

# Forward–backward asymmetry of Drell–Yan lepton pairs in pp collisions at $\sqrt{s} = 8$ TeV

CMS Collaboration\*

CERN, 1211 Geneva 23, Switzerland

Received: 18 January 2016 / Accepted: 22 May 2016 / Published online: 14 June 2016

© CERN for the benefit of the CMS collaboration 2016. This article is published with open access at Springerlink.com

**Abstract** A measurement of the forward–backward asymmetry  $A_{FB}$  of oppositely charged lepton pairs ( $\mu\mu$  and  $ee$ ) produced via  $Z/\gamma^*$  boson exchange in pp collisions at  $\sqrt{s} = 8$  TeV is presented. The data sample corresponds to an integrated luminosity of  $19.7 \text{ fb}^{-1}$  collected with the CMS detector at the LHC. The measurement of  $A_{FB}$  is performed for dilepton masses between 40 GeV and 2 TeV and for dilepton rapidity up to 5. The  $A_{FB}$  measurements as a function of dilepton mass and rapidity are compared with the standard model predictions.

## 1 Introduction

A forward–backward asymmetry  $A_{FB}$  in the production of Drell–Yan lepton pairs arises from the presence of both vector and axial-vector couplings of electroweak bosons to fermions. For a given dilepton invariant mass  $M$  the differential cross section at the parton level at leading order (LO) can be expressed as

$$\frac{d\sigma}{d(\cos\theta^*)} = A(1 + \cos^2\theta^*) + B \cos\theta^*, \quad (1)$$

where  $\theta^*$  represents the emission angle of the negatively charged lepton relative to the quark momentum in the rest frame of the dilepton system, and  $A$  and  $B$  are parameters that depend on  $M$ , the electroweak mixing angle  $\theta_W$ , and the weak isospin and charge of the incoming and outgoing fermions. The  $A_{FB}$  quantity is

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}, \quad (2)$$

where  $\sigma_F$  ( $\sigma_B$ ) is the total cross section for the forward (backward) events, defined by  $\cos\theta^* > 0$  ( $\cos\theta^* < 0$ ).  $A_{FB}$  depends on  $M$ , quark flavor, and the electroweak mixing angle  $\theta_W$ . Near the Z boson mass peak  $A_{FB}$  is close to zero

because of the small value of the lepton vector coupling to Z bosons. Due to weak–electromagnetic interference,  $A_{FB}$  is large and negative for  $M$  below the Z peak ( $M < 80$  GeV) and large and positive above the Z peak ( $M > 110$  GeV). Deviations from the SM predictions could result from the presence of additional neutral gauge bosons [1–5], quark–lepton compositeness [6], supersymmetric particles, or extra dimensions [7]. Around the Z peak, measurements of  $A_{FB}$  can also be used to extract the effective weak mixing angle  $\sin^2\theta_{\text{lept}}^{\text{eff}}(m_Z)$  [8,9] as well as the u and d quark weak coupling [9–12].

To reduce the uncertainties due to the transverse momentum ( $p_T$ ) of the incoming quarks, this measurement uses the Collins–Soper (CS) frame [13]. In this frame,  $\theta_{CS}^*$  is defined as the angle between the negatively charged lepton momentum and the axis that bisects the angle between the quark momentum direction and the opposite direction to the antiquark momentum. In the laboratory frame,  $\theta_{CS}^*$  is calculated as

$$\cos\theta_{CS}^* = \frac{2(P_1^+ P_2^- - P_1^- P_2^+)}{\sqrt{Q^2(Q^2 + Q_T^2)}}, \quad (3)$$

where  $Q$  and  $Q_T$  represent the four-momentum and the  $p_T$  of the dilepton system, respectively, while  $P_1$  ( $P_2$ ) represents the four-momentum of  $\ell^-$  ( $\ell^+$ ) with  $P_i^\pm = (E_i \pm P_{z,i})/\sqrt{2}$ , and  $E_i$  represents the energy of the lepton.

The production of lepton pairs arises mainly from the annihilation of valence quarks with sea antiquarks. At the LHC, the quark and antiquark directions are not known for each collision because both beams consist of protons. In general, however, the quark carries more momentum than the antiquark as the antiquark must originate from the parton sea. Therefore, on average, the dilepton system is boosted in the direction of the valence quark [2,14,15]. In this paper, the positive axis is defined to be along the boost direction using the following transformation on an event-by-event basis:

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

$$\cos \theta_{CS}^* \rightarrow \frac{|Q_z|}{Q_z} \cos \theta_{CS}^*, \quad (4)$$

where  $Q_z$  is the longitudinal momentum of the dilepton system. The fraction of events for which the quark direction is the same as the direction of the boost depends on  $M$  and increases with the absolute value of the dilepton rapidity  $y = \frac{1}{2} \ln[(E + Q_z)/(E - Q_z)]$ .

$A_{FB}$  was previously measured by the CMS [16] and ATLAS [8] experiments using data samples collected at  $\sqrt{s} = 7$  TeV. The techniques used in this analysis are similar to those used in the previous CMS measurement at 7 TeV, and the rapidity range of this measurement is extended to  $|\eta| = 5$  by including electrons in the forward calorimeter. Since large  $Z$  boson rapidities are better correlated with the direction of the valence quark,  $A_{FB}$  is measured as a function of the invariant mass and the rapidity of  $Z$  boson. The number of selected events at 8 TeV is about a factor of 5 larger than the number of events at 7 TeV. The larger data sample collected at 8 TeV extends the measurement of  $A_{FB}$  in the high-mass region where the number of events in the 7 TeV samples was limited.

## 2 The CMS detector

The central feature of the CMS detector is a superconducting solenoid with a 6 m internal diameter that provides a magnetic field of 3.8 T. Inside the solenoid are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Extensive forward calorimetry complements the coverage provided by the barrel and endcap calorimeters. Outside the solenoid, gas-ionization detectors embedded in the steel flux-return yoke are used to measure muons.

Muons are measured in the pseudorapidity [17] range  $|\eta| < 2.4$  using the silicon tracker and muon systems. The muon detectors are constructed using three different technologies: drift tubes for  $|\eta| < 1.2$ , cathode strip chambers for  $0.9 < |\eta| < 2.4$ , and resistive plate chambers for  $|\eta| < 1.6$ . Matching muons to tracks measured in the silicon tracker results in a relative  $p_T$  resolution of 1.3–2.0% in the barrel, and better than 6% in the endcaps for muons with  $20 < p_T < 100$  GeV [18].

Electrons are measured in the range  $|\eta| < 2.5$  using both the tracking system and the ECAL. The energy resolution for electrons produced in  $Z$  boson decays varies from 1.7% in the barrel ( $|\eta| < 1.48$ ) to 4.5% in the endcap region ( $|\eta| > 1.48$ ) [19].

The  $\eta$  coverage of the CMS detector is extended up to  $|\eta| = 5$  by the hadron forward (HF) calorimeters [20]. The HF is constructed from steel absorbers as shower initiators

and quartz fibers as active material. Half of the fibers extend over the full depth of the detector (long fibers) while the other half does not cover the first 22 cm measured from the front face (short fibers). As the two sets of fibers are read out separately, electromagnetic showers can be distinguished from hadronic showers. Electrons in the HF are measured in the range  $3 < |\eta| < 5$ . The energy resolution for HF electrons is  $\sim 32\%$  at 50 GeV and the angular resolution is up to 0.05 in  $\eta$  and  $\phi$ .

The CMS experiment uses a two-level trigger system. The level-1 trigger, composed of custom-designed processing hardware, selects events of interest based on information from the muon detectors and calorimeters [21]. The high-level trigger is software based, running a faster version of the offline reconstruction code on the full detector information, including the tracker [22]. 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. [17].

## 3 Data and Monte Carlo samples

The analysis is performed using the pp collision data collected with the CMS detector in 2012 at a center-of-mass energy of 8 TeV. The total integrated luminosity for the entire data set amounts to  $19.7 \text{ fb}^{-1}$ .

The simulated  $Z/\gamma^* \rightarrow \mu\mu$  and  $Z/\gamma^* \rightarrow ee$  signal samples are generated at next-to-leading order (NLO) based in perturbative QCD using POWHEG [23–26] with the NLO CT10 parton distribution functions (PDFs) [27]. The parton showering and hadronization are simulated using the PYTHIA v6.426 [28] generator with the Z2\* tune [29].

The background processes,  $Z/\gamma^* \rightarrow \tau\tau$ ,  $t\bar{t}$ ,  $tW^-$  and  $\bar{t}W^+$ , are generated with POWHEG, and the inclusive  $W$  production with MADGRAPH [30]. The backgrounds from  $WW$ ,  $WZ$ , and  $ZZ$  production are generated using PYTHIA v6.426. The  $\tau$  lepton decays in the background processes are simulated using TAUOLA [31]. For all processes, the detector response is simulated using a detailed description of the CMS detector based on the GEANT4 package [32, 33]. GFLASH [34] is used for the HF [35], and the event reconstruction is performed with the same algorithms used for the data. The data contain multiple proton-proton interactions per bunch crossing (pileup) with an average value of 21. A pileup reweighting procedure is applied to the Monte Carlo (MC) simulation so the pileup distribution matches the data.

## 4 Event selection

The inclusive dimuon events are selected by a trigger that requires two muons, the leading one with  $p_T > 17$  GeV

and the second one with  $p_T > 8 \text{ GeV}$ . Muons are selected offline by the standard CMS muon identification [18], which requires at least one muon chamber hit in the global muon track fit, muon segments in at least two muon stations, at least one hit in the pixel detector, more than five inner tracker layers with hits, and a  $\chi^2/\text{dof}$  less than 10 for the global muon fit. The vertex with the highest  $p_T$  sum for associated tracks is defined as the primary vertex. The distance between the muon candidate trajectories and the primary vertex is required to be smaller than 2 mm in the transverse plane and smaller than 5 mm in the longitudinal direction. This requirement significantly reduces the background from cosmic ray muons. To remove muons produced during jet fragmentation, the fractional track isolation,  $\sum p_T^{\text{trk}}/p_T^\mu$ , is required to be smaller than 0.1, where the sum runs over all tracks originating from the primary vertex within a cone of  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$  around each of the identified muons. Furthermore, each selected muon is required to have  $p_T > 20 \text{ GeV}$  and  $|\eta| < 2.4$ .

The inclusive dielectron events include electrons that are produced in an extended lepton pseudorapidity range,  $|\eta| < 5$ . The events with dilepton rapidity  $|y| < 2.4$  are selected by triggers requiring either two central electrons,  $|\eta| < 2.4$ , with  $p_T > 17$  and  $> 8 \text{ GeV}$ . In the analysis, the central electron candidates are required to have  $p_T > 20 \text{ GeV}$ , have opposite charges, and to pass tight electron identification and isolation requirements [19]. The particle-flow (PF) event reconstruction [36,37] consists of reconstructing and identifying each single particle with an optimized combination of all subdetector information. In this process, the identification of the particle type (photon, electron, muon, charged hadron, or neutral hadron) plays an important role in the determination of the particle direction and energy. The fractional PF isolation,  $\sum p_T^{\text{PF}}/p_T^e$ , is required to be smaller than 0.1. The isolation variable is calculated from the energy sum over all PF candidates within a cone of size 0.3 around each of the identified electrons. This sample is used to perform the analysis for the dilepton rapidity,  $|y| < 2.4$ .

For the events with dilepton rapidity  $2.4 < |y| < 5$ , one central ( $|\eta| < 2.4$ ) and one forward electron ( $3 < |\eta| < 5$ ) are used requiring one isolated central electron trigger with  $p_T > 27 \text{ GeV}$ . In this case, the central (forward) electron candidate is required to have  $p_T > 30$  (20) GeV, as well as to pass stringent electron identification and isolation requirements (forward electron identification criteria). Since the  $2.4 < |\eta| < 3$  region is outside the tracker acceptance, the particle flow variables cannot be defined in this region, and are therefore not considered in the analysis.

Forward electron identification requires an isolated energy deposition in the core of the electron cluster [35]. To reduce the contribution from jet background in the forward region, both electrons are required to be on the same side of the detector ( $\eta_{e_1} \eta_{e_2} > 0$ ) and almost back-to-back in azimuth

( $|\Delta\phi(e_1, e_2)| > 2\pi/3$ ). Because the forward electrons do not have charge information, no oppositely-charged requirement is applied.

After the event selection, about 8 million  $\mu\mu$  and 4.3 million ee events remain with  $|y| < 2.4$ , and 0.5 million ee events with  $2.4 < |y| < 5$ .

## 5 Simulation corrections

Scale factors are derived and applied to the simulated MC events to account for differences of detector performance between data and the MC simulation. The efficiencies for the trigger, lepton identification, and lepton isolation are measured using a “tag-and-probe” method [18,38] for both data and simulation. For the muon channel, the trigger efficiency is measured as a function of  $\eta$  only because the  $p_T$  dependence is small for  $p_T > 20 \text{ GeV}$ , while in the electron channel the efficiency is measured as a function of  $E_T$  and  $\eta$ . Similarly, the identification and isolation efficiencies for the muons and central electrons are measured in data and simulation as a function of  $p_T$  and  $\eta$ . The difference in trigger efficiency between data and simulation is 1 to 4% for the muon channel, depending on the  $\eta$  region, and less than 1% for the electron channel. The differences in the muon identification and isolation efficiencies are less than 1%. For central electrons the absolute difference is at the 5% level in the barrel and increases to 12% in the endcaps.

For forward electrons, the identification efficiency is measured as a function of  $E_T$  and  $\eta$ . We observe a 9 to 18% difference in the identification efficiency between data and MC simulation. The simulation is scaled using these factors to reproduce the data. Forward electrons require additional corrections in GFLASH simulation in order to match the  $\eta$  distribution of the data. Furthermore, a global normalization factor of  $0.6 \pm 0.3$  is applied to account for the data/simulation difference in the event yields in HF. Its effect is negligible in the  $A_{\text{FB}}(M)$  measurement.

The muon momentum and electron energy scales are affected by detector misalignment and imperfect calibration, which cause a degradation in the energy measurements and the measurement of  $A_{\text{FB}}$ . Such effects are accounted for by additional momentum and energy corrections, which are applied to muons and electrons in both data and simulation. It has been shown [18] that the primary cause of the bias in the reconstructed muon momentum is the misalignment of the tracking system. To remove this bias, a muon momentum correction extracted as a function of the muon charge,  $\theta$ , and  $\phi$  [39] is applied for both data and MC events. The overall muon momentum corrections for muons with  $p_T > 20 \text{ GeV}$  are measured with a precision of better than 0.04%.

For central electrons, an ECAL energy scale correction is applied. The overall energy scale for electrons with

$7 < p_T < 70$  GeV is measured with a precision better than 0.3% [19]. To match the electron energy resolutions in data, additional smearing is applied to the energy of central electrons in the MC simulation. For forward electrons, the predicted energy of the forward electron is calculated using Z boson mass, the energy of the central electron, and the angular positions ( $\eta$  and  $\phi$ ) of central and forward electrons. The residual energy correction for forward electrons as a function of  $E_T$  is determined from the average of the difference between the reconstructed energy and the predicted energy. The corrections are applied in data and simulation as a function of the electron  $E_T$  and range between  $-18$  and  $+12$ %. The energy resolution of the forward electron in the MC simulation is also tuned to match the data.

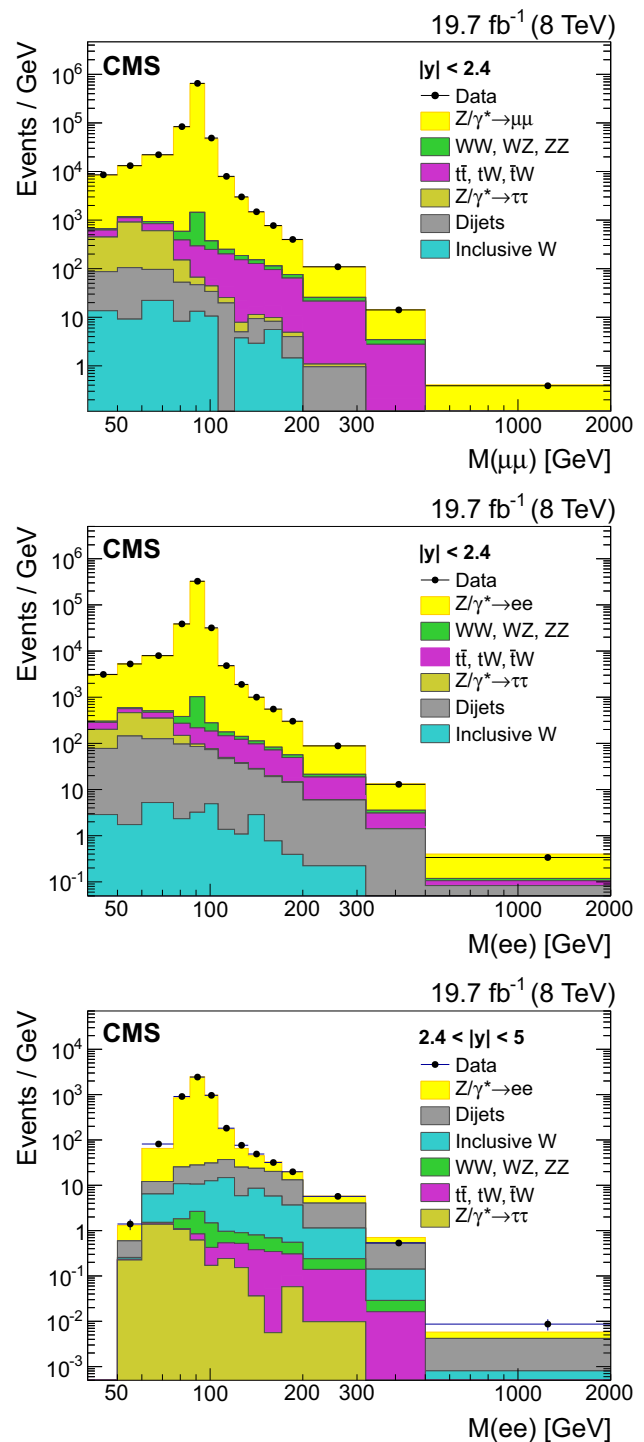
## 6 Backgrounds

The main sources of background at low dilepton mass are  $Z/\gamma^* \rightarrow \tau\tau$  events and QCD dijet events. At high mass, the main background comes from  $t\bar{t}$  events. The diboson (WW, WZ, ZZ) and inclusive W background contributions are small. The background contributions are estimated versus  $M$  and  $|y|$  for forward and backward events separately. Different techniques are used for estimating background contributions in the muon and electron channels.

The dijet background for both muon and electron channels is estimated with data using control samples. The muon channel uses same-sign dimuon events, which mostly originate from dijets. The number of same-sign events after the final event selection is used to estimate the number of opposite-sign dimuons that originate from dijets. The contribution from the diboson process is subtracted in the same-sign events using MC simulation.

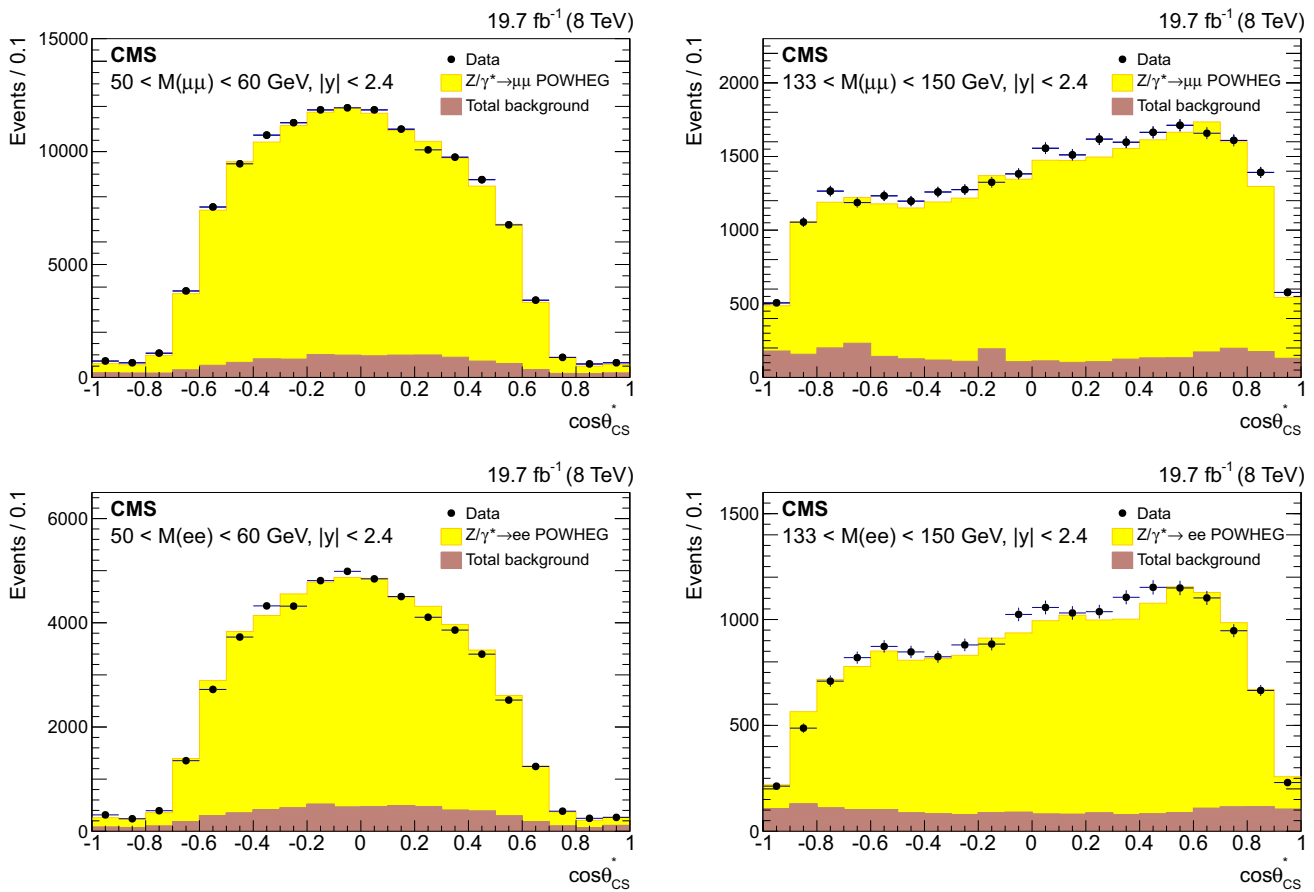
For the electron channel, a fitting method is used to estimate the dijet background. The kinematic distributions of the ee events in  $M$  and  $|y|$  are fitted with a sum of signal and background templates to determine the dijet component. A signal template is extracted from the  $Z/\gamma^* \rightarrow ee$  MC sample. A background template is obtained by applying a reverse isolation requirement on the central electron in data. The signal and non-QCD background contributions, which are small, are subtracted from this nonisolated electron sample using simulation.

In the muon channel, events selected with an  $e\mu$  lepton pair are used to determine the backgrounds from  $Z/\gamma^* \rightarrow \tau\tau$ ,  $t\bar{t}$ , W+jets,  $tW$ , and  $\bar{t}W$  processes. The overall rate for  $\mu\mu$  background events from these sources is proportional to the number of observed  $e\mu$  events. Here the MC simulation is used only to calculate the ratio of  $\mu\mu$  events to  $e\mu$  events. The background rate extracted with this method is in agreement with MC simulations. Therefore, in the electron analysis these backgrounds are modelled using MC simulations.



**Fig. 1** The invariant mass distributions for  $\mu\mu$  (top),  $ee$  (middle) events with  $|y| < 2.4$ , and  $ee$  (bottom) events with  $2.4 < |y| < 5$ . Only statistical uncertainties are shown. The stacked histograms represent the sum of the background contributions and the signal

The cross sections are normalized to next-to-next-to-leading-order FEWZ predictions [40]. Also, the diboson backgrounds are estimated using MC simulation for both the muon and electron channels.



**Fig. 2** The  $\cos\theta_{CS}^*$  distributions for  $\mu\mu$  ( $ee$ ) events are presented in the *top* (*bottom*) panels. Only statistical uncertainties are shown. The stacked histograms represent the sum of the background con-

tribution and the signal. The plots on the *left* (*right*) panels correspond to events with dilepton invariant mass  $50 < M < 60$  GeV ( $133 < M < 150$  GeV)

The invariant mass distributions for  $\mu\mu$  and  $ee$  events in two  $|y|$  ranges are shown in Fig. 1, which also includes the MC predictions for both the signal and estimated background contributions. The MC predictions are normalized using the cross section for each process and the integrated luminosity.

### 7 Measurement of $A_{FB}$

The events are assigned to “forward” or “backward” regions as described in Sect. 1.  $A_{FB}$  is measured using the selected dilepton events as a function of dilepton mass in five regions of absolute rapidity: 0–1, 1–1.25, 1.25–1.5, 1.5–2.4, and 2.4–5. The most forward region has 7 mass bins, from 40 to 320 GeV, while the others have 14 mass bins, which extend up to 2 TeV. The shape of the  $\cos\theta_{CS}^*$  distribution changes with the dilepton mass. The top panels of Fig. 2 show the reconstructed  $\cos\theta_{CS}^*$  distributions for  $\mu\mu$  events, with  $|y| < 2.4$ . The bottom panels show the reconstructed  $\cos\theta_{CS}^*$  for  $ee$  events, with  $|y| < 2.4$ . The distributions are shown for two representative mass bins. The distributions for dilepton

events at low mass ( $50 < M < 60$  GeV) are shown in the left panels, and at high mass ( $133 < M < 150$  GeV) in the right panels. The MC predictions are normalized to the integrated luminosity of the data.

The measured  $A_{FB}$  value is corrected for detector resolution, acceptance, efficiency, and the effect of final-state QED radiation (FSR) using a two-dimensional iterative unfolding method based on Bayes’ theorem [41,42]. The  $A_{FB}$  quantity is unfolded to account for event migration between mass bins and between positive and negative  $\cos\theta_{CS}^*$  region. Since the ambiguity of the quark direction is more significant at low  $|y|$ , the dilution of  $A_{FB}$  is larger in the low  $|y|$  region.

### 8 Systematic uncertainties

The largest experimental uncertainties originate from the background estimation, the electron energy correction, the muon momentum correction, and the unfolding procedure. The dominant contribution to the background uncertainty is the statistical uncertainty in the background data control sam-

**Table 1** The maximum value of the systematic uncertainty in  $A_{\text{FB}}$  as a function of  $M$  from each source for different regions of  $|y|$

Systematic uncertainty	$ y $ bins				
	0–1	1–1.25	1.25–1.5	1.5–2.4	
Muon channel					
Background	0.062	0.080	0.209	0.051	
Momentum correction	0.006	0.015	0.020	0.022	
Unfolding	0.001	0.003	0.004	0.003	
Pileup reweighting	0.002	0.004	0.003	0.004	
Efficiency scale factors	<0.001	0.002	0.003	0.005	
PDFs	0.001	0.004	0.008	0.047	
FSR	<0.001	0.001	0.001	0.002	
Systematic uncertainty	$ y $ bins				
	0–1	1–1.25	1.25–1.5	1.5–2.4	2.4–5
Electron channel					
Background	0.064	0.015	0.008	0.004	0.033
Energy correction	0.011	0.015	0.012	0.012	0.123
Unfolding	0.005	0.007	0.006	0.004	0.001
Pileup reweighting	0.003	0.002	0.002	0.001	0.007
Efficiency scale factors	<0.001	<0.001	<0.001	<0.001	0.008
Forward $\eta$ scale factor	–	–	–	–	0.002
Forward $\eta$ asymmetry	–	–	–	–	0.029
Global normalization factor	–	–	–	–	0.060
PDFs	0.002	0.004	0.005	0.008	0.014
FSR	<0.001	0.001	0.001	0.001	0.002

ple. The theoretical uncertainty of the cross section in the MC background samples also contributes to the systematic uncertainty in the estimation of the background.

After energy corrections to central electrons are applied, we find that there is a 0.4 % offset in the position of the Z peak between data and simulation in the barrel and a 0.5 % offset in the endcaps. This difference is assigned as the systematic uncertainty in the central electron energy calibration.

In order to estimate the uncertainty in the energy calibration of forward electrons, the parametrized function of the correction factor is scaled up and down by its statistical uncertainty. The difference in  $A_{\text{FB}}$  before and after changing the correction factor is assigned as a systematic uncertainty.

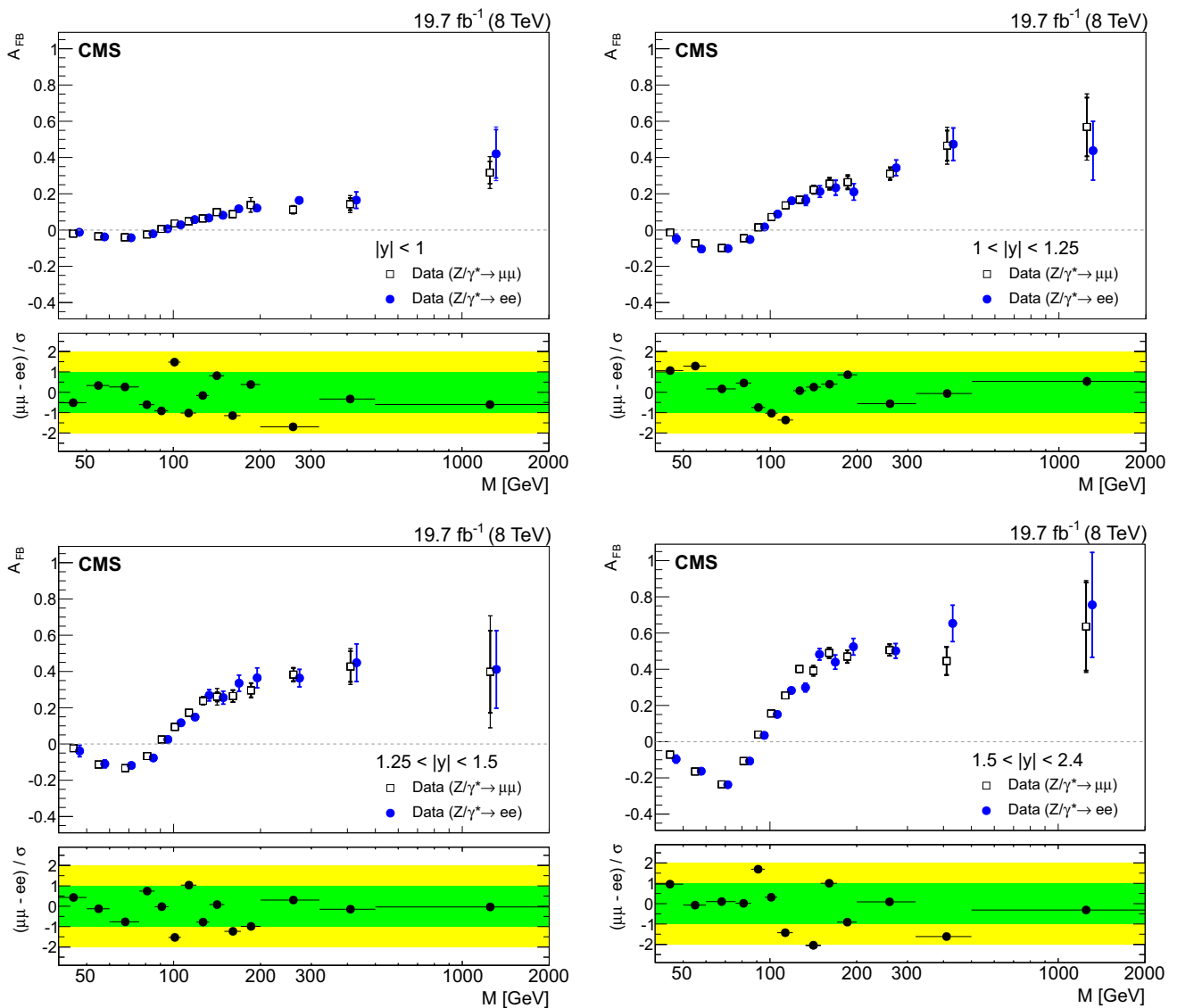
The systematic uncertainty in the muon momentum correction is estimated with a similar approach. The muon momentum correction is scaled up and down by its statistical uncertainty and the difference in  $A_{\text{FB}}$  resulting from the change of the muon momentum correction is assigned as systematic uncertainty. We find that the contributions of the uncertainties in the efficiency scale factors (trigger, identification, and isolation) and in the pileup reweighting factors to the uncertainty in  $A_{\text{FB}}$  are small.

For forward HF electrons, the uncertainties in the electron  $\eta$  correction and in the global normalization factor contribute to the systematic uncertainty in  $A_{\text{FB}}$ . In addition, the energy calibration varies approximately 5 % between  $+\eta$  and  $-\eta$ . To account for this asymmetric effect in the energy calibration, the  $A_{\text{FB}}$  distribution is measured using one forward electron in  $+\eta$  or  $-\eta$ , separately, along with one central electron and half of the difference in  $A_{\text{FB}}$  is assigned as a systematic uncertainty. The systematic uncertainty varies from 0.005 to 0.03 as a function of dielectron invariant mass.

The systematic uncertainty in the unfolding procedure is estimated using a closure test in simulation. Any residual shown in the closure test of the unfolding procedure is assigned as the systematic uncertainty.

The theoretical uncertainties which affect the detector acceptance originate from the uncertainties in PDFs (CT10 [27,43] and NNPDF 2.0 [44]) and from uncertainties in the FSR modeling [45].

The systematic uncertainty in  $A_{\text{FB}}$  depends on the mass of the dilepton pair. Table 1 gives the maximum value of this uncertainty from each source, for different regions of  $|y|$ .



**Fig. 3** The unfolded  $A_{FB}$  distributions for muons (*open squares*) and electrons (*solid circles*) for the four central rapidity regions. The statistical (*thick vertical bar*) and statistical plus systematics (*thin vertical bar*) uncertainties are presented. The *solid circles* are shifted slightly

to compare the result better. The *lower panel* in each plot shows the difference of the unfolded  $A_{FB}$  in muons and electrons divided by the total uncertainty (stat.  $\oplus$  syst.)

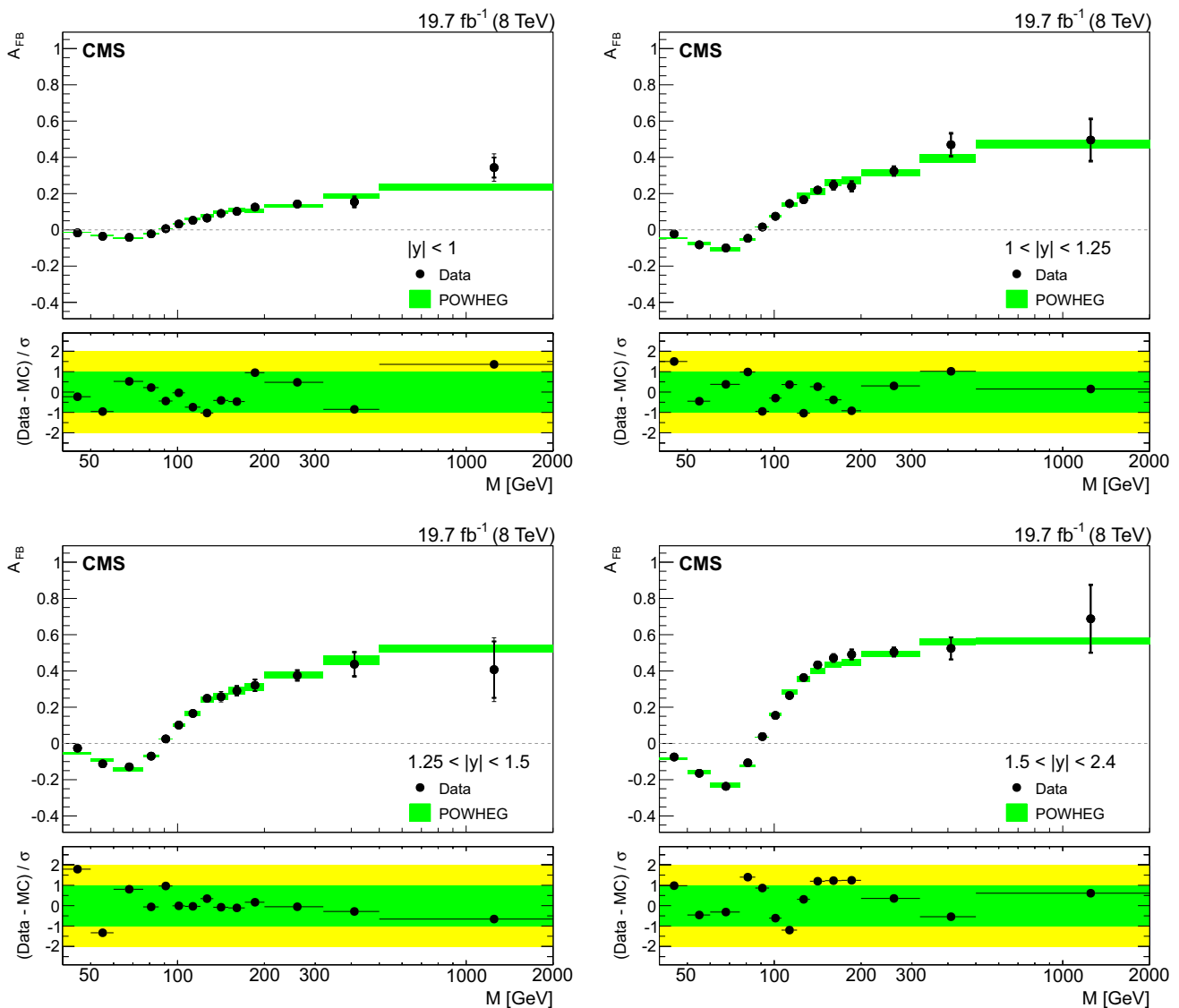
### 9 Results

A comparison of the unfolded, background-subtracted  $A_{FB}(M)$  distributions for  $\mu\mu$  and  $ee$  events in the four central rapidity regions is shown in Fig. 3. The statistical and systematic uncertainties are added in quadrature. The measured  $A_{FB}(M)$  distributions agree for  $\mu\mu$  and  $ee$  events in all rapidity regions.

The unfolded  $A_{FB}(M)$  measurements for  $\mu\mu$  and  $ee$  events, within  $|y| < 2.4$ , are combined under the assumption that the uncertainties in the muon and electron channels are

uncorrelated. Any effect of the correlation between the  $\mu\mu$  and  $ee$  systematic uncertainties in the pileup correction, FSR modeling, and the normalization of MC simulations in the background estimation is found to have a negligible effect on the combination.

Figure 4 shows the combined results for the four central rapidity regions up to 2.4. The combined result is compared with the POWHEG (NLO) prediction with CT10 PDFs. The effective weak mixing angle,  $\sin^2 \theta_{lept}^{eff} = 0.2312$ , is used for the POWHEG prediction. For all rapidity regions, the combined  $A_{FB}(M)$  values are in a good agreement with the



**Fig. 4** The combined ( $\mu^+\mu^-$  and  $e^+e^-$ ) unfolded  $A_{FB}$  distributions in the four central rapidity regions. The statistical (*thick vertical bar*) and statistical plus systematics (*thin vertical bar*) uncertainties are presented. The measurements are compared with the prediction

of POWHEG. The total uncertainties (considering the statistical, PDF, and scale uncertainties) in the POWHEG prediction are shown as *shaded bands*. The *lower panel* in each plot shows the difference of  $A_{FB}$  in data and prediction divided by the total uncertainty of data and prediction

POWHEG prediction. The uncertainty in the theoretical prediction (POWHEG) originates from the statistical uncertainty in the MC sample, the uncertainties in the PDFs, and the variations of factorization and renormalization scales (simultaneous variation between values  $2M$ ,  $M$ , and  $M/2$ , with  $M$  corresponding to the middle of the invariant mass bin). Table 2 summarizes the combined  $A_{FB}$  quantity for each rapidity region.

The unfolded  $A_{FB}$  distribution for the forward rapidity region ( $2.4 < |y| < 5$ ) is shown in Fig. 5. The forward rapidity region extends the scope of the measurement beyond that of the previous CMS result at  $\sqrt{s} = 7$  TeV. Because  $A_{FB}$

in the forward rapidity region is diluted less, the measured  $A_{FB}$  quantity is closer to the parton-level asymmetry after the unfolding process, than it is in the central rapidity bins. The unfolded  $A_{FB}$  ( $M_{e^+e^-}$ ) for  $2.4 < |y| < 5$  agrees with the POWHEG predictions.

## 10 Summary

We report a measurement of the forward–backward asymmetry of oppositely charged  $\mu\mu$  and  $ee$  pairs produced via a  $Z/\gamma^*$  boson exchange at  $\sqrt{s} = 8$  TeV with a data sample

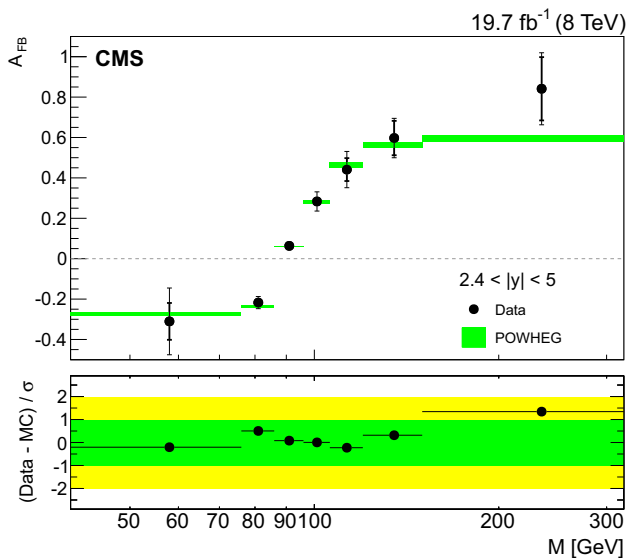


**Table 2** The combined (ee and  $\mu\mu$ )  $A_{FB}$  measurements, with statistical and systematic uncertainties for the four rapidity regions with  $|y| < 2.4$ . The  $A_{FB}$  quantity for ee events is also shown for  $2.4 < |y| < 5$ 

$M$ (GeV)	$A_{FB}$ (data)	Stat. err	Syst. err	Tot. err	$M$ (GeV)	$A_{FB}$ (data)	Stat. err	Syst. err	Tot. err
$ y  < 1$					$1 <  y  < 1.25$				
40–50	−0.0167	0.0049	0.0045	0.0067	40–50	−0.0225	0.0108	0.0092	0.0142
50–60	−0.0355	0.0042	0.0031	0.0052	50–60	−0.0825	0.0092	0.0060	0.0110
60–76	−0.0415	0.0033	0.0031	0.0045	60–76	−0.0999	0.0071	0.0044	0.0084
76–86	−0.0221	0.0022	0.0019	0.0029	76–86	−0.0468	0.0048	0.0042	0.0064
86–96	0.0065	0.0004	0.0003	0.0005	86–96	0.0157	0.0009	0.0005	0.0011
96–106	0.0320	0.0020	0.0016	0.0025	96–106	0.0747	0.0046	0.0042	0.0063
106–120	0.0524	0.0037	0.0024	0.0045	106–120	0.1448	0.0085	0.0029	0.0089
120–133	0.0652	0.0065	0.0035	0.0074	120–133	0.1663	0.0152	0.0083	0.0174
133–150	0.0905	0.0081	0.0070	0.0108	133–150	0.2191	0.0185	0.0064	0.0195
150–171	0.1020	0.0104	0.0075	0.0128	150–171	0.2469	0.0243	0.0123	0.0272
171–200	0.1251	0.0129	0.0145	0.0194	171–200	0.2401	0.0272	0.0143	0.0308
200–320	0.1423	0.0112	0.0099	0.0149	200–320	0.3245	0.0257	0.0115	0.0282
320–500	0.1541	0.0268	0.0195	0.0331	320–500	0.4697	0.0609	0.0302	0.0680
500–2000	0.3437	0.0554	0.0514	0.0756	500–2000	0.4954	0.1145	0.0400	0.1213
$1.25 <  y  < 1.5$					$1.5 <  y  < 2.4$				
40–50	−0.0261	0.0114	0.0087	0.0144	40–50	−0.0747	0.0073	0.0049	0.0088
50–60	−0.1122	0.0098	0.0078	0.0125	50–60	−0.1645	0.0070	0.0053	0.0088
60–76	−0.1293	0.0077	0.0039	0.0086	60–76	−0.2365	0.0059	0.0052	0.0079
76–86	−0.0700	0.0052	0.0040	0.0065	76–86	−0.1071	0.0041	0.0057	0.0070
86–96	0.0249	0.0010	0.0007	0.0013	86–96	0.0379	0.0008	0.0009	0.0013
96–106	0.1012	0.0051	0.0044	0.0067	96–106	0.1546	0.0041	0.0057	0.0070
106–120	0.1655	0.0095	0.0045	0.0105	106–120	0.2647	0.0078	0.0047	0.0091
120–133	0.2485	0.0169	0.0080	0.0187	120–133	0.3630	0.0141	0.0068	0.0156
133–150	0.2576	0.0210	0.0197	0.0287	133–150	0.4334	0.0179	0.0129	0.0221
150–171	0.2903	0.0259	0.0103	0.0279	150–171	0.4713	0.0230	0.0083	0.0245
171–200	0.3209	0.0315	0.0112	0.0335	171–200	0.4906	0.0276	0.0095	0.0292
200–320	0.3752	0.0286	0.0114	0.0308	200–320	0.5042	0.0244	0.0092	0.0261
320–500	0.4372	0.0655	0.0287	0.0715	320–500	0.5248	0.0610	0.0131	0.0624
500–2000	0.4071	0.1556	0.0824	0.1761	500–2000	0.6878	0.1862	0.0413	0.1907
$2.4 <  y  < 5$ (ee only)									
40–76	−0.3104	0.0912	0.1378	0.1652					
76–86	−0.2174	0.0214	0.0210	0.0300					
86–96	0.0635	0.0060	0.0146	0.0158					
96–106	0.2834	0.0183	0.0439	0.0475					
106–120	0.4412	0.0567	0.0696	0.0898					
120–150	0.5972	0.0851	0.0476	0.0975					
150–320	0.8412	0.1567	0.0851	0.1783					

corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ . The  $A_{FB}$  measurement is performed as a function of the dilepton invariant mass between 40 GeV and 2 TeV for  $\mu\mu$  and ee events in 4 dilepton rapidity bins up to  $|y| = 2.4$ . For ee events with  $2.4 < |y| < 5$ , the  $A_{FB}$  measurement is performed for dielectron masses between 40 and 320 GeV. The

large data sample collected at 8 TeV extends the measurement of  $A_{FB}$  in the high mass region compared to previous results. The final  $A_{FB}$  values are corrected for detector resolution, acceptance, and final state radiation effects. The measurements of  $A_{FB}(M)$  are consistent with standard model predictions.



**Fig. 5** The unfolded  $A_{FB}$  distribution for the forward rapidity region ( $2.4 < |y| < 5$ ) using one central electron ( $|\eta| < 2.4$ ) and one HF electron ( $3 < |\eta| < 5$ ). The *inner thick vertical bars* correspond to the statistical uncertainty and the *outer thin vertical bars* to the total uncertainties. The measurements are compared with the prediction of POWHEG. The total uncertainties (considering the statistical, PDF, and scale uncertainties) in the POWHEG prediction are shown as *shaded bands*. The *lower panel* shows the difference of  $A_{FB}$  in data and prediction divided by the total uncertainty of data and prediction

**Acknowledgments** We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEP Center, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research,

India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the OPUS program of the National Science Center (Poland); the Compagnia di San Paolo (Torino); MIUR project 20108T4XTM (Italy); the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); the Chulalongkorn Academic into Its second Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

**Open Access** This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

Funded by SCOAP<sup>3</sup>.

## References

1. D. London, J.L. Rosner, Extra gauge bosons in  $E_6$ . *Phys. Rev. D* **34**, 1530 (1986). doi:[10.1103/PhysRevD.34.1530](https://doi.org/10.1103/PhysRevD.34.1530)
2. J.L. Rosner, Off-peak lepton asymmetries from new  $Z$ 's. *Phys. Rev. D* **35**, 2244 (1987). doi:[10.1103/PhysRevD.35.2244](https://doi.org/10.1103/PhysRevD.35.2244)
3. M. Cvetič, S. Godfrey, in *Discovery and identification of extra gauge bosons*, ed. T. Barklow, S. Dawson, H. Haber, J. Siegrist. Electroweak Symmetry Breaking and New Physics at the TeV Scale (World Scientific, Singapore, 1995), p. 383. [arXiv:hep-ph/9504216](https://arxiv.org/abs/hep-ph/9504216). Advanced Series on Directions in High Energy Physics, Vol. 16. doi:[10.1142/9789812830265\\_0007](https://doi.org/10.1142/9789812830265_0007)
4. J.L. Rosner, Forward-backward asymmetries in hadronically produced lepton pairs. *Phys. Rev. D* **54**, 1078 (1996). doi:[10.1103/PhysRevD.54.1078](https://doi.org/10.1103/PhysRevD.54.1078). [arXiv:hep-ph/9512299](https://arxiv.org/abs/hep-ph/9512299)
5. A. Bodek, U. Baur, Implications of a 300–500 GeV/ $c^2$   $Z'$  boson on  $p\bar{p}$  collider data at  $\sqrt{s} = 1.8$  TeV. *Eur. Phys. J. C* **21**, 607 (2001). doi:[10.1007/s100520100778](https://doi.org/10.1007/s100520100778). [arXiv:hep-ph/0102160](https://arxiv.org/abs/hep-ph/0102160)
6. CDF Collaboration, Limits on Quark–Lepton compositeness scales from dileptons produced in 1.8 TeV  $p\bar{p}$  collisions. *Phys. Rev. Lett.* **79**, 2198 (1997). doi:[10.1103/PhysRevLett.79.2198](https://doi.org/10.1103/PhysRevLett.79.2198)
7. H. Davoudiasl, J.L. Hewett, T.G. Rizzo, Phenomenology of the Randall–Sundrum gauge hierarchy model. *Phys. Rev. Lett.* **84**, 2080 (2000). doi:[10.1103/PhysRevLett.84.2080](https://doi.org/10.1103/PhysRevLett.84.2080). [arXiv:hep-ph/9909255](https://arxiv.org/abs/hep-ph/9909255)
8. ATLAS Collaboration, Measurement of the forward-backward asymmetry of electron and muon pair-production in  $pp$  collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector. *JHEP* **09**, 049 (2015). doi:[10.1007/JHEP09\(2015\)049](https://doi.org/10.1007/JHEP09(2015)049). [arXiv:hep-ex/1503.03709](https://arxiv.org/abs/hep-ex/1503.03709)
9. CMS Collaboration, Measurement of the weak mixing angle with the Drell–Yan process in proton–proton collisions at the LHC. *Phys. Rev. D* **84**, 112002 (2011). doi:[10.1103/PhysRevD.84.112002](https://doi.org/10.1103/PhysRevD.84.112002). [arXiv:hep-ex/1110.2682](https://arxiv.org/abs/hep-ex/1110.2682)
10. D0 Collaboration, Measurement of the Forward-Backward Charge Asymmetry and Extraction of  $\sin^2\theta_W^{\text{eff}}$  in  $p\bar{p} \rightarrow Z/\gamma^* + X \rightarrow e^+e^- + X$  Events Produced at  $\sqrt{s} = 1.96$  TeV. *Phys. Rev. Lett.* **101**, 191801 (2008). doi:[10.1103/PhysRevLett.101.191801](https://doi.org/10.1103/PhysRevLett.101.191801). [arXiv:hep-ex/0804.3220](https://arxiv.org/abs/hep-ex/0804.3220)
11. CDF Collaboration, Indirect measurement of  $\sin^2\theta_W$  (or  $M_W$ ) using  $e^+e^-$  pairs in the  $Z$ -boson region with  $p\bar{p}$  collisions at a center-of-momentum energy of 1.96 TeV. *Phys. Rev. D* **88**, 072002 (2013). doi:[10.1103/PhysRevD.88.072002](https://doi.org/10.1103/PhysRevD.88.072002). [arXiv:hep-ex/1307.0770](https://arxiv.org/abs/hep-ex/1307.0770)
12. CDF Collaboration, Indirect measurement of  $\sin^2\theta_W$  (or  $M_W$ ) using  $\mu^+\mu^-$  pairs from  $\gamma^*/Z$  bosons produced in  $p\bar{p}$  col-

- lisions at a center-of-momentum energy of 1.96 TeV. Phys. Rev. D **89**, 072005 (2014). doi:[10.1103/PhysRevD.89.072005](https://doi.org/10.1103/PhysRevD.89.072005). arXiv:[hep-ex/1402.2239](https://arxiv.org/abs/hep-ex/1402.2239)
13. J.C. Collins, D.E. Soper, Angular distribution of dileptons in high-energy hadron collisions. Phys. Rev. D **16**, 2219 (1977). doi:[10.1103/PhysRevD.16.2219](https://doi.org/10.1103/PhysRevD.16.2219)
  14. P. Fisher, U. Becker, J. Kirkby, Very high precision tests of the electroweak theory. Phys. Lett. B **356**, 404 (1995). doi:[10.1016/0370-2693\(95\)00714-V](https://doi.org/10.1016/0370-2693(95)00714-V)
  15. M. Dittmar, Neutral current interference in the TeV region: the experimental sensitivity at the CERN LHC. Phys. Rev. D **55**, 161 (1997). doi:[10.1103/PhysRevD.55.161](https://doi.org/10.1103/PhysRevD.55.161). arXiv:[hep-ex/9606002](https://arxiv.org/abs/hep-ex/9606002)
  16. CMS Collaboration, Forward-backward asymmetry of Drell-Yan lepton pairs in pp collisions at  $\sqrt{s} = 7$ . Phys. Lett. B **718**, 752 (2013). doi:[10.1016/j.physletb.2012.10.082](https://doi.org/10.1016/j.physletb.2012.10.082)
  17. CMS Collaboration, The CMS experiment at the CERN LHC. JINST **3**, S08004 (2008). doi:[10.1088/1748-0221/3/08/S08004](https://doi.org/10.1088/1748-0221/3/08/S08004). arXiv:[physics.ins-det/1206.4071](https://arxiv.org/abs/physics.ins-det/1206.4071)
  18. CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at  $\sqrt{s} = 7$  TeV. JINST **7**, P10002 (2012). doi:[10.1088/1748-0221/7/10/P10002](https://doi.org/10.1088/1748-0221/7/10/P10002). arXiv:[physics.ins-det/1206.4071](https://arxiv.org/abs/physics.ins-det/1206.4071)
  19. CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at  $\sqrt{s} = 8$ . JINST **10**, P06005 (2015). doi:[10.1088/1748-0221/10/06/P06005](https://doi.org/10.1088/1748-0221/10/06/P06005). arXiv:[physics.ins-det/1502.02701](https://arxiv.org/abs/physics.ins-det/1502.02701)
  20. CMS HCAL Collaboration, Design, performance, and calibration of CMS forward calorimeter wedges. Eur. Phys. J. C **53**, 139 (2008). doi:[10.1140/epjc/s10052-007-0459-4](https://doi.org/10.1140/epjc/s10052-007-0459-4)
  21. CMS Collaboration, The TriDAS project: technical design report, Volume 1: the trigger system. CMS TDR CERN-LHCC-2000-038, 2000
  22. CMS Collaboration, The TriDAS project: technical design report, volume 2: data acquisition and high-level trigger. CMS TDR CERN-LHCC-2000-026, 2002
  23. P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms. JHEP **11**, 040 (2004). doi:[10.1088/1126-6708/2004/11/040](https://doi.org/10.1088/1126-6708/2004/11/040). arXiv:[hep-ph/0409146](https://arxiv.org/abs/hep-ph/0409146)
  24. S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method. JHEP **11**, 070 (2007). doi:[10.1088/1126-6708/2007/11/070](https://doi.org/10.1088/1126-6708/2007/11/070). arXiv:[hep-ph/0709.2092](https://arxiv.org/abs/hep-ph/0709.2092)
  25. S. Alioli, P. Nason, C. Oleari, E. Re, NLO vector-boson production matched with shower in POWHEG. JHEP **07**, 060 (2008). doi:[10.1088/1126-6708/2008/07/060](https://doi.org/10.1088/1126-6708/2008/07/060). arXiv:[hep-ph/0805.4802](https://arxiv.org/abs/hep-ph/0805.4802)
  26. S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX. JHEP **06**, 043 (2010). doi:[10.1007/JHEP06\(2010\)043](https://doi.org/10.1007/JHEP06(2010)043). arXiv:[hep-ph/1002.2581](https://arxiv.org/abs/hep-ph/1002.2581)
  27. H.-L. Lai et al., New parton distributions for collider physics. Phys. Rev. D **82**, 074024 (2010). doi:[10.1103/PhysRevD.82.074024](https://doi.org/10.1103/PhysRevD.82.074024). arXiv:[hep-ph/1007.2241](https://arxiv.org/abs/hep-ph/1007.2241)
  28. T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual. JHEP **05**, 026 (2006). doi:[10.1088/1126-6708/2006/05/026](https://doi.org/10.1088/1126-6708/2006/05/026). arXiv:[hep-ph/0603175](https://arxiv.org/abs/hep-ph/0603175)
  29. CMS Collaboration, Study of the underlying event at forward rapidity in pp collisions at  $\sqrt{s} = 0.9, 2.76, \text{ and } 7$  TeV. JHEP **04**, 072 (2013). doi:[10.1007/JHEP04\(2013\)072](https://doi.org/10.1007/JHEP04(2013)072). arXiv:[hep-ph/1302.2394](https://arxiv.org/abs/hep-ph/1302.2394)
  30. J. Alwall et al., MadGraph 5: going beyond. JHEP **06**, 128 (2011). doi:[10.1007/JHEP06\(2011\)128](https://doi.org/10.1007/JHEP06(2011)128). arXiv:[1106.0522](https://arxiv.org/abs/1106.0522)
  31. N. Davidson et al., Universal interface of TAUOLA technical and physics documentation. Comput. Phys. Commun. **183**, 821 (2012). doi:[10.1016/j.cpc.2011.12.009](https://doi.org/10.1016/j.cpc.2011.12.009). arXiv:[hep-ph/1002.0543](https://arxiv.org/abs/hep-ph/1002.0543)
  32. GEANT4 Collaboration, GEANT4—a simulation toolkit. Nucl. Instr. Methods A **506**, 250 (2003). doi:[10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)
  33. J. Allison et al., GEANT4 developments and applications. IEEE Trans. Nucl. Sci. **53**, 270 (2006). doi:[10.1109/TNS.2006.869826](https://doi.org/10.1109/TNS.2006.869826)
  34. CMS Collaboration, Parameterized simulation of the CMS calorimeter using GFlash. In nuclear science symposium conference record (NSS/MIC), 2009 IEEE, p. 2074. Orlando, FL, 2009. doi:[10.1109/NSSMIC.2009.5402114](https://doi.org/10.1109/NSSMIC.2009.5402114)
  35. CMS Collaboration, Measurement of the rapidity and transverse momentum distributions of Z bosons in pp collisions at  $\sqrt{s} = 7$  TeV. Phys. Rev. D **85**, 032002 (2013). doi:[10.1103/PhysRevD.85.032002](https://doi.org/10.1103/PhysRevD.85.032002). arXiv:[hep-ex/1110.4973](https://arxiv.org/abs/hep-ex/1110.4973)
  36. CMS Collaboration, Particle-flow event reconstruction in CMS and performance for jets, taus, and  $E_T^{miss}$ . CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009
  37. CMS Collaboration, Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector. CMS Physics Analysis Summary CMS-PAS-PFT-10-001, 2010
  38. CMS Collaboration, Measurement of the inclusive W and Z production cross sections in pp collisions at  $\sqrt{s} = 7$  TeV. JHEP **10**, 132 (2011). doi:[10.1007/JHEP10\(2011\)132](https://doi.org/10.1007/JHEP10(2011)132). arXiv:[hep-ex/1107.4789](https://arxiv.org/abs/hep-ex/1107.4789)
  39. A. Bodek et al., Extracting muon momentum scale corrections for hadron collider experiments. Eur. Phys. J. C **72**, 10 (2012). doi:[10.1140/epjc/s10052-012-2194-8](https://doi.org/10.1140/epjc/s10052-012-2194-8). arXiv:[hep-ex/1208.3710](https://arxiv.org/abs/hep-ex/1208.3710)
  40. Y. Li, F. Petriello, Combining QCD and electroweak corrections to dilepton production in the framework of the FEWZ simulation code. Phys. Rev. D **86**, 094034 (2012). doi:[10.1103/PhysRevD.86.094034](https://doi.org/10.1103/PhysRevD.86.094034). arXiv:[hep-ph/1208.5967](https://arxiv.org/abs/hep-ph/1208.5967)
  41. G. D'Agostini, A multidimensional unfolding method based on Bayes' theorem. Nucl. Instrum. Methods A **362**, 487 (1995). doi:[10.1016/0168-9002\(95\)00274-X](https://doi.org/10.1016/0168-9002(95)00274-X)
  42. T. Adye, Unfolding algorithms and tests using RooUnfold. In: Proceedings of the PHYSTAT 2011 workshop on statistical issues related to discovery claims in search experiments and unfolding, p. 313 (2011). doi:[10.5170/CERN-2011-006](https://doi.org/10.5170/CERN-2011-006). arXiv:[physics.data-an/1105.1160](https://arxiv.org/abs/physics.data-an/1105.1160)
  43. P.M. Nadolsky et al., Implications of CTEQ global analysis for collider observables. Phys. Rev. D **78**, 013004 (2008). doi:[10.1103/PhysRevD.78.013004](https://doi.org/10.1103/PhysRevD.78.013004). arXiv:[0802.0007](https://arxiv.org/abs/0802.0007)
  44. NNPDF Collaboration, A first unbiased global NLO determination of parton distributions and their uncertainties. Nucl. Phys. B **838**, 136 (2010). doi:[10.1016/j.nuclphysb.2010.05.008](https://doi.org/10.1016/j.nuclphysb.2010.05.008). arXiv:[1002.4407](https://arxiv.org/abs/1002.4407)
  45. CMS Collaboration, Measurements of inclusive W and Z cross sections in pp collisions at  $\sqrt{s} = 7$  TeV. JHEP **01**, 080 (2011). doi:[10.1007/JHEP01\(2011\)080](https://doi.org/10.1007/JHEP01(2011)080). arXiv:[hep-ex/1012.2466](https://arxiv.org/abs/hep-ex/1012.2466)

**CMS Collaboration****Yerevan Physics Institute, Yerevan, Armenia**

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

**Institut für Hochenergiephysik der OeAW, Wien, Austria**

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth<sup>1</sup>, V. M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler<sup>1</sup>, V. Knünz, A. König, M. Krammer<sup>1</sup>, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady<sup>2</sup>, B. Rahbaran, H. Rohringer, J. Schieck<sup>1</sup>, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz<sup>1</sup>

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

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

**Universiteit Antwerpen, Antwerpen, Belgium**

S. Alderweireldt, T. Cornelis, E. A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, M. Van De Klundert, H. Van Haeve, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

**Vrije Universiteit Brussel, Brussel, Belgium**

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G. P. Van Onsem, I. Van Parijs

**Université Libre de Bruxelles, Bruxelles, Belgium**

P. Barria, H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, G. Fasanella, L. Favart, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Reis, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang<sup>3</sup>

**Ghent University, Ghent, Belgium**

K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, D. Dobur, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A. A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, N. Strobbe, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

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

S. Basegmez, C. Beluffi<sup>4</sup>, O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, G. G. Da Silveira, C. Delaere, D. Favart, L. Forthomme, A. Giammanco<sup>5</sup>, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, M. Musich, C. Nuttens, L. Perrini, A. Pin, K. Piotrkowski, A. Popov<sup>6</sup>, L. Quertenmont, M. Selvaggi, M. Vidal Marono

**Université de Mons, Mons, Belgium**

N. Bely, G. H. Hammad

**Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil**

W. L. Aldá Júnior, F. L. Alves, G. A. Alves, L. Brito, M. Correa Martins Junior, M. Hamer, C. Hensel, C. Mora Herrera, A. Moraes, M. E. Pol, P. Rebello Teles

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>7</sup>, A. Custódio, E. M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L. M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W. L. Prado Da Silva, A. Santoro, A. Sznajder, E. J. Tonelli Manganote<sup>7</sup>, A. Vilela Pereira

**Universidade Estadual Paulista<sup>a</sup>, Universidade Federal do ABC<sup>b</sup>, São Paulo, Brazil**

S. Ahuja<sup>a</sup>, C. A. Bernardes<sup>b</sup>, A. De Souza Santos<sup>b</sup>, S. Dogra<sup>a</sup>, T. R. Fernandez Perez Tomei<sup>a</sup>, E. M. Gregores<sup>b</sup>, P. G. Mercadante<sup>b</sup>, C.S. Moon<sup>a,8</sup>, S. F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>, D. Romero Abad, J. C. Ruiz Vargas

**Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria**

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

**University of Sofia, Sofia, Bulgaria**

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

**Institute of High Energy Physics, Beijing, China**

M. Ahmad, J. G. Bian, G. M. Chen, H. S. Chen, M. Chen, T. Cheng, R. Du, C. H. Jiang, R. Plestina<sup>9</sup>, F. Romeo, S. M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang

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

C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S. J. Qian, D. Wang, Z. Xu

**Universidad de Los Andes, Bogota, Colombia**

C. Avila, A. Cabrera, L. F. Chaparro Sierra, C. Florez, J. P. Gomez, B. Gomez Moreno, J. C. Sanabria

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

N. Godinovic, D. Lelas, I. Puljak, P. M. Ribeiro Cipriano

**Faculty of Science, University of Split, Split, Croatia**

Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

**University of Cyprus, Nicosia, Cyprus**

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

**Charles University, Prague, Czech Republic**

M. Bodlak, M. Finger<sup>10</sup>, M. Finger Jr.<sup>10</sup>

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

Y. Assran<sup>11</sup>, S. Elgammal<sup>12</sup>, A. Ellithi Kamel<sup>13</sup>, M. A. Mahmoud<sup>14</sup>, Y. Mohammed<sup>14</sup>

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

**Department of Physics, University of Helsinki, Helsinki, Finland**

P. Eerola, J. Pekkanen, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

**Lappeenranta University of Technology, Lappeenranta, Finland**

J. Talvitie, T. Tuuva

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

M. Besancon, F. Couderc, M. Dejaradin, D. Denegri, B. Fabbro, J. L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

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

I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms, O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, S. Lisniak, L. Mastrolorenzo, P. Miné, I. N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J. B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

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

J.-L. Agram<sup>15</sup>, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E. C. Chabert, N. Chanon, C. Collard, E. Conte<sup>15</sup>, X. Coubez, J.-C. Fontaine<sup>15</sup>, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J. A. Merlin<sup>2</sup>, K. Skovpen, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C. A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, F. Lagarde, I. B. Laktineh, M. Lethuillier, L. Mirabito, A. L. Pequegnot, S. Perries, J. D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

**Georgian Technical University, Tbilisi, Georgia**

T. Toriashvili<sup>16</sup>

**Tbilisi State University, Tbilisi, Georgia**

I. Bagaturia<sup>17</sup>

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

C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M. K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, J. F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov<sup>6</sup>

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

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teysier, S. Thüer

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann<sup>2</sup>, A. Nehr Korn, A. Nowack, I. M. Nugent, C. Pistone, O. Pooth, A. Stahl

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A. J. Bell, K. Borras<sup>18</sup>, A. Burgmeier, A. Cakir, A. Campbell, S. Choudhury<sup>19</sup>, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo<sup>20</sup>, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel<sup>21</sup>, H. Jung, A. Kalogeropoulos, O. Karacheban<sup>18</sup>, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann<sup>21</sup>, R. Mankel, I. Marfin<sup>21</sup>, I.-A. Melzer-Pellmann, A. B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M. Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K. D. Trippkewitz, R. Walsh, C. Wissing

**University of Hamburg, Hamburg, Germany**

V. Blobel, M. Centis Vignali, A. R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R. S. Höing, A. Junkes, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, D. Nowatschin, J. Ott, F. Pantaleo<sup>2</sup>, T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, J. Schwandt, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderden, A. Vanhoefer, B. Vormwald

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, S. Fink, F. Frensch, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann<sup>2</sup>, S. M. Heindl, U. Husemann, I. Katkov<sup>6</sup>, A. Kornmayer<sup>2</sup>, P. Lobelle Pardo, B. Maier, H. Mildner, M. U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, G. Sieber, H. J. Simonis, F. M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, C. Wöhrmann, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Geralis, V. A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Psallidas, I. Topsis-Giotis

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

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

**University of Ioánnina, Ioannina, Greece**

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradass, J. Strologas

**Wigner Research Centre for Physics, Budapest, Hungary**G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath<sup>22</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>23</sup>, A. J. Zsigmond**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**N. Beni, S. Czellar, J. Karancsi<sup>24</sup>, J. Molnar, Z. Szillasi**University of Debrecen, Debrecen, Hungary**M. Bartók<sup>25</sup>, A. Makovec, P. Raics, Z. L. Trocsanyi, B. Ujvari**National Institute of Science Education and Research, Bhubaneswar, India**

P. Mal, K. Mandal, D. K. Sahoo, N. Sahoo, S. K. Swain

**Panjab University, Chandigarh, India**

S. Bansal, S. B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U. Bhawandeep, A. K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, J. B. Singh, G. Walia

**University of Delhi, Delhi, India**

Ashok Kumar, A. Bhardwaj, B. C. Choudhary, R. B. Garg, A. Kumar, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

**Saha Institute of Nuclear Physics, Kolkata, India**

S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, Sa. Jain, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

**Bhabha Atomic Research Centre, Mumbai, India**A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A. K. Mohanty<sup>2</sup>, L. M. Pant, P. Shukla, A. Topkar**Tata Institute of Fundamental Research, Mumbai, India**T. Aziz, S. Banerjee, S. Bhowmik<sup>26</sup>, R. M. Chatterjee, R. K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu<sup>27</sup>, G. Kole, S. Kumar, B. Mahakud, M. Maity<sup>26</sup>, G. Majumder, K. Mazumdar, S. Mitra, G. B. Mohanty, B. Parida, T. Sarkar<sup>26</sup>, N. Sur, B. Sutar, N. Wickramage<sup>28</sup>**Indian Institute of Science Education and Research (IISER), Pune, India**

S. Chauhan, S. Dube, S. Sharma

**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**H. Bakhshiansohi, H. Behnamian, S. M. Etesami<sup>29</sup>, A. Fahim<sup>30</sup>, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>31</sup>, M. Zeinali**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

**INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy**M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, C. Caputo<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,c</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a,b</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a,2</sup>, R. Venditti<sup>a,b</sup>, P. Verwilligen<sup>a</sup>**INFN Sezione di Bologna<sup>a</sup>, Università di Bologna<sup>b</sup>, Bologna, Italy**G. Abbiendi<sup>a</sup>, C. Battilana<sup>2</sup>, A. C. Benvenuti<sup>a</sup>, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F. R. Cavallo<sup>a</sup>, S. S. Chhibra<sup>a,b</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G. M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F. L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A. M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G. P. Siroli<sup>a,b</sup>, N. Tosi<sup>a,b</sup>, R. Travaglini<sup>a,b</sup>

**INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, Catania, Italy**G. Cappello<sup>a</sup>, M. Chiorboli<sup>a,b</sup>, S. Costa<sup>a,b</sup>, F. Giordano<sup>a,b</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>**INFN Sezione di Firenze<sup>a</sup>, Università di Firenze<sup>b</sup>, Firenze, Italy**G. Barbagli<sup>a</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, S. Gozzi<sup>a,b</sup>, V. Gori<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, A. Tropiano<sup>a,b</sup>, L. Viliani<sup>a,b,2</sup>**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

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

**INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genova, Italy**V. Calvelli<sup>a,b</sup>, F. Ferro<sup>a</sup>, M. Lo Vetere<sup>a,b</sup>, M. R. Monge<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>**INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milan, Italy**L. Brianza, M. E. Dinardo<sup>a,b</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a</sup>, R. Gerosa<sup>a,b</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R. A. Manzoni<sup>a,b</sup>, B. Marzocchi<sup>a,b,2</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, N. Redaelli<sup>a</sup>, T. Tabarelli de Fatis<sup>a,b</sup>**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Naples, Italy, Università della Basilicata<sup>c</sup>, Potenza, Italy, Università G. Marconi<sup>d</sup>, Rome, Italy**S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, S. Di Guida<sup>a,d,2</sup>, M. Esposito<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, A. O. M. Iorio<sup>a,b</sup>, G. Lanza<sup>a</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,2</sup>, M. Merola<sup>a</sup>, P. Paolucci<sup>a,2</sup>, C. Sciacca<sup>a,b</sup>, F. Thyssen**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy, Università di Trento<sup>c</sup>, Trento, Italy**P. Azzi<sup>a,2</sup>, N. Bacchetta<sup>a</sup>, L. Benato<sup>a,b</sup>, D. Bisello<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, M. Dall'Osso<sup>a,b,2</sup>, T. Dorigo<sup>a</sup>, S. Fantinel<sup>a</sup>, F. Fanzago<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, F. Gonella<sup>a</sup>, A. Gozzelino<sup>a</sup>, S. Lacaprara<sup>a</sup>, M. Margoni<sup>a,b</sup>, A. T. Meneguzzo<sup>a,b</sup>, F. Montecassiano<sup>a</sup>, J. Pazzini<sup>a,b</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, M. Tosi<sup>a,b</sup>, M. Zanetti, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b,2</sup>, G. Zumerle<sup>a,b</sup>**INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy**A. Braghieri<sup>a</sup>, A. Magnani<sup>a</sup>, P. Montagna<sup>a,b</sup>, S. P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a</sup>, P. Vitulo<sup>a,b</sup>**INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**L. Alunni Solestizi<sup>a,b</sup>, M. Biasini<sup>a,b</sup>, G. M. Bilei<sup>a</sup>, D. Ciangottini<sup>a,b,2</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, G. Mantovani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Saha<sup>a</sup>, A. Santocchia<sup>a,b</sup>**INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy**K. Androsova<sup>a,32</sup>, P. Azzurri<sup>a</sup>, G. Bagliesi<sup>a</sup>, J. Bernardini<sup>a</sup>, T. Boccali<sup>a</sup>, R. Castaldi<sup>a</sup>, M. A. Ciocci<sup>a,32</sup>, R. Dell'Orso<sup>a</sup>, S. Donato<sup>a,c,2</sup>, G. Fedi, L. Foà<sup>a,c†</sup>, A. Giassi<sup>a</sup>, M. T. Grippo<sup>a,32</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, L. Martini<sup>a,b</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, A. Savoy-Navarro<sup>a,33</sup>, A. T. Serban<sup>a</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, A. Venturi<sup>a</sup>, P. G. Verdini<sup>a</sup>**INFN Sezione di Roma<sup>a</sup>, Università di Roma<sup>b</sup>, Rome, Italy**L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, G. D'imperio<sup>a,b,2</sup>, D. Del Re<sup>a,b</sup>, M. Diemoz<sup>a</sup>, S. Gelli<sup>a,b</sup>, C. Jorda<sup>a</sup>, E. Longo<sup>a,b</sup>, F. Margaroli<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, R. Paramatti<sup>a</sup>, F. Preiato<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>, P. Traczyk<sup>a,b,2</sup>**INFN Sezione di Torino<sup>a</sup>, Università di Torino<sup>b</sup>, Turin, Italy, Università del Piemonte Orientale<sup>c</sup>, Novara, Italy**N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c,2</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, R. Bellan<sup>a,b</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, A. Degano<sup>a,b</sup>, N. Demaria<sup>a</sup>, L. Finco<sup>a,b,2</sup>, B. Kiania<sup>a,b</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. M. Obertino<sup>a,b</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G. L. Pinna Angioni<sup>a,b</sup>, F. Ravera<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>, U. Tamponi<sup>a</sup>**INFN Sezione di Trieste<sup>a</sup>, Università di Trieste<sup>b</sup>, Trieste, Italy**S. Belforte<sup>a</sup>, V. Candelise<sup>a,b,2</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, B. Gobbo<sup>a</sup>, C. La Licata<sup>a,b</sup>, M. Marone<sup>a,b</sup>, A. Schizzi<sup>a,b</sup>, A. Zanetti<sup>a</sup>**Kangwon National University, Chunchon, Korea**

A. Kropivnitskaya, S. K. Nam



**Kyungpook National University, Taegu, Korea**

D. H. Kim, G. N. Kim, M. S. Kim, D. J. Kong, S. Lee, Y. D. Oh, A. Sakharov, D. C. Son

**Chonbuk National University, Chonju, Korea**

J. A. Brochero Cifuentes, H. Kim, T. J. Kim

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

S. Song

**Korea University, Seoul, Korea**

S. Choi, Y. Go, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K. Lee, K. S. Lee, S. Lee, S. K. Park, Y. Roh

**Seoul National University, Seoul, Korea**

H. D. Yoo

**University of Seoul, Seoul, Korea**

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

**Sungkyunkwan University, Suwon, Korea**

Y. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

**Vilnius University, Vilnius, Lithuania**

A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z. A. Ibrahim, J. R. Komaragiri, M. A. B. Md Ali<sup>34</sup>, F. Mohamad Idris<sup>35</sup>, W. A. T. Wan Abdullah, M. N. Yusli

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

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz<sup>36</sup>, A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

I. Pedraza, H. A. Salazar Ibarquen

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

A. Morelos Pineda

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

P. H. Butler

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

A. Ahmad, M. Ahmad, Q. Hassan, H. R. Hoorani, W. A. Khan, T. Khurshid, M. Shoaib

**National Centre for Nuclear Research, Swierk, Poland**

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szeleper, P. Zalewski

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

G. Brona, K. Bunkowski, A. Byszuk<sup>37</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

**Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal**

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P. G. Ferreira Parracho, M. Gallinaro, N. Leonardo, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucchio, J. Varela, P. Vischia

**Joint Institute for Nuclear Research, Dubna, Russia**

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev,

A. Malakhov, V. Matveev<sup>38</sup>, P. Moisenz, V. Palichik, V. Perehygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

**Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg, Russia**

V. Golovtsov, Y. Ivanov, V. Kim<sup>39</sup>, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**

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

**Institute for Theoretical and Experimental Physics, Moscow, Russia**

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

**National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia**

A. Bylinkin

**P. N. Lebedev Physical Institute, Moscow, Russia**

V. Andreev, M. Azarkin<sup>40</sup>, I. Dremin<sup>40</sup>, M. Kirakosyan, A. Leonidov<sup>40</sup>, G. Mesyats, S. V. Rusakov

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

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin<sup>41</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, L. Tourchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic<sup>42</sup>, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J. P. Fernández Ramos, J. Flix, M. C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J. M. Hernandez, M. I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M. S. Soares

**Universidad Autónoma de Madrid, Madrid, Spain**

C. Albajar, J. F. de Trocóniz, M. Missiroli, D. Moran

**Universidad de Oviedo, Oviedo, Spain**

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J. M. Vizán Garcia

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

I. J. Cabrillo, A. Calderon, J. R. Castiñeiras De Saa, P. De Castro Manzano, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F. J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A. Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A. H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J. F. Benitez, G. M. Berruti, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, R. Castello, G. Cerminara, M. D’Alfonso, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M. J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M. T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M. V. Nemallapudi, H. Neugebauer, S. Orfanelli<sup>43</sup>, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, T. Reis, G. Rolandi<sup>44</sup>,

M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas<sup>45</sup>, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G. I. Veres<sup>23</sup>, N. Wardle, H. K. Wöhri, A. Zagodzinska<sup>37</sup>, W. D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

**Institute for Particle Physics, ETH Zurich, Zurich, Switzerland**

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzì, M. Quittnat, M. Rossini, A. Starodumov<sup>46</sup>, M. Takahashi, V. R. Tavolaro, K. Theofilatos, R. Wallny

**Universität Zürich, Zurich, Switzerland**

T. K. Aarrestad, C. Amsler<sup>47</sup>, L. Caminada, M. F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F. J. Ronga, D. Salerno, Y. Yang

**National Central University, Chung-Li, Taiwan**

M. Cardaci, K. H. Chen, T. H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C. M. Kuo, W. Lin, Y. J. Lu, S. S. Yu

**National Taiwan University (NTU), Taipei, Taiwan**

Arun Kumar, R. Bartek, P. Chang, Y. H. Chang, Y. W. Chang, Y. Chao, K. F. Chen, P. H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y. F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J. f. Tsai, Y. M. Tzeng

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

B. Asavapibhop, K. Kovitangoon, G. Singh, N. Srimanobhas, N. Suwonjandee

**Cukurova University, Adana, Turkey**

A. Adiguzel, M. N. Bakirci<sup>48</sup>, S. Cerci<sup>49</sup>, Z. S. Demiroglu, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E. E. Kangal<sup>50</sup>, A. Kayis Topaksu, G. Onengut<sup>51</sup>, K. Ozdemir<sup>52</sup>, A. Polatoz, M. Vergili, C. Zorbilmez

**Physics Department, Middle East Technical University, Ankara, Turkey**

I. V. Akin, B. Bilin, S. Bilmis, B. Isildak<sup>53</sup>, G. Karapinar<sup>54</sup>, M. Yalvac, M. Zeyrek

**Bogazici University, Istanbul, Turkey**

E. Gülmez, M. Kaya<sup>55</sup>, O. Kaya<sup>56</sup>, E. A. Yetkin<sup>57</sup>, T. Yetkin<sup>58</sup>

**Istanbul Technical University, Istanbul, Turkey**

K. Cankocak, S. Sen<sup>59</sup>, F. I. Vardarli

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

B. Grynyov

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

L. Levchuk, P. Sorokin

**University of Bristol, Bristol, UK**

R. Aggleton, F. Ball, L. Beck, J. J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G. P. Heath, H. F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D. M. Newbold<sup>60</sup>, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V. J. Smith

**Rutherford Appleton Laboratory, Didcot, UK**

K. W. Bell, A. Belyaev<sup>61</sup>, C. Brew, R. M. Brown, L. Calligaris, D. Cieri, D. J. A. Cockerill, J. A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C. H. Shepherd-Themistocleous, A. Thea, I. R. Tomalin, T. Williams, W. J. Womersley, S. D. Worm

**Imperial College, London, UK**

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, N. Cripps,

P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, M. Kenzie, R. Lane, R. Lucas<sup>60</sup>, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko<sup>46</sup>, J. Pela, M. Pesaresi, K. Petridis, D. M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta<sup>62</sup>, T. Virdee, S. C. Zenz

**Brunel University, Uxbridge, UK**

J. E. Cole, P. R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, I. D. Reid, P. Symonds, L. Teodorescu, M. Turner

**Baylor University, Waco, USA**

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

**The University of Alabama, Tuscaloosa, USA**

O. Charaf, S. I. Cooper, C. Henderson, P. Rumerio

**Boston University, Boston, USA**

D. Arcaro, A. Avetisyan, T. Bose, C. Fantasia, D. Gastler, P. Lawson, D. Rankin, C. Richardson, J. Rohlf, J. St. John, L. Sulak, D. Zou

**Brown University, Providence, USA**

J. Alimena, E. Berry, S. Bhattacharya, D. Cutts, N. Dhingra, A. Ferapontov, A. Garabedian, J. Hakala, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, R. Syarif

**University of California, Davis, Davis, USA**

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P. T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

**University of California, Los Angeles, USA**

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

**University of California, Riverside, Riverside, USA**

K. Burt, R. Clare, J. Ellison, J. W. Gary, G. Hanson, J. Heilman, M. Ivova PANEVA, P. Jandir, E. Kennedy, F. Lacroix, O. R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, H. Wei, S. Wimpenny, B. R. Yates

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

J. G. Branson, G. B. Cerati, S. Cittolin, R. T. D'Agnolo, M. Derdzinski, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech<sup>63</sup>, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

**University of California, Santa Barbara, Santa Barbara, USA**

J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, N. Mccoll, S. D. Mullin, J. Richman, D. Stuart, I. Suarez, C. West, J. Yoo

**California Institute of Technology, Pasadena, USA**

D. Anderson, A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H. B. Newman, C. Pena, M. Pierini, M. Spiropulu, J. R. Vlimant, S. Xie, R. Y. Zhu

**Carnegie Mellon University, Pittsburgh, USA**

M. B. Andrews, V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

**University of Colorado Boulder, Boulder, USA**

J. P. Cumalat, W. T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, K. Stenson, S. R. Wagner

**Cornell University, Ithaca, USA**

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J. R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, W. Sun, S. M. Tan, W. D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

**Fermi National Accelerator Laboratory, Batavia, USA**

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, S. Banerjee, L. A. T. Bauerdick, A. Beretvas, J. Berryhill, P. C. Bhat, G. Bolla, K. Burkett, J. N. Butler, H. W. K. Cheung, F. Chlebana, S. Cihangir, V. D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R. M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A. W. Jung, B. Klima, B. Kreis, S. Kwan<sup>†</sup>, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J. M. Marraffino, V. I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, E. Sexton-Kennedy, A. Soha, W. J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, H. A. Weber, A. Whitbeck, F. Yang

**University of Florida, Gainesville, USA**

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G. P. Di Giovanni, R. D. Field, I. K. Furic, S. V. Gleyzer, J. Hugon, J. Konigsberg, A. Korytov, J. F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic<sup>64</sup>, G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

**Florida International University, Miami, USA**

S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J. L. Rodriguez

**Florida State University, Tallahassee, USA**

A. Ackert, J. R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K. F. Johnson, A. Khatiwada, H. Prosper, M. Weinberg

**Florida Institute of Technology, Melbourne, USA**

M. M. Baarmand, V. Bhopatkar, S. Colafranceschi<sup>65</sup>, M. Hohlmann, H. Kalakhety, D. Noonan, T. Roy, F. Yumiceva

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

M. R. Adams, L. Apanasevich, D. Berry, R. R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C. E. Gerber, D. J. Hofman, P. Kurt, C. O'Brien, I. D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas, Z. Wu, M. Zakaria

**The University of Iowa, Iowa City, USA**

B. Bilki<sup>66</sup>, W. Clarida, K. Dilsiz, S. Durgut, R. P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>67</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>57</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

**Johns Hopkins University, Baltimore, USA**

I. Anderson, B. A. Barnett, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A. V. Gritsan, P. Maksimovic, M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

**The University of Kansas, Lawrence, USA**

P. Baringer, A. Bean, G. Benelli, C. Bruner, R. P. Kenny III, D. Majumder, M. Malek, M. Murray, S. Sanders, R. Stringer, Q. Wang

**Kansas State University, Manhattan, USA**

A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L. K. Saini, N. Skhirtladze, S. Toda

**Lawrence Livermore National Laboratory, Livermore, USA**

D. Lange, F. Rebassoo, D. Wright

**University of Maryland, College Park, USA**

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S. C. Eno, C. Ferraioli, J. A. Gomez, N. J. Hadley, S. Jabeen, R. G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A. C. Mignerey, Y. H. Shin, A. Skuja, M. B. Tonjes, S. C. Tonwar

**Massachusetts Institute of Technology, Cambridge, USA**

A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I. A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, Y. Iiyama, G. M. Innocenti, M. Klute, D. Kovalskyi, Y. S. Lai, Y.-J. Lee, A. Levin, P. D. Luckey, A. C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Ralph, C. Roland,

G. Roland, J. Salfeld-Nebgen, G. S. F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T. W. Wang, B. Wyslouch, M. Yang, V. Zhukova

**University of Minnesota, Minneapolis, USA**

B. Dahmes, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S. C. Kao, K. Klapoetke, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

**University of Mississippi, Oxford, USA**

J. G. Acosta, S. Oliveros

**University of Nebraska-Lincoln, Lincoln, USA**

E. Avdeeva, K. Bloom, S. Bose, D. R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, J. Monroy, F. Ratnikov, J. E. Siado, G. R. Snow

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

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio, B. Roozbahani

**Northeastern University, Boston, USA**

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Hortiangtham, A. Massironi, D. M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

**Northwestern University, Evanston, USA**

K. A. Hahn, A. Kubik, J. F. Low, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Trovato, M. Velasco

**University of Notre Dame, Notre Dame, USA**

A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D. J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>38</sup>, T. Pearson, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

**The Ohio State University, Columbus, USA**

L. Antonelli, J. Brinson, B. Bylsma, L. S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, W. Ji, K. Kotov, T. Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B. L. Winer, H. W. Wulsin

**Princeton University, Princeton, USA**

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J. S. Werner, A. Zuranski

**University of Puerto Rico, Mayaguez, USA**

S. Malik

**Purdue University, West Lafayette, USA**

V. E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M. K. Jha, M. Jones, K. Jung, D. H. Miller, N. Neumeister, B. C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

**Purdue University Calumet, Hammond, USA**

N. Parashar, J. Stupak

**Rice University, Houston, USA**

A. Adair, B. Akgun, Z. Chen, K. M. Ecklund, F. J. M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B. P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

**University of Rochester, Rochester, USA**

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, P. Tan, M. Verzetti

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

S. Arora, A. Barker, J. P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein,

R. Gray, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, K. Nash, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

**University of Tennessee, Knoxville, USA**

M. Foerster, G. Riley, K. Rose, S. Spanier, A. York

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

O. Bouhali<sup>68</sup>, A. Castaneda Hernandez<sup>68</sup>, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Kamon<sup>69</sup>, V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K. A. Ulmer<sup>2</sup>

**Texas Tech University, Lubbock, USA**

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P. R. Duderod, J. Faulkner, S. Kunori, K. Lamichhane, S. W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

**Vanderbilt University, Nashville, USA**

E. Appelt, A. G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, H. Ni, P. Sheldon, B. Snook, S. Tuo, J. Velkovska, Q. Xu

**University of Virginia, Charlottesville, USA**

M. W. Arenton, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, J. Wood, F. Xia

**Wayne State University, Detroit, USA**

C. Clarke, R. Harr, P. E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

**University of Wisconsin-Madison, Madison, WI, USA**

D. A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomber, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G. A. Pierro, G. Polese, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W. H. Smith, D. Taylor, N. Woods

† **Deceased**

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
- 4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
- 5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
- 6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 7: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 8: Also at Centre National de la Recherche Scientifique (CNRS)-IN2P3, Paris, France
- 9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 10: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 11: Now at Suez University, Suez, Egypt
- 12: Also at Now at British University in Egypt, Cairo, Egypt
- 13: Also at Cairo University, Cairo, Egypt
- 14: Also at Fayoum University, El-Fayoum, Egypt
- 15: Also at Université de Haute Alsace, Mulhouse, France
- 16: Also at Tbilisi State University, Tbilisi, Georgia
- 17: Also at Ilia State University, Tbilisi, Georgia
- 18: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 19: Also at Indian Institute of Science Education and Research, Bhopal, India
- 20: Also at University of Hamburg, Hamburg, Germany
- 21: Also at Brandenburg University of Technology, Cottbus, Germany
- 22: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 23: Also at Eötvös Loránd University, Budapest, Hungary

- 24: Also at University of Debrecen, Debrecen, Hungary
- 25: Also at Wigner Research Centre for Physics, Budapest, Hungary
- 26: Also at University of Visva-Bharati, Santiniketan, India
- 27: Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 28: Also at University of Ruhuna, Matara, Sri Lanka
- 29: Also at Isfahan University of Technology, Isfahan, Iran
- 30: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
- 31: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 32: Also at Università degli Studi di Siena, Siena, Italy
- 33: Also at Purdue University, West Lafayette, USA
- 34: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 35: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 36: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 37: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 38: Also at Institute for Nuclear Research, Moscow, Russia
- 39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 40: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 41: Also at California Institute of Technology, Pasadena, USA
- 42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 43: Also at National Technical University of Athens, Athens, Greece
- 44: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 45: Also at National and Kapodistrian University of Athens, Athens, Greece
- 46: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 47: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 48: Also at Gaziosmanpasa University, Tokat, Turkey
- 49: Also at Adiyaman University, Adiyaman, Turkey
- 50: Also at Mersin University, Mersin, Turkey
- 51: Also at Cag University, Mersin, Turkey
- 52: Also at Piri Reis University, Istanbul, 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 Mimar Sinan University, Istanbul, Istanbul, Turkey
- 58: Also at Yildiz Technical University, Istanbul, Turkey
- 59: Also at Hacettepe University, Ankara, Turkey
- 60: Also at Rutherford Appleton Laboratory, Didcot, UK
- 61: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
- 62: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 63: Also at Utah Valley University, Orem, USA
- 64: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 65: Also at Facoltà Ingegneria, Università di Roma, Rome, Italy
- 66: Also at Argonne National Laboratory, Argonne, USA
- 67: Also at Erzincan University, Erzincan, Turkey
- 68: Also at Texas A&M University at Qatar, Doha, Qatar
- 69: Also at Kyungpook National University, Taegu, Korea