron or muon isolation requirement is inverted; the QCD background estimate is based on the ratio of OS to SS yields. The visible mass distribution of the SS events is used to describe the background in the signal region. The W contribution is extracted from the region $M_T(\ell, E_T) > 60$ GeV, where it dominates the sample. In the $\tau_e\tau_\mu$ final state, the background contributions are expected to be small and are estimated from the simulation. The large-transverse-mass region is used to check the estimated background contributions from W , diboson, and $t\bar{t}$ backgrounds. For the $\tau_\mu\tau_\mu$ final state, the Drell–Yan muon-pair production events are selected with a reduced likelihood without including the muon DCA significance, and the resulting muon DCA significance distribution is fitted with signal and background shapes. The QCD multijet background estimate is obtained from a sample of SS dimuon events.

The numbers of selected events and the expected background contributions are summarized in Table 1. The statistical and systematic uncertainties in the methods used are also given, where

the uncertainties are added in quadrature.

Table 1: Numbers of expected background events and number of data events passing all the selection criteria in the four final states. The uncertainties shown include the statistical and systematic uncertainties added in quadrature.

	$\tau_\mu \tau_{\text{had}}$	$\tau_e \tau_{\text{had}}$	$\tau_e \tau_\mu$	$\tau_\mu \tau_\mu$ ($M_{\mu\mu} < 70 \text{ GeV}$)
$Z \rightarrow \ell^+ \ell^-$, jet misidentified as τ	6.4 ± 2.4	15.0 ± 6.2	-	-
$Z \rightarrow \ell^+ \ell^-$, lepton misidentified as τ	12.9 ± 3.5	109 ± 28	2.4 ± 0.3	20.1 ± 1.3
$t\bar{t}$	6.0 ± 3.0	2.6 ± 1.3	7.1 ± 1.3	0.15 ± 0.03
$W \rightarrow \ell\nu$	54.9 ± 4.8	30.6 ± 3.1	1.5 ± 0.5	2.5 ± 2.5
$W \rightarrow \tau\nu$	14.7 ± 1.3	7.0 ± 0.7		
QCD multijet	132 ± 14	181 ± 23		
WW/WZ/ZZ	1.6 ± 0.8	0.8 ± 0.4	3.0 ± 0.4	-
Total background	228 ± 16	346 ± 37	14.0 ± 1.8	22.8 ± 2.8
Total data	517	540	101	58

6 Systematic Uncertainties

The efficiencies for electron and muon reconstruction, identification, and isolation, as well as the trigger efficiencies are obtained from data. Correction factors for the values extracted from the simulation are determined using the method described in Ref. [6] (*tag-and-probe* method). The measured efficiencies have a small dependence on p_T and cover the full range of p_T used in the analysis. The uncertainties on the correction factors are in the range of 0.2–1.1%.

A similar technique is used to estimate the hadronic tau identification efficiency. A data sample of taus is selected using $Z \rightarrow \tau^+ \tau^- \rightarrow \tau_\mu \tau_{\text{had}}$ events. The events are preselected without applying the full tau identification but only kinematic cuts and a set of requirements to suppress the background from $Z \rightarrow \mu^+ \mu^-$, W , and QCD events. The efficiency is then calculated as a ratio of the number of events that pass the tau identification requirement to the number of all preselected events. The total uncertainty of the measurement arises from the statistical uncertainty of the sample and the systematic uncertainties related to the understanding of the backgrounds in the preselection sample and amounts to 23% [9].

To estimate the efficiency of the M_T selection and the likelihood selection efficiency for the $\tau_\mu \tau_\mu$ final state, an embedded sample is used where the muons in a $Z \rightarrow \mu^+ \mu^-$ data sample are replaced by simulated tau decays with the original muon momentum. The estimated uncertainties amount to 2%.

To estimate the effect of the energy-scale uncertainties on the acceptance, the energy of all reconstructed objects (electrons, muons, taus, and jets) is varied within their respective uncertainty. After each independent shift, the missing transverse energy is recalculated and the event selection is repeated. The event yield is compared to the nominal value and the relative difference is quoted as the systematic uncertainty. The systematic uncertainties are in the range from 1% to 3.5%.

To obtain the acceptance corrections, the D6T and Z2 PYTHIA tunes [21] were used in the simulation. The effect of the use of different tunes on the final extracted cross section is smaller than 1% and is not included in the systematic uncertainties.

The main source of theoretical uncertainty in the calculation of the experimental acceptance comes from the parton distribution functions (PDFs). The central acceptance value is obtained with the CT10 PDF [22]. The uncertainty is estimated using the error sets of the PDFs: CT10, MSTW2008NLO [23], and NNPDF2.0 [24], and amounts to 2%.

The experimental and theoretical uncertainties are summarized in Table 2.

Table 2: Summary of the sources of systematic uncertainties and their estimated effect on the measured $Z \rightarrow \tau^+\tau^-$ cross section.

Source	$\tau_\mu \tau_{\text{had}}$	$\tau_e \tau_{\text{had}}$	$\tau_e \tau_\mu$	$\tau_\mu \tau_\mu$
Trigger	0.2%	3%	0.2%	0.3%
Lepton identification and isolation	1.0%	1.1%	1%	1%
τ_{had} identification	23%		-	
Efficiency of M_T selection	2%		-	
Likelihood selection efficiency	-			2%
Acceptance due to τ_{had} energy scale, 3%	3.5%		-	
Acceptance due to e energy scale, 2%	-	1.6%	1.6%	-
Acceptance due to μ momentum scale, 1%	1%	-	1%	2%
Luminosity	4%			
Parton distribution functions	2%			

7 Cross Section Measurement

The cross section is obtained for each final state with the following formula:

$$\sigma(\text{pp} \rightarrow ZX) \times \mathcal{B}(Z \rightarrow \tau^+\tau^-) = \frac{N}{\mathcal{A} \epsilon \mathcal{B}' \mathcal{L}} , \quad (1)$$

where N is the number of extracted signal events, \mathcal{A} is the acceptance of signal events, ϵ is the signal selection efficiency, \mathcal{B}' is the branching fraction of the τ -decay mode considered [25], and \mathcal{L} is the integrated luminosity [26].

The visible mass distributions of the $\tau_\mu \tau_{\text{had}}$, $\tau_e \tau_{\text{had}}$, $\tau_e \tau_\mu$ and $\tau_\mu \tau_\mu$ final states are shown in Fig. 2. To extract the signal, a fit is performed using the visible mass shapes from the simulation, except for the QCD multijet and $Z \rightarrow \ell^+\ell^-$ backgrounds, which are obtained from data. For the simulation shapes, a variation of the electron and tau energy scales within their uncertainties is considered. The effect of the muon energy scale is negligible. The background normalizations correspond to the numbers listed in Table 1 and are allowed to vary within the estimated uncertainties. The background yields and signal shapes shown in Fig. 2 are those obtained from the fitting procedure.

Table 3: Acceptance, selection efficiency and fraction of selected events outside the generator-level mass window for the four final states considered.

	$\tau_\mu \tau_{\text{had}}$	$\tau_e \tau_{\text{had}}$	$\tau_e \tau_\mu$	$\tau_\mu \tau_\mu$
Acceptance \mathcal{A}	0.13	0.12	0.074	0.16
Selection efficiency ϵ	0.37	0.23	0.55	0.17
Mass window correction f_{out}	0.03	0.03	0.02	0.01

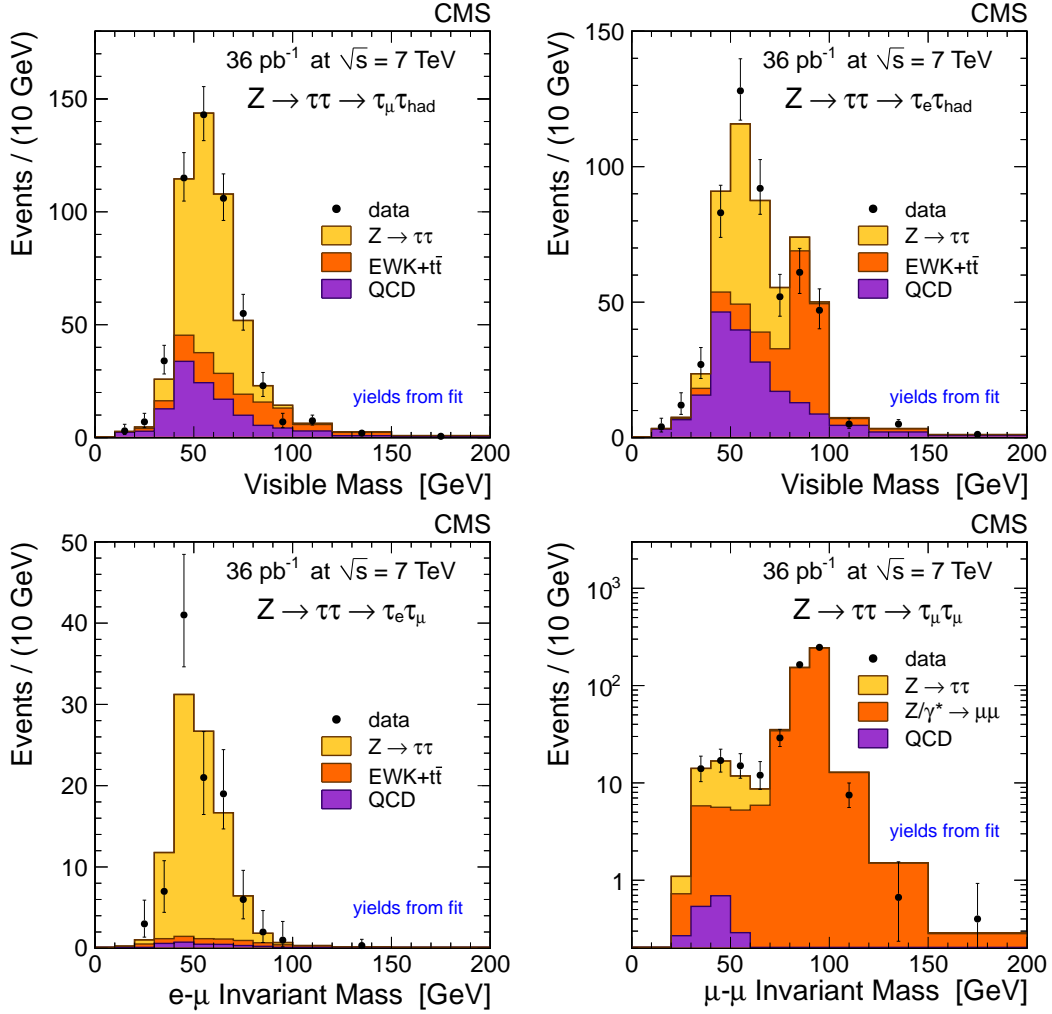


Figure 2: Visible mass distributions of the $\tau_\mu\tau_{\text{had}}$ (top left), $\tau_e\tau_{\text{had}}$ (top right), $\tau_e\tau_\mu$ (bottom left), and $\tau_\mu\tau_\mu$ (bottom right) final states.

The acceptances were obtained with the NLO QCD program POWHEG in the $Z \rightarrow \tau^+\tau^-$ mass region $60 < M_{\tau^+\tau^-} < 120$ GeV. Table 3 shows the acceptances and the selection efficiencies for the different final states considered. The number of extracted events from the fit, N_{fit} , is corrected for the fraction of signal events outside the generator-level mass window, f_{out} , where $N = N_{\text{fit}} \cdot (1 - f_{\text{out}})$ in Eq. 1. The correction factors used are also shown in Table 3.

The measured values of the cross section from the four final states considered are shown in Table 4, where the uncertainties shown are due to statistical, systematic, integrated luminosity and τ identification uncertainties.

The measured values are compatible with each other and with the NNLO theoretical prediction, 0.972 ± 0.042 nb [27]. They are also consistent with the CMS measurement based on $Z \rightarrow e^+e^-, \mu^+\mu^-$ events [6].

The dominant uncertainty on the $Z \rightarrow \tau^+\tau^-$ cross section measurement comes from the τ_{had} reconstruction and identification efficiency. A simultaneous fit to all four final states is performed to obtain the cross section and a scale factor for the τ_{had} efficiency, which is the ratio of the efficiency in the data to that in the simulation. The result of the global fit is shown in

Table 4: The measured values of the cross section from the four final states considered. The statistical, systematic and luminosity uncertainties are given. The uncertainty associated to the τ_{had} reconstruction and identification efficiency, $\tau_{\text{had}} - \text{ID}$, is shown separately.

Final state	$\sigma(\text{pp} \rightarrow ZX) \times \mathcal{B}(Z \rightarrow \tau^+\tau^-)$ nb	stat.	syst.	lumi.	τ ID
$\tau_\mu \tau_{\text{had}}$	0.83	0.07	0.04	0.03	0.19
$\tau_e \tau_{\text{had}}$	0.94	0.11	0.03	0.04	0.22
$\tau_e \tau_\mu$	0.99	0.12	0.06	0.04	
$\tau_\mu \tau_\mu$	1.14	0.27	0.04	0.05	

Fig. 3 (left), where the likelihood contours for the best estimates of the cross section and the τ_{had} efficiency scale factor are shown. In addition to the one-standard-deviation contour, the contours for which the likelihood L is reduced by $2\Delta \ln L = 2.30$ and 6.18 compared to the maximum value are also shown, corresponding to a coverage of 68% and 95% in the two-parameter plane, respectively. The value of the cross section extracted from the fit is

$$\sigma(\text{pp} \rightarrow ZX) \times \mathcal{B}(Z \rightarrow \tau^+\tau^-) = 1.00 \pm 0.05 \text{ (stat.)} \pm 0.08 \text{ (syst.)} \pm 0.04 \text{ (lumi.) nb,}$$

which is compared to the individual final state measurements in Fig. 3 (right). The value for the cross section is dominated by the dilepton final states which have smaller systematic uncertainties. In the simultaneous fit, the $\tau_{\text{had}} - \text{ID}$ scale factor is measured to be 0.93 ± 0.09 .

A more precise value of the hadronic tau reconstruction efficiency can be obtained by performing a fit of the $\tau_\mu \tau_{\text{had}}$ and $\tau_e \tau_{\text{had}}$ final states, where the cross section is fixed to the value measured by CMS in the electron and muon decay channels, $\sigma(\text{pp} \rightarrow ZX) \times \mathcal{B}(Z \rightarrow e^+e^-, \mu^+\mu^-) = 0.931 \pm 0.026 \text{ (stat.)} \pm 0.023 \text{ (syst.)} \pm 0.102 \text{ (lumi.) nb}$ [6]. The extracted value of the $\tau_{\text{had}} - \text{ID}$ scale factor is 0.96 ± 0.07 , which corresponds to a tau identification efficiency of $(47.4 \pm 3.3)\%$ in data, for hadronically decaying tau leptons in the $Z \rightarrow \tau^+\tau^-$ sample with visible $p_T > 20 \text{ GeV}$ within the detector acceptance.

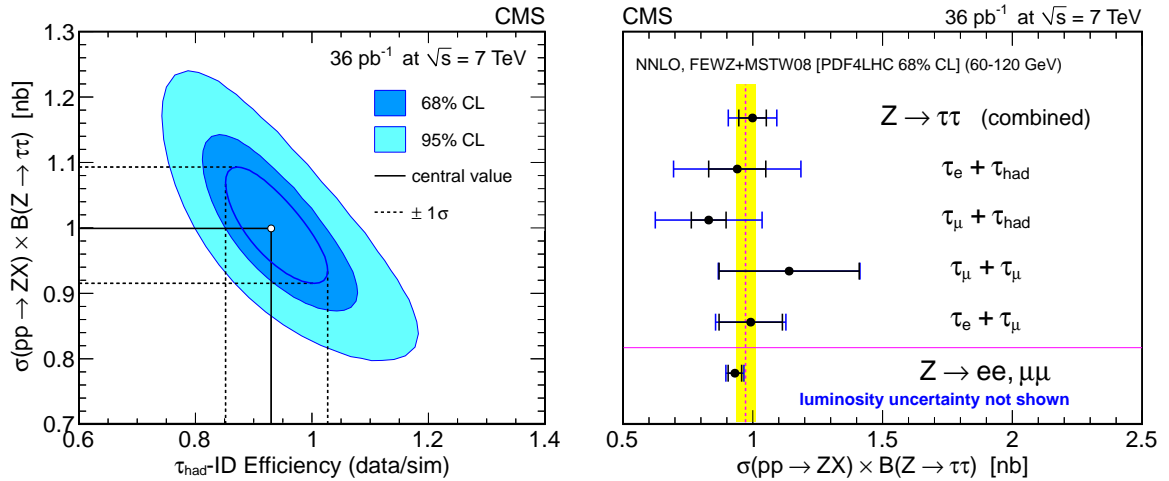


Figure 3: Likelihood contours for the joint parameter estimation of the cross section and the τ -identification (left). The fitted central values (solid line) and their estimated 1σ uncertainties (dashed lines) are also shown. Summary of the measured $Z \rightarrow \tau^+\tau^-$ cross sections in the invariant mass range of $60 < M_{\tau^+\tau^-} < 120 \text{ GeV}$ (right). The inner error bar represents the statistical uncertainty. The extracted cross section from the combined fit and the NNLO theoretical prediction are also shown.

8 Conclusions

A measurement of the cross section for the process $pp \rightarrow ZX$ with $Z \rightarrow \tau^+\tau^-$ has been performed, based on the $\tau_\mu\tau_{\text{had}}$, $\tau_e\tau_{\text{had}}$, $\tau_e\tau_\mu$, and $\tau_\mu\tau_\mu$ final states. A clear signal is established in the visible mass distributions for all channels. The measured cross section, $\sigma(pp \rightarrow ZX) \times \mathcal{B}(Z \rightarrow \tau^+\tau^-) = 1.00 \pm 0.05$ (stat.) ± 0.08 (syst.) ± 0.04 (lumi.) nb, is consistent with theoretical expectations, and the CMS measurement for the $Z \rightarrow e^+e^-$ and $\mu^+\mu^-$ decay channels. A global fit of the $\tau_\mu\tau_{\text{had}}$ and $\tau_e\tau_{\text{had}}$ channels provides a 7% constraint on the efficiency for reconstructing hadronic tau decays in CMS.

Acknowledgements

We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTDS (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

References

- [1] J. Gunion et al., “The Higgs Hunter’s Guide”. Westview Press, 2000.
- [2] CMS Collaboration, “Search for Neutral MSSM Higgs Bosons Decaying to Tau Pairs in pp Collisions at $\sqrt{s} = 7$ TeV”, *Submitted to Phys. Rev. Lett.* (2011).
- [3] CMS Collaboration, “CMS technical design report, volume II: Physics performance”, *J. Phys.* **G34** (2007) 995. doi:10.1088/0954-3899/34/6/S01.
- [4] CDF Collaboration, “Measurement of $\sigma(p\bar{p} \rightarrow Z) \cdot Br(Z \rightarrow 2\tau)$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev.* **D75** (2007) 092004. doi:10.1103/PhysRevD.75.092004.
- [5] D0 Collaboration, “Measurement of $\sigma(p\bar{p} \rightarrow Z + X) Br(Z \rightarrow \tau^+\tau^-)$ at $\sqrt{s} = 1.96$ -TeV”, *Phys. Lett.* **B670** (2009) 292, arXiv:0808.1306. doi:10.1016/j.physletb.2008.11.010.
- [6] CMS Collaboration, “Measurements of Inclusive W and Z Cross Sections in pp Collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **01** (2011) 080, arXiv:1012.2466. doi:10.1007/JHEP01(2011)080.
- [7] CMS Collaboration, “CMS Strategies for tau reconstruction and identification using particle-flow techniques”, *CMS Physics Analysis Summary CMS-PAS-PFT-08-001* (2008).
- [8] CMS Collaboration, “Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and E_T ”, *CMS Physics Analysis Summary CMS-PAS-PFT-09-001* (2009).

- [9] CMS Collaboration, "Performance of tau reconstruction algorithms in 2010 data collected with CMS", *CMS Physics Analysis Summary CMS-PAS-TAU-11-001* (2011).
- [10] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004. doi:10.1088/1748-0221/3/08/S08004.
- [11] CMS Collaboration, "Performance of muon identification in pp collisions at $\sqrt{s} = 7$ TeV", *CMS Physics Analysis Summary CMS-PAS-MUO-10-002* (2010).
- [12] CMS Collaboration, "Electron Reconstruction and Identification at $\sqrt{s} = 7$ TeV", *CMS Physics Analysis Summary CMS-PAS-EGM-10-004* (2010).
- [13] CMS Collaboration, "CMS High Level Trigger", *LHCC Report CERN-LHCC-2007-021* (2007).
- [14] CMS Collaboration, "Tracking and Primary Vertex Results in First 7 TeV Collisions", *CMS Physics Analysis Summary CMS-PAS-TRK-10-005* (2010).
- [15] T. Sjöstrand, S. Mrenna, and P. Z. Skands, "PYTHIA 6.4 Physics and Manual", *JHEP* **05** (2006) 026, arXiv:hep-ph/0603175. doi:10.1088/1126-6708/2006/05/026.
- [16] S. Alioli, P. Nason, C. Oleari et al., "NLO vector-boson production matched with shower in POWHEG", *JHEP* **07** (2008) 060, arXiv:0805.4802. doi:10.1088/1126-6708/2008/07/060.
- [17] P. Nason, "A new method for combining NLO QCD with shower Monte Carlo algorithms", *JHEP* **11** (2004) 040, arXiv:hep-ph/0409146. doi:10.1088/1126-6708/2004/11/040.
- [18] S. Frixione, P. Nason, and C. Oleari, "Matching NLO QCD computations with Parton Shower simulations: the POWHEG method", *JHEP* **11** (2007) 070, arXiv:0709.2092. doi:10.1088/1126-6708/2007/11/070.
- [19] F. Maltoni and T. Stelzer, "MadEvent: Automatic event generation with MadGraph", *JHEP* **02** (2003) 027, arXiv:hep-ph/0208156. doi:10.1088/1126-6708/2003/02/027.
- [20] S. Jadach, Z. Was, R. Decker et al., "The tau decay library TAUOLA: Version 2.4", *Comput. Phys. Commun.* **76** (1993) 361. doi:10.1016/0010-4655(93)90061-G.
- [21] R. Field, "Early LHC Underlying Event Data-Findings and Surprises", (2010). arXiv:1010.3558v1.
- [22] M. Guzzi et al., "CT10 parton distributions and other developments in the global QCD analysis", arXiv:1101.0561.
- [23] A. D. Martin, W. J. Stirling, R. S. Thorne et al., "Parton distributions for the LHC", *Eur. Phys. J.* **C63** (2009) 189, arXiv:0901.0002. doi:10.1140/epjc/s10052-009-1072-5.
- [24] R. D. Ball et al., "A first unbiased global NLO determination of parton distributions and their uncertainties", *Nucl. Phys.* **B838** (2010) 136, arXiv:1002.4407. doi:10.1016/j.nuclphysb.2010.05.008.
- [25] Particle Data Group Collaboration, "Review of particle physics", *J. Phys.* **G37** (2010) 075021. doi:10.1088/0954-3899/37/7A/075021.

-
- [26] CMS Collaboration, “Absolute luminosity normalization”, *CMS Detector Performance Summary* **CMS-DPS-2011-002** (2008).
- [27] K. Melnikov and F. Petriello, “Electroweak gauge boson production at hadron colliders through $\mathcal{O}(\alpha_s^2)$ ”, *Phys. Rev.* **D74** (2006) 114017, arXiv:hep-ph/0609070.
doi:10.1103/PhysRevD.74.114017.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer¹, S. Häsnel, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, G. Kasieczka, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, H. Rohringer, R. Schöfbeck, J. Strauss, F. Teischinger, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

L. Benucci, E.A. De Wolf, X. Janssen, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, O. Devroede, R. Gonzalez Suarez, A. Kalogeropoulos, J. Maes, M. Maes, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium

O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, P.E. Marage, L. Thomas, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium

V. Adler, A. Cimmino, S. Costantini, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. McCartin, D. Ryckbosch, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, N. Zaganidis

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

S. Basegmez, G. Bruno, J. Caudron, L. Ceard, E. Cortina Gil, J. De Favereau De Jeneret, C. Delaere¹, D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, S. Oryn, D. Pagano, A. Pin, K. Piotrkowski, N. Schul

Université de Mons, Mons, Belgium

N. Bely, T. Caeberts, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, D. De Jesus Damiao, M.E. Pol, M.H.G. Souza

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

W. Carvalho, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, F. Torres Da Silva De Araujo

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

F.A. Dias, T.R. Fernandez Perez Tomei, E. M. Gregores², C. Lagana, F. Marinho, P.G. Mercadante², S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

N. Darnenov¹, L. Dimitrov, V. Genchev¹, P. Iaydjiev¹, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, I. Vankov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, A. Karadzhinova, V. Kozhuharov, L. Litov, M. Mateev, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

Y. Ban, S. Guo, Y. Guo, W. Li, Y. Mao, S.J. Qian, H. Teng, L. Zhang, B. Zhu, W. Zou

Universidad de Los Andes, Bogota, Colombia

A. Cabrera, B. Gomez Moreno, A.A. Ocampo Rios, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, K. Lelas, R. Plestina³, D. Polic, I. Puljak

University of Split, Split, Croatia

Z. Antunovic, M. Dzelalija

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, S. Duric, K. Kadija, S. Morovic

University of Cyprus, Nicosia, Cyprus

A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic

M. Finger, M. Finger Jr.

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

Y. Assran⁴, S. Khalil⁵, M.A. Mahmoud⁶

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

A. Hektor, M. Kadastik, M. Müntel, M. Raidal, L. Rebane

Department of Physics, University of Helsinki, Helsinki, Finland

V. Azzolini, P. Eerola, G. Fedi

Helsinki Institute of Physics, Helsinki, Finland

S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

K. Banzuzi, A. Korpela, T. Tuuva

Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France

D. Sillou

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov, P. Verrecchia

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj⁷, C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Haguenaer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaut, B. Wyslouch⁸, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram⁹, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte⁹, F. Drouhin⁹, C. Ferro, J.-C. Fontaine⁹, D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim⁹, A.-C. Le Bihan, Y. Mikami, P. Van Hove

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

F. Fassi, D. Mercier

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

C. Baty, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

D. Lomidze

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

G. Anagnostou, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, N. Mohr, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, M. Weber, B. Wittmer

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

M. Ata, W. Bender, E. Dietz-Laursonn, M. Erdmann, J. Frangenheim, T. Hebbeker, A. Hinzmann, K. Hoepfner, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske[†], C. Magass, M. Merschmeyer, A. Meyer, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Tonutti

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

M. Bontenackels, M. Davids, M. Duda, G. Flügge, H. Geenen, M. Giffels, W. Haj Ahmad, D. Heydhausen, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl, M. Thomas, D. Tornier, M.H. Zoeller

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz¹⁰, A. Bethani, K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung¹, M. Kasemann, I. Katkov¹¹, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann¹⁰, R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, D. Pitzl, A. Raspereza, A. Raval, M. Rosin, R. Schmidt¹⁰, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

C. Autermann, V. Blobel, S. Bobrovskiy, J. Draeger, H. Enderle, U. Gebbert, K. Kaschube, G. Kaussen, R. Klanner, J. Lange, B. Mura, S. Naumann-Emme, F. Nowak, N. Pietsch, C. Sander,

H. Schettler, P. Schleper, M. Schröder, T. Schum, J. Schwandt, H. Stadie, G. Steinbrück, J. Thomsen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, J. Bauer, V. Buege, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, C. Hackstein, F. Hartmann, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, D. Piparo, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, M. Schmanau, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, T. Weiler, M. Zeise, V. Zhukov¹¹, E.B. Ziebarth

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

G. Daskalakis, T. Geralis, K. Karafasoulis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari, E. Petrakou

University of Athens, Athens, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu¹, P. Hidas, D. Horvath¹², A. Kapusi, K. Krajczar¹³, F. Sikler¹, G.I. Veres¹³, G. Vesztergombi¹³

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, J. Molnar, J. Palinkas, Z. Szillasi, V. Veszpremi

University of Debrecen, Debrecen, Hungary

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

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A.P. Singh, J.B. Singh, S.P. Singh

University of Delhi, Delhi, India

S. Ahuja, S. Bhattacharya, B.C. Choudhary, P. Gupta, S. Jain, S. Jain, A. Kumar, K. Ranjan, R.K. Shivpuri

Bhabha Atomic Research Centre, Mumbai, India

R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty¹, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, M. Guchait¹⁴, A. Gurtu, M. Maity¹⁵, D. Majumder, G. Majumder, K. Mazumdar, G.B. Mohanty, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad, N.K. Mondal

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

H. Arfaei, H. Bakhshiansohi¹⁶, S.M. Etesami, A. Fahim¹⁶, M. Hashemi, A. Jafari¹⁶, M. Khakzad, A. Mohammadi¹⁷, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali¹⁸

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c,1},

M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b}, G. Maggi^{a,c}, M. Maggi^a, N. Manna^{a,b}, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, G.A. Pierro^a, A. Pompili^{a,b}, G. Pugliese^{a,c}, F. Romano^{a,c}, G. Roselli^{a,b}, G. Selvaggi^{a,b}, L. Silvestris^a, R. Trentadue^a, S. Tupputi^{a,b}, G. Zito^a

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

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^a, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^a, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^a, P. Giacomelli^a, M. Giunta^a, C. Grandi^a, S. Marcellini^a, G. Masetti, M. Meneghelli^{a,b}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odoricci^a, A. Perrotta^a, F. Primavera^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G. Siroli^{a,b}

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

S. Albergo^{a,b}, G. Cappello^{a,b}, M. Chiorboli^{a,b,1}, S. Costa^{a,b}, A. Tricomi^{a,b}, C. Tuve^a

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

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,1}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi¹⁹, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy

P. Fabbricatore, R. Musenich

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

A. Benaglia^{a,b}, F. De Guio^{a,b,1}, L. Di Matteo^{a,b}, A. Ghezzi^{a,b}, S. Malvezzi^a, A. Martelli^{a,b}, A. Massironi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}, V. Tancini^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli "Federico II" ^b, Napoli, Italy

S. Buontempo^a, C.A. Carrillo Montoya^{a,1}, N. Cavallo^{a,20}, A. De Cosa^{a,b}, F. Fabozzi^{a,20}, A.O.M. Iorio^{a,1}, L. Lista^a, M. Merola^{a,b}, P. Paolucci^a

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

P. Azzi^a, N. Bacchetta^a, P. Bellan^{a,b}, A. Branca^a, R. Carlin^{a,b}, P. Checchia^a, M. De Mattia^{a,b}, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Kaminskiy^{a,b,11}, S. Lacaprara^{a,21}, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, M. Mazzucato^a, A.T. Meneguzzo^{a,b}, M. Nespolo^{a,1}, M. Passaseo^a, L. Perrozzi^{a,1}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, S. Vanini^{a,b}, S. Ventura^a, P. Zotto^{a,b}

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

P. Baesso^{a,b}, U. Berzano^a, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}, C. Viviani^{a,b}

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

M. Biasini^{a,b}, G.M. Bilei^a, B. Caponeri^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, A. Lucaroni^{a,b,1}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b}, F. Romeo^{a,b}, A. Santocchia^{a,b}, S. Taroni^{a,b,1}, M. Valdata^{a,b}

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

P. Azzurri^{a,c}, G. Bagliesi^a, J. Bernardini^{a,b}, T. Boccali^{a,1}, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c}, R. Dell'Orso^a, F. Fiori^{a,b}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,22}, A. Messineo^{a,b}, F. Palla^a, G. Segneri^a, A.T. Serban^a, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b,1}, A. Venturi^{a,1}, P.G. Verdini^a

INFN Sezione di Roma ^a, Università di Roma "La Sapienza" ^b, Roma, Italy

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, D. Franci^{a,b}, M. Grassi^{a,1}, E. Longo^{a,b}, S. Nourbakhsh^a, G. Organtini^{a,b}, F. Pandolfi^{a,b,1}, R. Paramatti^a, S. Rahatlou^{a,b}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, C. Biino^a, C. Botta^{a,b,1}, N. Cartiglia^a, R. Castello^{a,b}, M. Costa^{a,b}, N. Demaria^a, A. Graziano^{a,b,1}, C. Mariotti^a, M. Marone^{a,b}, S. Maselli^a, E. Migliore^{a,b}, G. Mila^{a,b}, V. Monaco^{a,b}, M. Musich^{a,b}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, V. Sola^{a,b}, A. Solano^{a,b}, A. Staiano^a, A. Vilela Pereira^{a,b}

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

S. Belforte^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, D. Montanino^{a,b}, A. Penzo^a

Kangwon National University, Chunchon, Korea

S.G. Heo, S.K. Nam

Kyungpook National University, Daegu, Korea

S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, S.R. Ro, D. Son, D.C. Son, T. Son

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

Zero Kim, J.Y. Kim, S. Song

Korea University, Seoul, Korea

S. Choi, B. Hong, M.S. Jeong, M. Jo, H. Kim, J.H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, H.B. Rhee, E. Seo, S. Shin, K.S. Sim

University of Seoul, Seoul, Korea

M. Choi, S. Kang, H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

M.J. Bilinskas, I. Grigelionis, M. Janulis, D. Martisiute, P. Petrov, T. Sabonis

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

H. Castilla-Valdez, E. De La Cruz-Burelo, R. Lopez-Fernandez, R. Magaña Villalba, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H.A. Salazar Ibarguen

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

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand

D. Krofcheck, J. Tam

University of Canterbury, Christchurch, New Zealand

P.H. Butler, R. Doesburg, H. Silverwood

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

M. Ahmad, I. Ahmed, M.I. Asghar, H.R. Hoorani, W.A. Khan, T. Khurshid, S. Qazi

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

G. Brona, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Soltan Institute for Nuclear Studies, Warsaw, Poland

T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szeleper, G. Wrochna, P. Zalewski

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

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Musella, A. Nayak, P.Q. Ribeiro, J. Seixas, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, I. Belotelov, P. Bunin, I. Golutvin, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, P. Moisenz, V. Palichik, V. Pereygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, V. Kaftanov[†], M. Kossov¹, A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

E. Boos, M. Dubinin²³, L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, S. Bitioukov, V. Grishin¹, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, S. Slabospitsky, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic²⁴, M. Djordjevic, D. Krpic²⁴, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cepeda, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizan Garcia

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini²⁵, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez²⁶, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, A.J. Bell²⁷, D. Benedetti, C. Bernet³, W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, M. Bona, H. Breuker, K. Bunkowski, T. Camporesi, G. Cerminara, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, S. Di Guida, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, S. Gennai, G. Georgiou, H. Gerwig, D. Gigi, K. Gill, D. Giordano, F. Glege, R. Gomez-Reino Garrido, M. Gouzevitch, P. Govoni, S. Gowdy, L. Guiducci, M. Hansen, C. Hartl, J. Harvey, J. Hegeman, B. Hegner, H.F. Hoffmann, A. Honma, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, P. Lecoq, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, A. Maurisset, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold¹, M. Nguyen, T. Orimoto, L. Orsini, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, G. Polese, A. Racz, J. Rodrigues Antunes, G. Rolandi²⁸, T. Rommelskirchen, C. Rovelli, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, M. Simon, P. Sphicas²⁹, M. Spiropulu²³, M. Stoye, P. Tropea, A. Tsiros, P. Vichoudis, M. Voutilainen, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille³⁰, A. Starodumov³¹

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

P. Bortignon, L. Caminada³², N. Chanon, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, A. Hervé, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica³², P. Martinez Ruiz del Arbol, P. Meridiani, P. Milenovic³³, F. Moortgat, C. Nägeli³², P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, B. Stieger, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, M. Weber, L. Wehrli, J. Weng

Universität Zürich, Zurich, Switzerland

E. Aguiló, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, C. Regenfus, P. Robmann, A. Schmidt, H. Snoek

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, R. Volpe, J.H. Wu, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, J.G. Shiu, Y.M. Tzeng, M. Wang

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci³⁴, S. Cerci³⁵, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, A. Kayis Topaksu, A. Nart, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut³⁶, D. Sunar Cerci³⁵, B. Tali, H. Topakli³⁴, D. Uzun, L.N. Vergili, M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey

M. Deliomeroğlu, D. Demir³⁷, E. Gülmez, B. Isildak, M. Kaya³⁸, O. Kaya³⁸, S. Ozkorucuklu³⁹, N. Sonmez⁴⁰

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

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Bostock, J.J. Brooke, T.L. Cheng, E. Clement, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, M. Hansen, D. Hartley, G.P. Heath, H.F. Heath, J. Jackson, L. Kreczko, S. Metson, D.M. Newbold⁴¹, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, S. Ward

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso⁴², K.W. Bell, A. Belyaev⁴², C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom

R. Bainbridge, G. Ball, J. Ballin, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, B.C. MacEvoy, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko³¹, A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi⁴³, D.M. Raymond, S. Rogerson, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, D. Wardrope, T. Whyntie

Brunel University, Uxbridge, United Kingdom

M. Barrett, M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, W. Martin, I.D. Reid, L. Teodorescu

Baylor University, Waco, USA

K. Hatakeyama

Boston University, Boston, USA

T. Bose, E. Carrera Jarrin, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA

A. Avetisyan, S. Bhattacharya, J.P. Chou, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, G. Landsberg, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA

R. Breedon, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, P.T. Cox, J. Dolen, R. Erbacher, E. Friis, W. Ko, A. Kopecky, R. Lander, H. Liu, S. Maruyama, T. Miceli,

M. Nikolic, D. Pellett, J. Robles, S. Salur, T. Schwarz, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, C. Veelken

University of California, Los Angeles, Los Angeles, USA

V. Andreev, K. Arisaka, D. Cline, R. Cousins, A. Deisher, J. Duris, S. Erhan, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev

University of California, Riverside, Riverside, USA

J. Babb, A. Chandra, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, O.R. Long, A. Luthra, H. Nguyen, B.C. Shen[†], R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA

W. Andrews, J.G. Branson, G.B. Cerati, E. Dusinger, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, V. Sharma, S. Simon, Y. Tu, A. Vartak, S. Wasserbaech⁴⁴, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant

California Institute of Technology, Pasadena, USA

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, K. Shin, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

J.P. Cumalat, M.E. Dinardo, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner, S.L. Zang

Cornell University, Ithaca, USA

L. Agostino, J. Alexander, D. Cassel, A. Chatterjee, S. Das, N. Eggert, L.K. Gibbons, B. Heltsley, W. Hopkins, A. Khukhunaishvili, B. Kreis, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, A. Ryd, E. Salvati, X. Shi, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA

A. Biselli, G. Cirino, D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, F. Borchering, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, W. Cooper, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, K. Gunthoti, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, H. Jensen, M. Johnson, U. Joshi, R. Khatiwada, B. Klima, K. Kousouris, S. Kunori, S. Kwan, C. Leonidopoulos, P. Limon, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. Miao, K. Mishra, S. Mrenna, Y. Musienko⁴⁵, C. Newman-Holmes, V. O'Dell, R. Pordes, O. Prokofyev, N. Saoulidou, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan,

L. Taylor, S. Tkaczyk, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, K. Matchev, G. Mitselmakher, L. Muniz, C. Prescott, R. Remington, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, M. Snowball, D. Wang, J. Yelton, M. Zakaria

Florida International University, Miami, USA

C. Ceron, V. Gaultney, L. Kramer, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, D. Mesa, J.L. Rodriguez

Florida State University, Tallahassee, USA

T. Adams, A. Askew, D. Bandurin, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, L. Quertenmont, S. Sekmen, V. Veeraraghavan

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, B. Dorney, S. Guragain, M. Hohlmann, H. Kalakhety, R. Ralich, I. Vodopiyanov

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

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, G.J. Kunde⁴⁶, F. Lacroix, M. Malek, C. O'Brien, C. Silvestre, A. Smoron, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA

U. Akgun, E.A. Albayrak, B. Bilki, W. Clarida, F. Duru, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya⁴⁷, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, J. Wetzels, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA

B.A. Barnett, B. Blumenfeld, A. Bonato, C. Eskew, D. Fehling, G. Giurciu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, A. Whitbeck

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA

A.f. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze, Z. Wan

Lawrence Livermore National Laboratory, Livermore, USA

J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA

A. Baden, M. Boutemour, S.C. Eno, D. Ferencek, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, Y. Lu, A.C. Mignerey, K. Rossato, P. Rumerio, F. Santanastasio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA

B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, P. Everaerts,

G. Gomez Ceballos, M. Goncharov, K.A. Hahn, P. Harris, Y. Kim, M. Klute, Y.-J. Lee, W. Li, C. Loizides, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, E.A. Wenger, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA

S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, P.R. Duderø, G. Franzoni, J. Haupt, K. Klapoetke, Y. Kubota, J. Mans, V. Rekovic, R. Rusack, M. Sasseville, A. Singovsky

University of Mississippi, University, USA

L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, USA

K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, T. Kelly, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

Northeastern University, Boston, USA

G. Alverson, E. Barberis, D. Baumgartel, O. Boeriu, M. Chasco, S. Reucroft, J. Swain, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA

A. Anastassov, A. Kubik, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA

L. Antonelli, D. Berry, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, T. Kolberg, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, J. Ziegler

The Ohio State University, Columbus, USA

B. Bylsma, L.S. Durkin, J. Gu, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, G. Williams

Princeton University, Princeton, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, A. Hunt, J. Jones, E. Laird, D. Lopes Pegna, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA

J.G. Acosta, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

Purdue University, West Lafayette, USA

E. Alagoz, V.E. Barnes, G. Bolla, L. Borrello, D. Bortoletto, A. Everett, A.F. Garfinkel, L. Gutay, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, C. Liu, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA

P. Jindal, N. Parashar

Rice University, Houston, USA

C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, H. Flacher, A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, D. Orbaker, G. Petrillo, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian, M. Yan

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

O. Atramentov, A. Barker, D. Duggan, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, R. Patel, A. Richards, K. Rose, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA

J. Asaadi, R. Eusebi, J. Gilmore, A. Gurrola, T. Kamon, V. Khotilovich, R. Montalvo, C.N. Nguyen, I. Osipenkov, Y. Pakhotin, J. Pivarski, A. Safonov, S. Sengupta, A. Tatarinov, D. Toback, M. Weinberger

Texas Tech University, Lubbock, USA

N. Akchurin, C. Bardak, J. Damgov, C. Jeong, K. Kovitanggoon, S.W. Lee, Y. Roh, A. Sill, I. Volobouev, R. Wigmans, E. Yazgan

Vanderbilt University, Nashville, USA

E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, M. Issah, W. Johns, P. Kurt, C. Maguire, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, R. Yohay

Wayne State University, Detroit, USA

S. Gollapinni, R. Harr, P.E. Karchin, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

University of Wisconsin, Madison, USA

M. Anderson, M. Bachtis, J.N. Bellinger, D. Carlsmith, S. Dasu, J. Efron, K. Flood, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, F. Palmonari, D. Reeder, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

†: Deceased

1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

2: Also at Universidade Federal do ABC, Santo Andre, Brazil

3: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

4: Also at Suez Canal University, Suez, Egypt

5: Also at British University, Cairo, Egypt

6: Also at Fayoum University, El-Fayoum, Egypt

7: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland

8: Also at Massachusetts Institute of Technology, Cambridge, USA

- 9: Also at Université de Haute-Alsace, Mulhouse, France
- 10: Also at Brandenburg University of Technology, Cottbus, Germany
- 11: Also at Moscow State University, Moscow, Russia
- 12: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 13: Also at Eötvös Loránd University, Budapest, Hungary
- 14: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 15: Also at University of Visva-Bharati, Santiniketan, India
- 16: Also at Sharif University of Technology, Tehran, Iran
- 17: Also at Shiraz University, Shiraz, Iran
- 18: Also at Isfahan University of Technology, Isfahan, Iran
- 19: Also at Facoltà Ingegneria Università di Roma "La Sapienza", Roma, Italy
- 20: Also at Università della Basilicata, Potenza, Italy
- 21: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- 22: Also at Università degli studi di Siena, Siena, Italy
- 23: Also at California Institute of Technology, Pasadena, USA
- 24: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 25: Also at University of California, Los Angeles, Los Angeles, USA
- 26: Also at University of Florida, Gainesville, USA
- 27: Also at Université de Genève, Geneva, Switzerland
- 28: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 29: Also at University of Athens, Athens, Greece
- 30: Also at The University of Kansas, Lawrence, USA
- 31: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 32: Also at Paul Scherrer Institut, Villigen, Switzerland
- 33: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 34: Also at Gaziosmanpasa University, Tokat, Turkey
- 35: Also at Adiyaman University, Adiyaman, Turkey
- 36: Also at Mersin University, Mersin, Turkey
- 37: Also at Izmir Institute of Technology, Izmir, Turkey
- 38: Also at Kafkas University, Kars, Turkey
- 39: Also at Suleyman Demirel University, Isparta, Turkey
- 40: Also at Ege University, Izmir, Turkey
- 41: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 42: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 43: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 44: Also at Utah Valley University, Orem, USA
- 45: Also at Institute for Nuclear Research, Moscow, Russia
- 46: Also at Los Alamos National Laboratory, Los Alamos, USA
- 47: Also at Erzincan University, Erzincan, Turkey