



# Angular coefficients of Z bosons produced in pp collisions at $\sqrt{s} = 8$ TeV and decaying to $\mu^+\mu^-$ as a function of transverse momentum and rapidity



CMS Collaboration\*

CERN, Switzerland

## ARTICLE INFO

### Article history:

Received 14 April 2015

Received in revised form 8 July 2015

Accepted 27 August 2015

Available online 1 September 2015

Editor: M. Doser

### Keywords:

CMS

Physics

Z boson production

## ABSTRACT

Measurements of the five most significant angular coefficients,  $A_0$  through  $A_4$ , for Z bosons produced in pp collisions at  $\sqrt{s} = 8$  TeV and decaying to  $\mu^+\mu^-$  are presented as a function of the transverse momentum and rapidity of the Z boson. The integrated luminosity of the dataset collected with the CMS detector at the LHC corresponds to  $19.7 \text{ fb}^{-1}$ . These measurements provide comprehensive information about the Z boson production mechanisms, and are compared to the QCD predictions at leading order, next-to-leading order, and next-to-next-to-leading order in perturbation theory.

© 2015 CERN for the benefit of the CMS Collaboration. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP<sup>3</sup>.

We report the first measurement of the angular coefficients of Z bosons produced in pp collisions and decaying to muon pairs. These coefficients govern the decay of the Z boson and thereby the kinematics of the lepton. Their values follow from the vector and axial vector (V–A) structure of boson–fermion couplings. The general structure of the lepton angular distribution in the boson rest frame is given by

$$\begin{aligned} \frac{d^2\sigma}{d\cos\theta^*d\phi^*} \propto & \left[ (1 + \cos^2\theta^*) + A_0 \frac{1}{2}(1 - 3\cos^2\theta^*) \right. \\ & + A_1 \sin(2\theta^*) \cos\phi^* + A_2 \frac{1}{2} \sin^2\theta^* \cos(2\phi^*) \\ & + A_3 \sin\theta^* \cos\phi^* + A_4 \cos\theta^* + A_5 \sin^2\theta^* \sin(2\phi^*) \\ & \left. + A_6 \sin(2\theta^*) \sin\phi^* + A_7 \sin\theta^* \sin\phi^* \right]. \end{aligned} \quad (1)$$

Here,  $\theta^*$  and  $\phi^*$  are the polar and azimuthal angles of the negatively charged lepton in the rest frame of the lepton pair. In this analysis we choose the Collins–Soper (CS) frame [1] to measure the angular coefficients  $A_i$ , considering the momentum of the beam proton closest in rapidity to the Z boson as the “target momentum” in [1]. The parameters  $A_0$ ,  $A_1$ , and  $A_2$  are related to the polarization of the Z boson, whilst  $A_3$  and  $A_4$  are also sensitive to the V–A structure of the couplings of the muons. All angular coefficients

vanish as the Z boson transverse momentum  $q_T$  approaches zero except for  $A_4$ , which is the electroweak parity violation term.

The only previous measurement of four of the angular coefficients was performed by the CDF Collaboration in  $p\bar{p}$  interactions for  $q_T$  up to 55 GeV [2]. The angular coefficients in pp collisions are expected to differ from those in  $p\bar{p}$  collisions for several reasons. For  $p\bar{p}$  collisions, the Z boson production occurs predominantly via the  $q\bar{q}$  annihilation process, whilst the contribution of the qg Compton process is larger in pp collisions than  $p\bar{p}$  collisions. Using the POWHEG estimation [3–6] the fraction of qg process in pp collisions at the LHC is 47%; it is 35% near  $q_T = 0$  and increases to  $\sim 80\%$  at  $q_T > 100$  GeV. For the  $q\bar{q}$  process in the CS frame,  $A_0 = A_2 = q_T^2/(M_Z^2 + q_T^2)$  [7–10], where  $M_Z$  is the Z boson mass. For the qg Compton process,  $A_0 = A_2 \approx 5q_T^2/(M_Z^2 + 5q_T^2)$  [11]. The relation  $A_0 = A_2$  is known as the Lam–Tung relation [12], reflecting the full transverse polarization of vector boson coupling to quarks, as well as rotational invariance [13]. Processes containing non-planar configurations (e.g., from higher order multi-gluon emission) smear the transverse polarization, leading to  $A_2 < A_0$  [14]. In contrast to what happens at the Tevatron, the average handedness of Z bosons is nonzero at the LHC, as for the W boson [15–17].

The angular coefficients of Z bosons produced in pp collisions at  $\sqrt{s} = 8$  TeV and decaying to  $\mu^+\mu^-$  are measured as a function of  $q_T$  and rapidity  $y$ . The data, taken with the CMS detector at the LHC, corresponds to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ . The large Z boson event sample collected by the CMS experiment allows precision measurements of the angular distribution

\* E-mail address: [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch).

for  $q_T < 200$  GeV and  $|y| < 2.1$ . The coefficients, measured as a function of  $q_T$  and  $|y|$ , are compared with three perturbative QCD predictions by FEWZ at next-to-next-to-leading order (NNLO) [18], POWHEG at next-to-leading order (NLO) [3–6], and MADGRAPH at leading order (LO) [19].

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and plastic scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are measured in the pseudorapidity range  $|\eta| < 2.4$ , with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. A more detailed description of the CMS detector, together with a definition of the coordinate system and the relevant kinematic variables, can be found in Ref. [20].

Matching muons to tracks measured in the silicon tracker results in a relative  $p_T$  resolution for muons with  $20 < p_T < 100$  GeV of 1.3–2.0% in the barrel and better than 6% in the endcaps. A particle-flow (PF) event reconstruction algorithm [21,22] is used in this analysis. It consists of reconstructing and identifying each single particle with an optimized combination of all subdetector information. A trigger for single isolated muon is used, requiring  $p_T > 24$  GeV and  $|\eta| < 2.1$ . The leading in  $p_T$  reconstructed muon is matched to the muon selected by the trigger.

The signal process is simulated using the MADGRAPH 1.3.30 generator [19] with zero to four additional jets, interfaced with PYTHIA v6.4.24 [23] with the Z2\* tune [24]. The matching between the matrix element calculation and the parton shower is performed with the  $k_T$ -MLM algorithm [25]. The CTEQ6L1 [26] parton distribution functions (PDF) are used for the event generation. Multiple-parton interactions are simulated by PYTHIA. The POWHEG generator [3–6] interfaced with PYTHIA (same version used for MADGRAPH) and the CT10 PDF set [27] are used as an alternate to test any model dependence in the shapes of the angular distributions.

Background simulations are performed with MADGRAPH (W + jets,  $t\bar{t}$ ,  $\tau\tau$ ), POWHEG (single top quark [28,29]), and PYTHIA (WW, WZ, ZZ). The normalizations of the inclusive Drell–Yan, W boson [18], and  $t\bar{t}$  [30] distributions are set using NNLO cross sections. For single top quark production a higher order (approximate NNLO [31]) inclusive cross section is used. The generated events are passed through a detector simulation based on GEANT4 [32].

Each muon candidate is required to be reconstructed in the muon detectors and in the inner tracker, and the global track fit is required to have a reduced  $\chi^2 < 10$ . The vertex with the highest sum of  $p_T^2$  for associated tracks is defined as the primary vertex. The distance of the muon candidate trajectories with respect to the primary vertex must be smaller than 2 mm in the transverse plane and 5 mm along the beam axis. The leading (subleading) muon is required to have  $p_T > 25$  (10) GeV and  $|\eta| < 2.1$  (2.4). In order to suppress background events, the muons are required to be isolated from nearby particles. The relative isolation is calculated as the ratio of the scalar sum of  $p_T$  of all PF candidates from the same primary vertex, within a cone of  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ , and the  $p_T$  of the muon. For the leading (subleading) muon in  $p_T$ , the relative isolation must be less than 0.12 (0.5). Oppositely charged muon pairs with an invariant mass in the range 81–101 GeV are selected. In the rare case that more than two muons are selected, the muon pair with invariant mass closest to the Z boson mass is chosen. The muon pair must satisfy  $|y| < 2.1$  since at higher  $|y|$  the acceptance varies rapidly. After the event selection,  $4.3 \times 10^6$

events with Z boson candidates remain for  $|y| < 1.0$  and  $2.5 \times 10^6$  events for  $1.0 < |y| < 2.1$ .

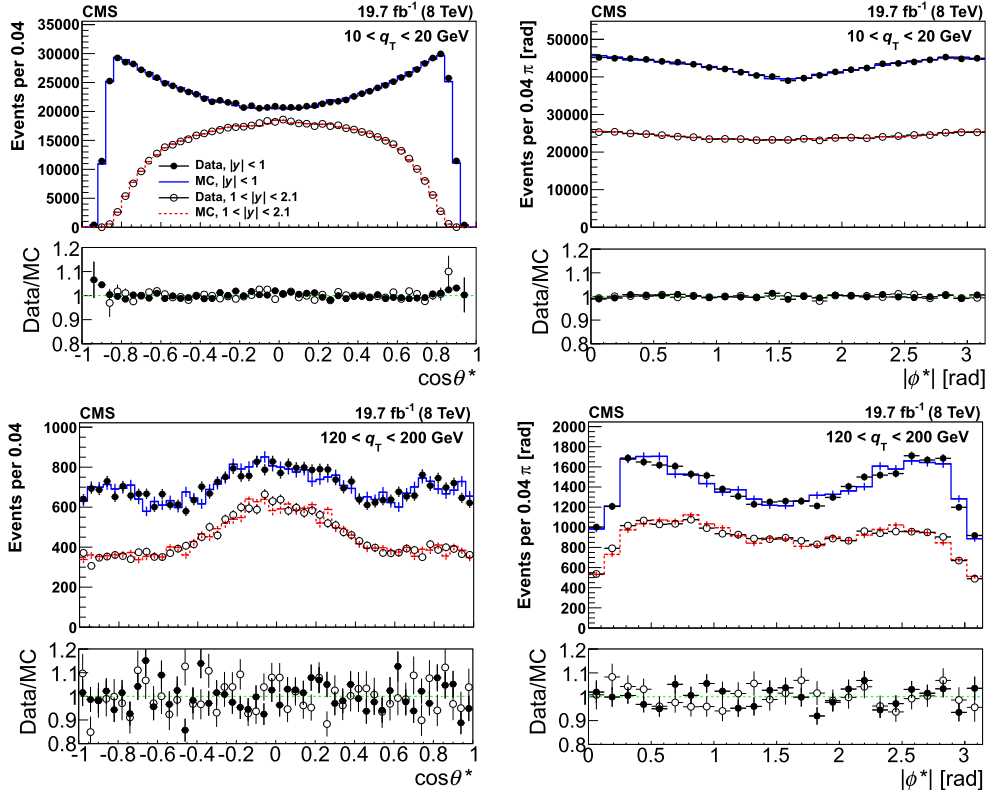
A “tag-and-probe” method [33] is used to measure the efficiencies for track reconstruction, trigger, muon isolation, and muon identification in data and simulation. Efficiency corrections are applied as multiplicative scale factors to the simulation values. The efficiency for track reconstruction is measured in bins of  $\eta$  since the  $p_T$  dependence is weak. The trigger efficiency is determined in bins of  $p_T$  and  $\eta$ , separately for  $\mu^+$  and  $\mu^-$ . The identification efficiency is measured in bins of  $p_T$  and  $\eta$ . Since the subleading muon can point in the direction of the hadronic activity, a looser isolation requirement is used and its efficiency is measured as a function of  $q_T$ ,  $\cos\theta^*$ , and  $\phi^*$ . The efficiency of the isolation requirement for the leading muon is measured as a function of  $p_T$  and  $\eta$  of the muon, as detector effects relate to these variables more directly than to the Z boson  $q_T$  and  $y$ .

After event selection, the background contribution ranges from  $\sim 0.1\%$  at low  $q_T$  to  $\sim 1.5\%$  at high  $q_T$ . The yields of the backgrounds from  $t\bar{t}$ ,  $\tau\tau$ , WW, tW, and W + jets production are estimated from data using lepton flavor universality. Most of these backgrounds typically have two prompt leptons, which may have the same flavor. The W + jets background is flavor asymmetric, but its contribution is small. We assume that the ratio of the number of oppositely charged background  $\mu\mu$  and  $e\mu$  events is the same in data and simulation. We use the ratio of the  $e\mu$  yields in data and simulation after applying muon and electron selection criteria [33,34] to normalize the simulation to data.

The acceptance and the efficiency at the event level vary in  $\cos\theta^*$  and  $\phi^*$ , and strongly with  $q_T$  and  $y$ . In order to avoid a bias in the acceptance due to the modeling of the Z boson kinematics, the simulation is reweighted in fine bins of  $q_T$  and  $y$  to match the background-subtracted data distribution. The weights are determined at the reconstruction level and applied at the generator level. The weighting is iterated four times, with negligible change between the second and fourth iteration.

The angular coefficients are measured in eight bins of  $q_T$  and two bins of  $|y|$ , by fitting the two-dimensional ( $\cos\theta^*$ ,  $\phi^*$ ) distribution in data with a linear combination of templates. These templates are built for each coefficient  $A_i$  by reweighting the simulation at generator level to the corresponding angular distribution, as given in Eq. (1). The templates are based on reconstructed muons, and thereby incorporate the effects of resolution, efficiency and acceptance. A template is also built for the term  $(1 + \cos^2\theta^*)$  of Eq. (1). An additional template, with shape and normalization fixed, is developed for fitting the backgrounds. A binned maximum-likelihood method with Poisson uncertainties is employed for the fit. The angular coefficients  $A_5$ ,  $A_6$ , and  $A_7$  are predicted to be very small; they are set to zero and excluded from the fit. Since  $A_0$  through  $A_4$  are sign invariant in  $\phi^*$ , the absolute value  $|\phi^*|$  is used. The fit is made in  $12 \times 12$  equidistant bins in  $\cos\theta^*$  and  $|\phi^*|$ . The statistical uncertainties from the fit are confirmed by comparison with pseudo-experiments.

To test the robustness of the result with respect to the analysis method and trigger effect, the angular coefficients  $A_0$ ,  $A_2$ ,  $A_3$ , and  $A_4$  are also measured by an independent analysis similar to that reported in Ref. [2], where one-dimensional (1D) templates produced using POWHEG are fitted to the distributions in  $\cos\theta^*$  and  $|\phi^*|$ . The 1D fit analysis is performed iteratively, so as to be unbiased with respect to the assumed templates and to possible correlations between  $\cos\theta^*$  and  $|\phi^*|$ . The analysis differs in the triggers, estimation of backgrounds, simulation, and selection criteria. The 1D fit analysis uses a sample that requires a dimuon trigger with asymmetric muon  $p_T$  thresholds of 17 and 8 GeV. Both results are consistent within their total systematic uncertainties, excluding uncertainties common to both analyses.



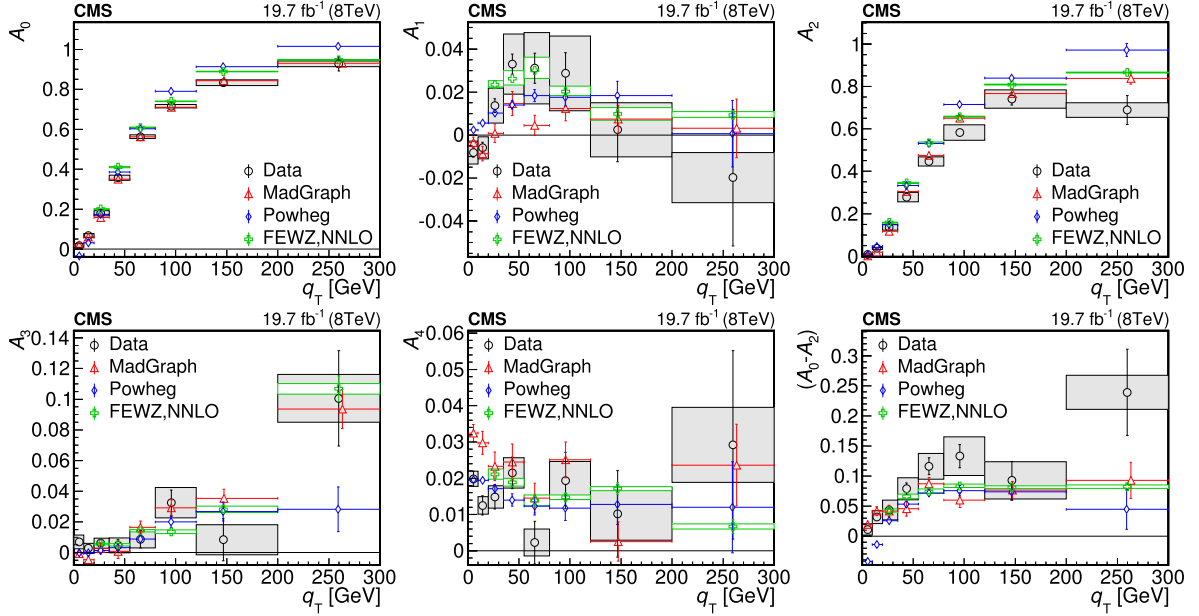
**Fig. 1.** A few examples of the observed 1D angular distributions in  $\cos\theta^*$  (left) and  $|\phi^*|$  (right) compared to the MC simulation using the best fit values of the angular coefficients. The top (bottom) plots show the distributions for  $10 < q_T < 20$  GeV ( $120 < q_T < 200$  GeV), a region where  $A_0$  and  $A_2$  are small (large). The background-subtracted data points are shown with filled (open) circles for  $|y| < 1$  ( $1 < |y| < 2.1$ ), whilst the corresponding MC results are shown with the solid (dashed) lines. Vertical bars represent the statistical uncertainties. The lower panels show the data-to-MC ratios.

Some examples of the measured  $\cos\theta^*$  and  $|\phi^*|$  distributions from the 1D analysis are given in Fig. 1. The measured and simulated distributions are shown together using the best fit values of the angular coefficients. The shape of the  $\cos\theta^*$  distribution changes with  $q_T$  and  $|y|$  because the acceptance and efficiency in  $\cos\theta^*$  depend strongly on these two variables. For  $|\phi^*|$ , the shape of the distribution changes moderately with  $q_T$ , and is almost insensitive to  $|y|$ . The comparison of data and simulation shown in Fig. 1 gives confidence that the acceptance and efficiency dependences are correctly modeled in the simulation.

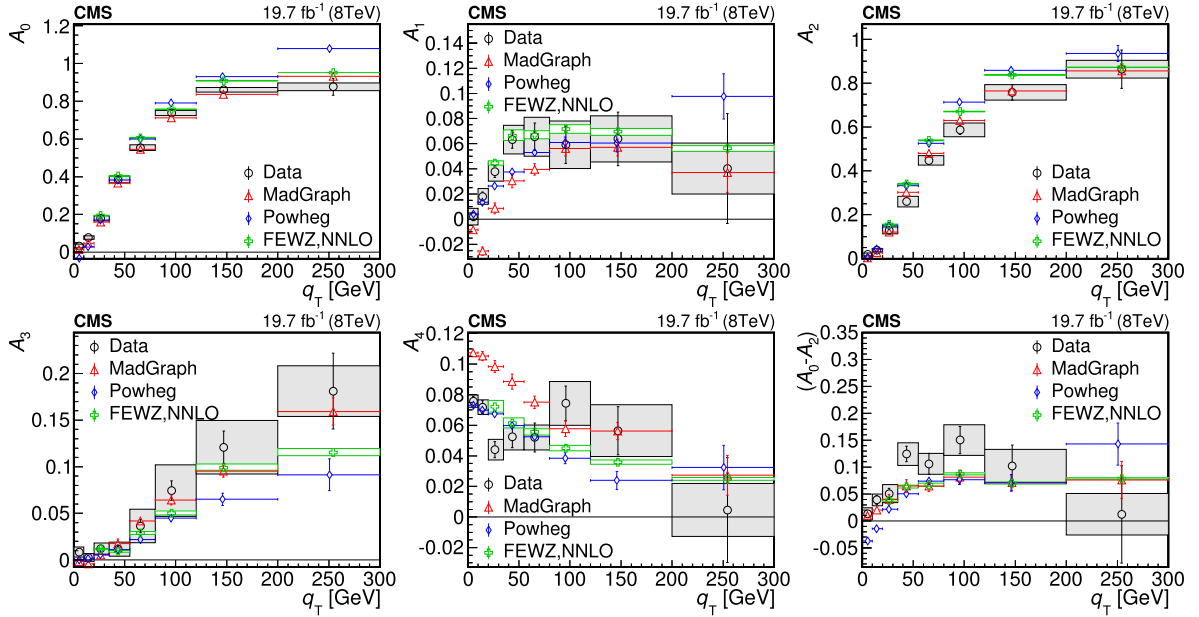
Several sources of systematic uncertainties are taken into account. The most significant source is the muon efficiency that includes the trigger, track reconstruction, isolation, and identification. The statistical uncertainties of the measured efficiency scale factors are taken into account by simulating 500 pseudo-experiments in which the templates are reformed, each time varying the scale factors randomly within the given uncertainty. The systematic uncertainties in the extraction of the efficiency (e.g., background estimates) are also included. Another significant uncertainty stems from the statistical precision of the templates, which is estimated using pseudo-experiments. The pileup uncertainty is estimated by varying the cross section of the minimum bias events by  $\pm 5\%$ . The muon momentum bias is measured in data and simulation, and corresponding corrections are applied [35]. The statistical uncertainties in the muon momentum correction factors are propagated to a systematic uncertainty using pseudo-experiments. In addition, a systematic uncertainty is assessed to take into account possible global offsets from the peak position of the Z boson mass. The systematic uncertainties for the background are estimated by varying the normalization scale factor of the  $e\mu$  sample by 10% and the yields of WZ and ZZ events by 50%. The sta-

tistical precision of the iterative reweighting is determined using pseudo-experiments. The difference between the last two iterations is assigned as additional systematic uncertainty. The effect of final-state radiation is taken into account by adding the energy of photons within a cone of radius 0.1 around the muon direction [36]. Weights are applied to the simulation to reflect the difference between a soft-collinear approach and the exact  $O(\alpha_{\text{QED}})$  result and the reconstructed template is rebuilt using the weighted simulation. The difference between templates is used to estimate the systematic uncertainty from final-state radiation. Finally, the acceptance uncertainty, related to the values of  $A_i$  assumed in the simulation, is estimated by reweighting with the fitted values of  $A_i$ , and the difference in results is included as a systematic uncertainty. Generally, the statistical uncertainties dominate in the highest bins in  $q_T$ , whilst the systematic uncertainty in the efficiency tends to be the most important elsewhere.

The results of the  $q_T$  and  $|y|$  dependent measurements of the angular coefficients  $A_0$  to  $A_4$  as well as the difference  $A_0 - A_2$  are presented along with MADGRAPH, POWHEG, and FEWZ (at NNLO) calculations in Figs. 2 and 3. The various systematic uncertainties of the five angular coefficients  $A_0$  to  $A_4$  are presented in Fig. 4. The values and uncertainties of the coefficients are provided in Tables 1 and 2. The PDF sets used in the calculations are CTEQ6L for MADGRAPH and CT10 for POWHEG (at NLO) and FEWZ (at NNLO). The MADGRAPH predictions for  $A_4$  are systematically higher than those of POWHEG and FEWZ because MADGRAPH uses a weak mixing angle calculated without considering radiative corrections. The measured  $A_0$  and  $A_2$  coefficients agree better with the prediction of MADGRAPH than with those of POWHEG and FEWZ, especially at high  $q_T$ . At  $q_T = 0$ , the POWHEG prediction for  $A_0$  is negative, which is unphysical and has been traced to approximations in



**Fig. 2.** Comparison of the five angular coefficients  $A_i$  and  $A_0 - A_2$  measured in the Collins–Soper frame in bins of  $q_T$  for  $|y| < 1$ . The circles show the measured results. The vertical bars represent the statistical uncertainties and the boxes the systematic uncertainties of the measurement. The triangles show the predictions from MADGRAPH, the diamonds from POWHEG, and the crosses from FEWZ at NNLO. The boxes at the FEWZ values indicate the PDF uncertainties.



**Fig. 3.** Comparison of the five angular coefficients and  $A_0 - A_2$  under the same conditions as Fig. 2, for the rapidity bin  $1 < |y| < 2.1$ .

the shower matching algorithm. The FEWZ prediction is shown for  $q_T > 20$  GeV, where the calculations are considered reliable. We find that  $A_0(q_T)$  and  $A_2(q_T)$  are larger in pp collisions than those measured in  $p\bar{p}$  collisions at the Tevatron. The larger contribution from the  $q\bar{q}$  process in pp collisions at the LHC is responsible for this difference. We observe the violation of the Lam–Tung relation ( $A_0 = A_2$ ) anticipated by QCD calculations beyond leading order [37]. We find that  $A_0 > A_2$ , especially for high  $q_T$ . In addition, we measure nonzero values of  $A_1$  and  $A_3$ . The comparison of the results for  $|y| < 1$  and  $1 < |y| < 2.1$  is shown in Fig. 5.

In summary, we presented the five major angular coefficients,  $A_0$  through  $A_4$ , for the production of the Z boson decaying to muon pairs as a function of  $q_T$  and  $|y|$  in pp collisions. These

results play an important role in future high-precision measurements, such as the measurement of the mass of the W boson and of the electroweak mixing angle. Some theoretical predictions deviate from the measurements in  $q_T$ . Further refinements of the theory are needed to achieve a better agreement with the experimental results.

### Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort.

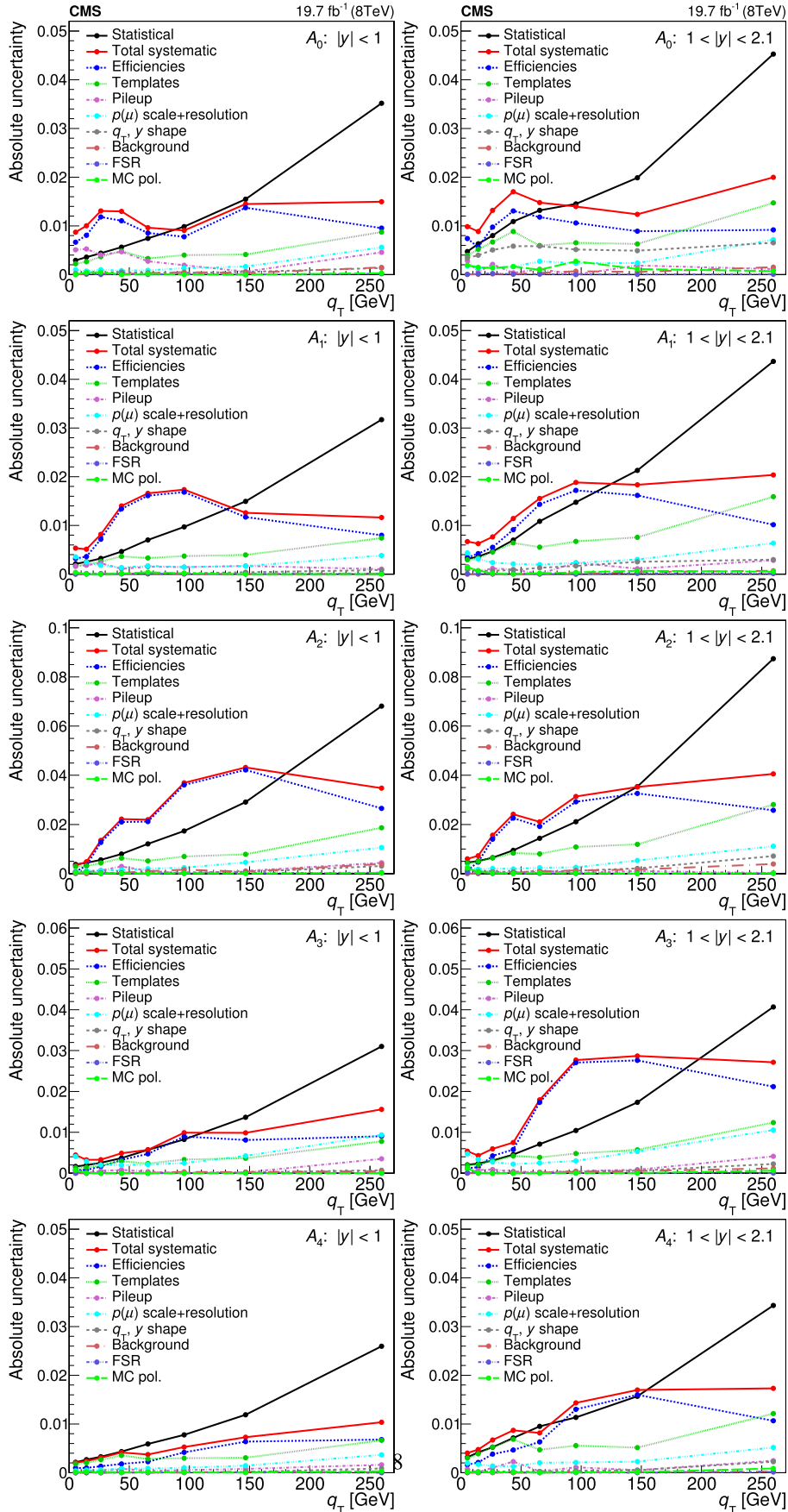
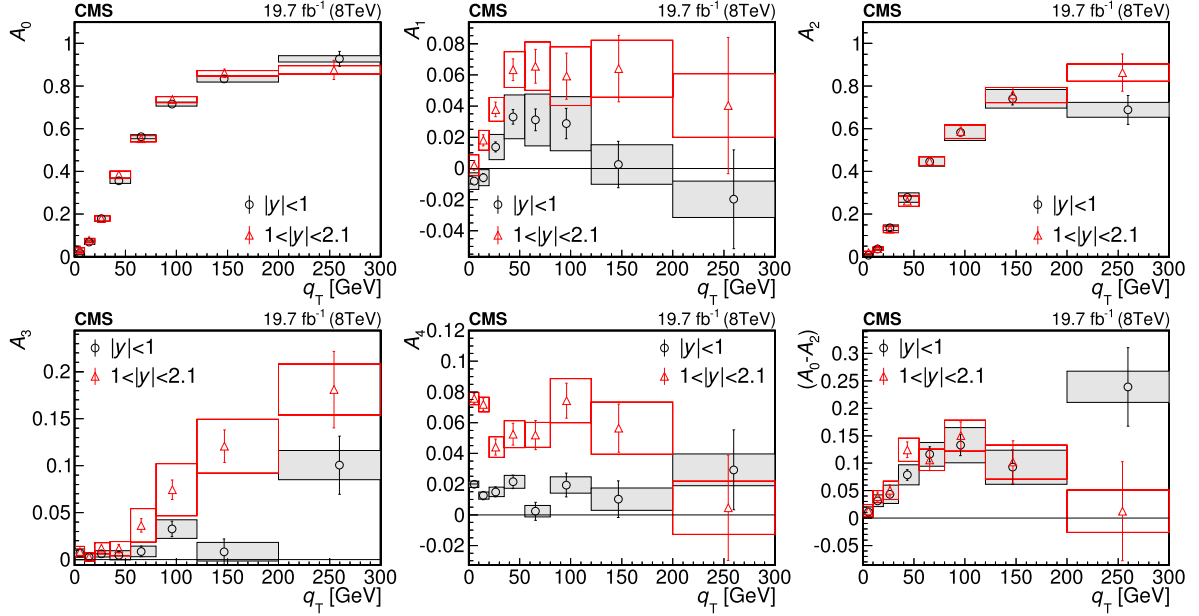


Fig. 4. Absolute uncertainties in the five angular coefficients  $A_0$  to  $A_4$ . Each figure shows the  $q_T$  dependence in the indicated ranges of  $|\eta|$ .



**Fig. 5.** Comparison of the five angular coefficients  $A_i$  and  $A_0 - A_2$  measured in the Collins–Soper frame in bins of  $q_T$  between  $|y| < 1$  (circles) and  $1 < |y| < 2.1$  (triangles). The vertical bars represent the statistical uncertainties and the boxes the systematic uncertainties of the measurement.

**Table 1**

The five angular coefficients  $A_0$  to  $A_4$  and  $A_0 - A_2$  in bins of  $q_T$  for  $|y| < 1$ .

$q_T$ [GeV]	$A_0$	$\pm\delta_{\text{stat}}$	$\pm\delta_{\text{syst}}$	$A_1$	$\pm\delta_{\text{stat}}$	$\pm\delta_{\text{syst}}$	$A_2$	$\pm\delta_{\text{stat}}$	$\pm\delta_{\text{syst}}$
0–10	0.018	$\pm 0.003$	$\pm 0.009$	-0.008	$\pm 0.002$	$\pm 0.005$	0.007	$\pm 0.004$	$\pm 0.003$
10–20	0.068	$\pm 0.004$	$\pm 0.010$	-0.006	$\pm 0.003$	$\pm 0.005$	0.037	$\pm 0.004$	$\pm 0.005$
20–35	0.179	$\pm 0.004$	$\pm 0.013$	0.014	$\pm 0.003$	$\pm 0.008$	0.136	$\pm 0.006$	$\pm 0.014$
35–55	0.357	$\pm 0.006$	$\pm 0.013$	0.033	$\pm 0.005$	$\pm 0.014$	0.278	$\pm 0.008$	$\pm 0.022$
55–80	0.563	$\pm 0.007$	$\pm 0.010$	0.031	$\pm 0.007$	$\pm 0.017$	0.447	$\pm 0.012$	$\pm 0.022$
80–120	0.716	$\pm 0.010$	$\pm 0.009$	0.029	$\pm 0.010$	$\pm 0.017$	0.583	$\pm 0.017$	$\pm 0.037$
120–200	0.834	$\pm 0.015$	$\pm 0.014$	0.002	$\pm 0.015$	$\pm 0.013$	0.741	$\pm 0.029$	$\pm 0.043$
>200	0.928	$\pm 0.035$	$\pm 0.015$	-0.020	$\pm 0.032$	$\pm 0.012$	0.689	$\pm 0.068$	$\pm 0.035$
$q_T$ [GeV]	$A_3$	$\pm\delta_{\text{stat}}$	$\pm\delta_{\text{syst}}$	$A_4$	$\pm\delta_{\text{stat}}$	$\pm\delta_{\text{syst}}$	$A_0 - A_2$	$\pm\delta_{\text{stat}}$	$\pm\delta_{\text{syst}}$
0–10	0.007	$\pm 0.002$	$\pm 0.004$	0.020	$\pm 0.002$	$\pm 0.002$	0.011	$\pm 0.005$	$\pm 0.009$
10–20	0.003	$\pm 0.002$	$\pm 0.003$	0.013	$\pm 0.003$	$\pm 0.002$	0.032	$\pm 0.006$	$\pm 0.011$
20–35	0.006	$\pm 0.003$	$\pm 0.003$	0.015	$\pm 0.003$	$\pm 0.003$	0.043	$\pm 0.007$	$\pm 0.016$
35–55	0.005	$\pm 0.004$	$\pm 0.005$	0.021	$\pm 0.004$	$\pm 0.004$	0.079	$\pm 0.010$	$\pm 0.018$
55–80	0.009	$\pm 0.006$	$\pm 0.006$	0.002	$\pm 0.006$	$\pm 0.004$	0.116	$\pm 0.014$	$\pm 0.022$
80–120	0.033	$\pm 0.008$	$\pm 0.010$	0.019	$\pm 0.008$	$\pm 0.005$	0.133	$\pm 0.019$	$\pm 0.032$
120–200	0.008	$\pm 0.014$	$\pm 0.010$	0.010	$\pm 0.012$	$\pm 0.007$	0.093	$\pm 0.031$	$\pm 0.031$
>200	0.101	$\pm 0.031$	$\pm 0.016$	0.029	$\pm 0.026$	$\pm 0.010$	0.239	$\pm 0.072$	$\pm 0.028$

**Table 2**

The five angular coefficients  $A_0$  to  $A_4$  and  $A_0 - A_2$  in bins of  $q_T$  for  $1 < |y| < 2.1$ .

$q_T$ [GeV]	$A_0$	$\pm\delta_{\text{stat}}$	$\pm\delta_{\text{syst}}$	$A_1$	$\pm\delta_{\text{stat}}$	$\pm\delta_{\text{syst}}$	$A_2$	$\pm\delta_{\text{stat}}$	$\pm\delta_{\text{syst}}$
0–10	0.032	$\pm 0.005$	$\pm 0.010$	0.002	$\pm 0.003$	$\pm 0.007$	0.019	$\pm 0.005$	$\pm 0.006$
10–20	0.077	$\pm 0.006$	$\pm 0.009$	0.018	$\pm 0.004$	$\pm 0.006$	0.038	$\pm 0.005$	$\pm 0.007$
20–35	0.179	$\pm 0.008$	$\pm 0.013$	0.038	$\pm 0.005$	$\pm 0.008$	0.129	$\pm 0.006$	$\pm 0.016$
35–55	0.385	$\pm 0.011$	$\pm 0.017$	0.063	$\pm 0.007$	$\pm 0.011$	0.260	$\pm 0.009$	$\pm 0.024$
55–80	0.554	$\pm 0.013$	$\pm 0.015$	0.066	$\pm 0.011$	$\pm 0.016$	0.448	$\pm 0.014$	$\pm 0.021$
80–120	0.737	$\pm 0.015$	$\pm 0.014$	0.059	$\pm 0.015$	$\pm 0.019$	0.587	$\pm 0.021$	$\pm 0.031$
120–200	0.860	$\pm 0.020$	$\pm 0.012$	0.064	$\pm 0.021$	$\pm 0.018$	0.758	$\pm 0.035$	$\pm 0.035$
>200	0.876	$\pm 0.045$	$\pm 0.020$	0.040	$\pm 0.044$	$\pm 0.020$	0.864	$\pm 0.087$	$\pm 0.041$
$q_T$ [GeV]	$A_3$	$\pm\delta_{\text{stat}}$	$\pm\delta_{\text{syst}}$	$A_4$	$\pm\delta_{\text{stat}}$	$\pm\delta_{\text{syst}}$	$A_0 - A_2$	$\pm\delta_{\text{stat}}$	$\pm\delta_{\text{syst}}$
0–10	0.009	$\pm 0.002$	$\pm 0.005$	0.076	$\pm 0.003$	$\pm 0.004$	0.013	$\pm 0.007$	$\pm 0.011$
10–20	0.003	$\pm 0.002$	$\pm 0.004$	0.072	$\pm 0.004$	$\pm 0.005$	0.039	$\pm 0.008$	$\pm 0.011$
20–35	0.012	$\pm 0.003$	$\pm 0.006$	0.044	$\pm 0.005$	$\pm 0.007$	0.051	$\pm 0.010$	$\pm 0.017$
35–55	0.012	$\pm 0.005$	$\pm 0.008$	0.052	$\pm 0.007$	$\pm 0.009$	0.124	$\pm 0.014$	$\pm 0.021$
55–80	0.036	$\pm 0.007$	$\pm 0.018$	0.052	$\pm 0.009$	$\pm 0.008$	0.106	$\pm 0.019$	$\pm 0.019$
80–120	0.074	$\pm 0.010$	$\pm 0.028$	0.074	$\pm 0.011$	$\pm 0.014$	0.150	$\pm 0.025$	$\pm 0.028$
120–200	0.121	$\pm 0.017$	$\pm 0.029$	0.056	$\pm 0.016$	$\pm 0.017$	0.102	$\pm 0.039$	$\pm 0.031$
>200	0.181	$\pm 0.041$	$\pm 0.027$	0.005	$\pm 0.034$	$\pm 0.017$	0.012	$\pm 0.090$	$\pm 0.039$

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: BMWF 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); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAIEK (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 Scientific and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; and the National Priorities Research Program by Qatar National Research Fund.

## References

- [1] J.C. Collins, D.E. Soper, Angular distribution of dileptons in high-energy hadron collisions, *Phys. Rev. D* 16 (1977) 2219, <http://dx.doi.org/10.1103/PhysRevD.16.2219>.
- [2] T. Aaltonen, et al., CDF Collaboration, First measurement of the angular coefficients of Drell-Yan  $e^+e^-$  pairs in the Z mass region from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV, *Phys. Rev. Lett.* 106 (2011) 241801, <http://dx.doi.org/10.1103/PhysRevLett.106.241801>, arXiv:1103.5699.
- [3] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, *J. High Energy Phys.* 11 (2004) 040, <http://dx.doi.org/10.1088/1126-6708/2004/11/040>, arXiv:hep-ph/0409146.
- [4] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, *J. High Energy Phys.* 11 (2007) 070, <http://dx.doi.org/10.1088/1126-6708/2007/11/070>, arXiv:0709.2092.
- [5] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, *J. High Energy Phys.* 06 (2010) 043, [http://dx.doi.org/10.1007/JHEP06\(2010\)043](http://dx.doi.org/10.1007/JHEP06(2010)043), arXiv:1002.2581.
- [6] S. Alioli, P. Nason, C. Oleari, E. Re, NLO vector-boson production matched with shower in POWHEG, *J. High Energy Phys.* 07 (2008) 060, <http://dx.doi.org/10.1088/1126-6708/2008/07/060>, arXiv:0805.4802.
- [7] J.C. Collins, Simple prediction of quantum chromodynamics for angular distribution of dileptons in hadron collisions, *Phys. Rev. Lett.* 42 (1979) 291, <http://dx.doi.org/10.1103/PhysRevLett.42.291>.
- [8] D. Boer, W. Vogelsang, Drell-Yan lepton angular distribution at small transverse momentum, *Phys. Rev. D* 74 (2006) 014004, <http://dx.doi.org/10.1103/PhysRevD.74.014004>, arXiv:hep-ph/0604177.
- [9] E.L. Berger, J.-W. Qiu, R.A. Rodriguez-Pedraza, Angular distribution of leptons from the decay of massive vector bosons, *Phys. Lett. B* 656 (2007) 74, <http://dx.doi.org/10.1016/j.physletb.2007.09.008>, arXiv:0707.3150.
- [10] A. Bodek, A simple event weighting technique for optimizing the measurement of the forward-backward asymmetry of Drell-Yan dilepton pairs at hadron colliders, *Eur. Phys. J. C* 67 (2010) 321, <http://dx.doi.org/10.1140/epjc/s10052-010-1287-5>, arXiv:0911.2850.
- [11] J. Lindfors, Angular distribution of large  $q_t$  muon pairs in different reference frames, *Phys. Scr.* 20 (1979) 19, <http://dx.doi.org/10.1088/0031-8949/20/1/003>.
- [12] C.S. Lam, W.-K. Tung, Structure function relations at large transverse momenta in lepton-pair production processes, *Phys. Lett. B* 80 (1979) 228, [http://dx.doi.org/10.1016/0370-2693\(79\)90204-1](http://dx.doi.org/10.1016/0370-2693(79)90204-1).
- [13] P. Faccioli, C. Lourenco, J. Seixas, Rotation-invariant relations in vector meson decays into fermion pairs, *Phys. Rev. Lett.* 105 (2010) 061601, <http://dx.doi.org/10.1103/PhysRevLett.105.061601>, arXiv:1005.2601.
- [14] P. Faccioli, C. Lourenco, J. Seixas, H.K. Woehri, Model-independent constraints on the shape parameters of dilepton angular distributions, *Phys. Rev. D* 83 (2011) 056008, <http://dx.doi.org/10.1103/PhysRevD.83.056008>, arXiv:1102.3946.
- [15] CMS Collaboration, Measurement of the polarization of W bosons with large transverse momenta in W + Jets events at the LHC, *Phys. Rev. Lett.* 107 (2011) 021802, <http://dx.doi.org/10.1103/PhysRevLett.107.021802>, arXiv:1104.3829.
- [16] ATLAS Collaboration, Measurement of the polarisation of W bosons produced with large transverse momentum in pp collisions at  $\sqrt{s} = 7$  TeV with the ATLAS experiment, *Eur. Phys. J. C* 72 (2012) 2001, <http://dx.doi.org/10.1140/epjc/s10052-012-2001-6>, arXiv:1203.2165.
- [17] Z. Bern, G. Diana, L.J. Dixon, F. Febres Cordero, D. Forde, T. Gleisberg, S. Höche, H. Ita, D.A. Kosower, D. Maître, K. Ozeren, Left-handed W bosons at the LHC, *Phys. Rev. D* 84 (2011) 034008, <http://dx.doi.org/10.1103/PhysRevD.84.034008>, arXiv:1103.5445.
- [18] R. Gavin, Y. Li, F. Petriello, S. Quackenbush, FEWZ 2.0: a code for hadronic Z production at next-to-next-to-leading order, *Comput. Phys. Commun.* 182 (2011) 2388, <http://dx.doi.org/10.1016/j.cpc.2011.06.008>, arXiv:1011.3540.
- [19] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, et al., The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* 07 (2014) 079, [http://dx.doi.org/10.1007/JHEP07\(2014\)079](http://dx.doi.org/10.1007/JHEP07(2014)079), arXiv:1405.0301.
- [20] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* 3 (2008) S08004, <http://dx.doi.org/10.1088/1748-0221/3/08/S08004>.
- [21] CMS Collaboration, Particle-flow event reconstruction in CMS and performance for jets, taus, and  $E_T^{\text{miss}}$ , CMS Physics Analysis Summary CMS-PAS-PFT-09-001, <http://cdsweb.cern.ch/record/1194487>, 2009.
- [22] 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), <http://cdsweb.cern.ch/record/1247373>.
- [23] T. Sjöstrand, S. Mrenna, P.Z. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* 05 (2006) 026, <http://dx.doi.org/10.1088/1126-6708/2006/05/026>, arXiv:hep-ph/0603175.
- [24] CMS Collaboration, Study of the underlying event at forward rapidity in pp collisions at  $\sqrt{s} = 0.9, 2.76,$  and  $7$  TeV, *J. High Energy Phys.* 04 (2013) 072, [http://dx.doi.org/10.1007/JHEP04\(2013\)072](http://dx.doi.org/10.1007/JHEP04(2013)072), arXiv:1302.2394.
- [25] J. Alwall, S. Höche, F. Krauss, N. Lavesson, L. Lönnblad, F. Maltoni, M.L. Mangano, M. Moretti, C.G. Papadopoulos, F. Piccinini, S. Schumann, M. Treccani, J. Winter, M. Worek, Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions, *Eur. Phys. J. C* 53 (2008) 473, <http://dx.doi.org/10.1140/epjc/s10052-007-0490-5>, arXiv:0706.2569.
- [26] J. Pumplin, D.R. Stump, J. Huston, H.-L. Lai, P. Nadolsky, W.-K. Tung, New generation of parton distributions with uncertainties from global QCD analysis, *J. High Energy Phys.* 07 (2002) 012, <http://dx.doi.org/10.1088/1126-6708/2002/07/012>, arXiv:hep-ph/0201195.
- [27] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P.M. Nadolsky, J. Pumplin, C.-P. Yuan, New parton distributions for collider physics, *Phys. Rev. D* 82 (2010) 074024, <http://dx.doi.org/10.1103/PhysRevD.82.074024>, arXiv:1007.2241.
- [28] S. Alioli, P. Nason, C. Oleari, E. Re, NLO single-top production matched with shower in POWHEG: s- and t-channel contributions, *J. High Energy Phys.* 09 (2009) 111, [http://dx.doi.org/10.1007/JHEP09\(2009\)111](http://dx.doi.org/10.1007/JHEP09(2009)111), arXiv:0907.4076.
- [29] E. Re, Single-top Wt-channel production matched with parton showers using the POWHEG method, *Eur. Phys. J. C* 71 (2011) 1547, <http://dx.doi.org/10.1140/epjc/s10052-011-1547-z>, arXiv:1009.2450.
- [30] M. Czakon, P. Fiedler, A. Mitov, Total top-quark pair-production cross section at hadron colliders through  $\mathcal{O}(\alpha_s^4)$ , *Phys. Rev. Lett.* 110 (2013) 252004, <http://dx.doi.org/10.1103/PhysRevLett.110.252004>, arXiv:1303.6254.
- [31] N. Kidonakis, Differential and total cross sections for top pair and single top production, in: XX Int. Workshop on Deep-Inelastic Scattering and Related Subjects, Bonn, Germany, 2012, p. 831, arXiv:1205.3453.
- [32] S. Agostinelli, et al., GEANT4 Collaboration, GEANT4: A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip.* 506 (2003) 250, [http://dx.doi.org/10.1016/S0168-9002\(03\)01368-8](http://dx.doi.org/10.1016/S0168-9002(03)01368-8).
- [33] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at  $\sqrt{s} = 7$  TeV, *J. Instrum.* 7 (2012) P10002, <http://dx.doi.org/10.1088/1748-0221/7/10/P10002>, arXiv:1206.4071.

- [34] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at  $\sqrt{s} = 8$  TeV, J. Instrum. 10 (2015) P06005, <http://dx.doi.org/10.1088/1748-0221/10/06/P06005>, arXiv:1502.02701.
- [35] A. Bodek, A. van Dyne, J.Y. Han, W. Sakumoto, A. Strelnikov, Extracting muon momentum scale corrections for hadron collider experiments, Eur. Phys. J. C 72 (2012) 2194, <http://dx.doi.org/10.1140/epjc/s10052-012-2194-8>, arXiv:1208.3710.
- [36] CMS Collaboration, Measurements of inclusive W and Z cross sections in pp collisions at  $\sqrt{s} = 7$  TeV, J. High Energy Phys. 01 (2011) 080, [http://dx.doi.org/10.1007/JHEP01\(2011\)080](http://dx.doi.org/10.1007/JHEP01(2011)080), arXiv:1012.2466.
- [37] E. Mirkes, J. Ohnemus, Angular distributions of Drell–Yan lepton pairs at the Fermilab Tevatron: order  $\alpha_s^2$  corrections and Monte Carlo studies, Phys. Rev. D 51 (1995) 4891, <http://dx.doi.org/10.1103/PhysRevD.51.4891>, arXiv: hep-ph/9412289.

## CMS Collaboration

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

*Yerevan Physics Institute, Yerevan, Armenia*

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

*Institut für Hochenergiephysik der OeAW, Wien, Austria*

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

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

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

*Universiteit Antwerpen, Antwerpen, Belgium*

F. Blekman, S. Blyweert, J. D’Hondt, N. Daci, N. Heracleous, J. Keaveney, S. Lowette, M. Maes, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Vilella

*Vrije Universiteit Brussel, Brussel, Belgium*

C. Caillol, B. Clerbaux, G. De Lentdecker, D. Dobur, G. Fasanella, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè<sup>2</sup>, A. Randle-conde, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang, F. Zenoni

*Université Libre de Bruxelles, Bruxelles, Belgium*

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Crucy, A. Fagot, G. Garcia, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, E. Yazgan, N. Zaganidis

*Ghent University, Ghent, Belgium*

S. Basegmez, C. Beluffi<sup>3</sup>, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco<sup>4</sup>, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrkowski, A. Popov<sup>5</sup>, L. Quertenmont, M. Selvaggi, M. Vidal Marono

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

N. Belyi, T. Caebergs, E. Daubie, G.H. Hammad

*Université de Mons, Mons, Belgium*

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, J. Molina, C. Mora Herrera, M.E. Pol, P. Rebello Teles

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



E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>6</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, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>6</sup>, A. Vilela Pereira

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

C.A. Bernardes<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>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>

<sup>a</sup> *Universidade Estadual Paulista, São Paulo, Brazil*

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

A. Aleksandrov, V. Genchev<sup>2</sup>, R. Hadjiiska, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

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

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

*University of Sofia, Sofia, Bulgaria*

J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina<sup>7</sup>, F. Romeo, J. Tao, Z. Wang

*Institute of High Energy Physics, Beijing, China*

C. Asawatangtrakuldee, Y. Ban, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, F. Zhang<sup>8</sup>, L. Zhang, W. Zou

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

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

*Universidad de Los Andes, Bogota, Colombia*

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

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

Z. Antunovic, M. Kovac

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

V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, L. Sudic

*Institute Rudjer Boskovic, Zagreb, Croatia*

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

*University of Cyprus, Nicosia, Cyprus*

M. Bodlak, M. Finger, M. Finger Jr.<sup>9</sup>

*Charles University, Prague, Czech Republic*

Y. Assran<sup>10</sup>, A. Ellithi Kamel<sup>11</sup>, M.A. Mahmoud<sup>12</sup>, A. Radi<sup>13,14</sup>

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

M. Kadastik, M. Murumaa, M. Raidal, A. Tiko

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

P. Eerola, M. Voutilainen

*Department of Physics, University of Helsinki, 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

*Helsinki Institute of Physics, Helsinki, Finland*

J. Talvitie, T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

M. Besancon, F. Couderc, M. Dejardin, 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, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

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

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

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

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

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

S. Gadrat

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

S. Beauceron, N. Beaupere, C. Bernet<sup>7</sup>, G. Boudoul<sup>2</sup>, E. Bouvier, S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo<sup>2</sup>, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, 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, H. Xiao

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

Z. Tsamalaidze<sup>9</sup>

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

C. Autermann, S. Beranek, M. Bontenackels, M. Edelhoff, L. Feld, A. Heister, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, H. Weber, B. Wittmer, V. Zhukov<sup>5</sup>

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

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, 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, H. Reithler, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Thüer

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

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

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

M. Aldaya Martin, I. Asin, N. Bartosik, J. Behr, U. Behrens, A.J. Bell, A. Bethani, K. Borrás, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, J. Garay Garcia, A. Geiser, A. Gizhko,

P. Gunnellini, J. Hauk, M. Hempel<sup>16</sup>, H. Jung, A. Kalogeropoulos, O. Karacheban<sup>16</sup>, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann<sup>16</sup>, R. Mankel, I. Marfin<sup>16</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, P.M. Ribeiro Cipriano, B. Roland, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

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

*University of Hamburg, Hamburg, Germany*

M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann<sup>2</sup>, T. Hauth, U. Husemann, I. Katkov<sup>5</sup>, A. Kornmayer<sup>2</sup>, P. Lobelle Pardo, M.U. Mozer, T. Müller, Th. Müller, A. Nürnberg, G. Quast, K. Rabbertz, S. Röcker, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, C. Wöhrmann, R. Wolf

*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

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

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

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

*University of Athens, Athens, Greece*

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

*University of Ioánnina, Ioánnina, Greece*

G. Bencze, C. Hajdu, P. Hidas, D. Horvath<sup>17</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>18</sup>, A.J. Zsigmond

*Wigner Research Centre for Physics, Budapest, Hungary*

N. Beni, S. Czellar, J. Karacsi<sup>19</sup>, J. Molnar, J. Palinkas, Z. Szillasi

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

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

*University of Debrecen, Debrecen, Hungary*

S.K. Swain

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

S.B. Beri, V. Bhatnagar, R. Gupta, U. Bhawandeep, A.K. Kalsi, M. Kaur, R. Kumar, M. Mittal, N. Nishu, J.B. Singh

*Panjab University, Chandigarh, India*

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma

*University of Delhi, Delhi, India*

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

*Saha Institute of Nuclear Physics, Kolkata, India*

A. Abdulsalam, D. Dutta, V. Kumar, A.K. Mohanty<sup>2</sup>, L.M. Pant, P. Shukla, A. Topkar

*Bhabha Atomic Research Centre, Mumbai, India*

T. Aziz, S. Banerjee, S. Bhowmik<sup>20</sup>, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu<sup>21</sup>, G. Kole, S. Kumar, M. Maity<sup>20</sup>, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage<sup>22</sup>

*Tata Institute of Fundamental Research, Mumbai, India*

S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami<sup>23</sup>, A. Fahim<sup>24</sup>, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>25</sup>, M. Zeinali

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

M. Felcini, M. Grunewald

*University College Dublin, Dublin, Ireland*

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, S.S. Chhibra<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>, 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,2</sup>, G. Selvaggi<sup>a,b</sup>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a,2</sup>, R. Venditti<sup>a,b</sup>, P. Verwilligen<sup>a</sup>

<sup>a</sup> INFN Sezione di Bari, Bari, Italy

<sup>b</sup> Università di Bari, Bari, Italy

<sup>c</sup> Politecnico di Bari, Bari, Italy

G. Abbiendi<sup>a</sup>, C. Battilana, 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>, 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>

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>b</sup> Università di Bologna, Bologna, Italy

S. Albergo<sup>a,b</sup>, G. Cappello<sup>a</sup>, M. Chiorboli<sup>a,b</sup>, S. Costa<sup>a,b</sup>, F. Giordano<sup>a,2</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy

<sup>b</sup> Università di Catania, Catania, Italy

<sup>c</sup> CSFNSM, Catania, 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>, E. Gallo<sup>a</sup>, S. Gonzi<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>

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>b</sup> Università di Firenze, Firenze, Italy

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

*INFN Laboratori Nazionali di Frascati, Frascati, Italy*

F. Ferro <sup>a</sup>, M. Lo Vetere <sup>a,b</sup>, E. Robutti <sup>a</sup>, S. Tosi <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Genova, Genova, Italy

<sup>b</sup> Università di Genova, Genova, Italy

M.E. Dinardo <sup>a,b</sup>, S. Fiorendi <sup>a,b</sup>, S. Gennai <sup>a,2</sup>, R. Gerosa <sup>a,b,2</sup>, A. Ghezzi <sup>a,b</sup>, P. Govoni <sup>a,b</sup>, M.T. Lucchini <sup>a,b,2</sup>, S. Malvezzi <sup>a</sup>, R.A. Manzoni <sup>a,b</sup>, A. Martelli <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>

<sup>a</sup> INFN Sezione di Milano-Bicocca, Milano, Italy

<sup>b</sup> Università di Milano-Bicocca, Milano, Italy

S. Buontempo <sup>a</sup>, N. Cavallo <sup>a,c</sup>, S. Di Guida <sup>a,d,2</sup>, F. Fabozzi <sup>a,c</sup>, A.O.M. Iorio <sup>a,b</sup>, L. Lista <sup>a</sup>, S. Meola <sup>a,d,2</sup>, M. Merola <sup>a</sup>, P. Paolucci <sup>a,2</sup>

<sup>a</sup> INFN Sezione di Napoli, Napoli, Italy

<sup>b</sup> Università di Napoli 'Federico II', Napoli, Italy

<sup>c</sup> Università della Basilicata, Potenza, Italy

<sup>d</sup> Università G. Marconi, Roma, Italy

P. Azzi <sup>a</sup>, N. Bacchetta <sup>a</sup>, D. Bisello <sup>a,b</sup>, R. Carlin <sup>a,b</sup>, P. Checchia <sup>a</sup>, M. Dall'Osso <sup>a,b</sup>, T. Dorigo <sup>a</sup>, U. Dosselli <sup>a</sup>, F. Gasparini <sup>a,b</sup>, U. Gasparini <sup>a,b</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>, M. Passaseo <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>, P. Zotto <sup>a,b</sup>, A. Zucchetta <sup>a,b</sup>, G. Zumerle <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Padova, Padova, Italy

<sup>b</sup> Università di Padova, Padova, Italy

<sup>c</sup> Università di Trento, Trento, Italy

M. Gabusi <sup>a,b</sup>, A. Magnani <sup>a</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>

<sup>a</sup> INFN Sezione di Pavia, Pavia, Italy

<sup>b</sup> Università di Pavia, Pavia, Italy

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>, A. Spiezia <sup>a,b,2</sup>

<sup>a</sup> INFN Sezione di Perugia, Perugia, Italy

<sup>b</sup> Università di Perugia, Perugia, Italy

K. Androsov <sup>a,26</sup>, P. Azzurri <sup>a</sup>, G. Bagliesi <sup>a</sup>, J. Bernardini <sup>a</sup>, T. Boccali <sup>a</sup>, G. Broccolo <sup>a,c</sup>, R. Castaldi <sup>a</sup>, M.A. Ciocci <sup>a,26</sup>, R. Dell'Orso <sup>a</sup>, S. Donato <sup>a,c,2</sup>, G. Fedi, F. Fiori <sup>a,c</sup>, L. Foà <sup>a,c</sup>, A. Giassi <sup>a</sup>, M.T. Grippo <sup>a,26</sup>, F. Ligabue <sup>a,c</sup>, T. Lomtadze <sup>a</sup>, L. Martini <sup>a,b</sup>, A. Messineo <sup>a,b</sup>, C.S. Moon <sup>a,27</sup>, F. Palla <sup>a</sup>, A. Rizzi <sup>a,b</sup>, A. Savoy-Navarro <sup>a,28</sup>, A.T. Serban <sup>a</sup>, P. Spagnolo <sup>a</sup>, P. Squillacioti <sup>a,26</sup>, R. Tenchini <sup>a</sup>, G. Tonelli <sup>a,b</sup>, A. Venturi <sup>a</sup>, P.G. Verdini <sup>a</sup>

<sup>a</sup> INFN Sezione di Pisa, Pisa, Italy

<sup>b</sup> Università di Pisa, Pisa, Italy

<sup>c</sup> Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone <sup>a,b</sup>, F. Cavallari <sup>a</sup>, G. D'imperio <sup>a,b</sup>, D. Del Re <sup>a,b</sup>, M. Diemoz <sup>a</sup>, C. Jorda <sup>a</sup>, E. Longo <sup>a,b</sup>, F. Margaroli <sup>a,b</sup>, P. Meridiani <sup>a</sup>, F. Micheli <sup>a,b,2</sup>, G. Organtini <sup>a,b</sup>, R. Paramatti <sup>a</sup>, S. Rahatlou <sup>a,b</sup>, C. Rovelli <sup>a</sup>, F. Santanastasio <sup>a,b</sup>, L. Soffi <sup>a,b</sup>, P. Traczyk <sup>a,b,2</sup>

<sup>a</sup> INFN Sezione di Roma, Roma, Italy

<sup>b</sup> Università di Roma, Roma, Italy

N. Amapane <sup>a,b</sup>, R. Arcidiacono <sup>a,c</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>, S. Casasso <sup>a,b,2</sup>, M. Costa <sup>a,b</sup>, R. Covarelli, A. Degano <sup>a,b</sup>, N. Demaria <sup>a</sup>, L. Finco <sup>a,b,2</sup>, C. Mariotti <sup>a</sup>, S. Maselli <sup>a</sup>, G. Mazza <sup>a</sup>, E. Migliore <sup>a,b</sup>, V. Monaco <sup>a,b</sup>, M. Musich <sup>a</sup>, M.M. Obertino <sup>a,c</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>, 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>

<sup>a</sup> INFN Sezione di Torino, Torino, Italy

<sup>b</sup> Università di Torino, Torino, Italy

<sup>c</sup> Università del Piemonte Orientale, Novara, 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>, T. Umer <sup>a,b</sup>, A. Zanetti <sup>a</sup>

<sup>a</sup> INFN Sezione di Trieste, Trieste, Italy

<sup>b</sup> Università di Trieste, Trieste, Italy

S. Chang, A. Kropivnitskaya, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

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

Kyungpook National University, Daegu, Republic of Korea

T.J. Kim, M.S. Ryu

Chonbuk National University, Jeonju, Republic of Korea

J.Y. Kim, D.H. Moon, S. Song

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

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

Korea University, Seoul, Republic of Korea

H.D. Yoo

Seoul National University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

A. Juodagalvis

Vilnius University, Vilnius, Lithuania

J.R. Komaragiri, M.A.B. Md Ali <sup>29</sup>, W.A.T. Wan Abdullah

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

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

I. Pedraza, H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler, S. Reucroft

*University of Canterbury, Christchurch, New Zealand*

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

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

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

*National Centre for Nuclear Research, Swierk, Poland*

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

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

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

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

P. Bunin, M. Gavrilenko, I. Golutvin, A. Kamenev, V. Karjavin, V. Konoplyanikov, V. Korenkov, A. Lanev,  
A. Malakhov, V. Matveev<sup>30</sup>, V.V. Mitsyn, P. Moiseenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov,  
E. Tikhonenko, A. Zarubin

*Joint Institute for Nuclear Research, Dubna, Russia*

V. Golovtsov, Y. Ivanov, V. Kim<sup>31</sup>, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov,  
V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

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

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

*Institute for Nuclear Research, Moscow, Russia*

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

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

V. Andreev, M. Azarkin<sup>32</sup>, I. Dremin<sup>32</sup>, M. Kirakosyan, A. Leonidov<sup>32</sup>, G. Mesyats, S.V. Rusakov,  
A. Vinogradov

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

A. Belyaev, E. Boos, M. Dubinin<sup>33</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin,  
S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

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

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

P. Adzic<sup>34</sup>, M. Ekmedzic, J. Milosevic, V. Rekoic

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

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, M.S. Soares

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

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

*Universidad Autónoma de Madrid, Madrid, Spain*

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

*Universidad de Oviedo, Oviedo, Spain*

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, 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, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi<sup>35</sup>, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, B. Dorney, N. Dupont-Sagorin, 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, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, S. Orfanelli, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pimià, D. Piparo, M. Plagge, A. Racz, G. Rolandi<sup>36</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas<sup>37</sup>, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsiros, G.I. Veres<sup>18</sup>, N. Wardle, H.K. Wöhri, H. Wollny, W.D. Zeuner

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

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

*Paul Scherrer Institut, Villigen, Switzerland*

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, J. Hoss, G. Kasieczka, W. Luster mann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, N. Mohr, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, L. Rebane, M. Rossini, A. Starodumov<sup>38</sup>, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

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

C. Amsler<sup>39</sup>, M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, S. Taroni, Y. Yang

*Universität Zürich, Zurich, Switzerland*

M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

*National Central University, Chung-Li, Taiwan*



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

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

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

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

A. Adiguzel, M.N. Bakirci<sup>40</sup>, S. Cerci<sup>41</sup>, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal<sup>42</sup>, A. Kayis Topaksu, G. Onengut<sup>43</sup>, K. Ozdemir<sup>44</sup>, S. Ozturk<sup>40</sup>, A. Polatoz, D. Sunar Cerci<sup>41</sup>, B. Tali<sup>41</sup>, H. Topakli<sup>40</sup>, M. Vergili, C. Zorbilmez

*Cukurova University, Adana, Turkey*

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan<sup>45</sup>, B. Isildak<sup>46</sup>, G. Karapinar<sup>47</sup>, K. Ocalan<sup>48</sup>, S. Sekmen, U.E. Surat, M. Yalvac, M. Zeyrek

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

E.A. Albayrak<sup>49</sup>, E. Gülmez, M. Kaya<sup>50</sup>, O. Kaya<sup>51</sup>, T. Yetkin<sup>52</sup>

*Bogazici University, Istanbul, Turkey*

K. Cankocak, F.I. Vardarli

*Istanbul Technical University, Istanbul, Turkey*

L. Levchuk, P. Sorokin

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

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>53</sup>, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, V.J. Smith

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>54</sup>, C. Brew, R.M. Brown, 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

*Rutherford Appleton Laboratory, Didcot, United Kingdom*

M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, 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. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas<sup>53</sup>, L. Lyons, A.-M. Magnan, S. Malik, B. Mathias, J. Nash, A. Nikitenko<sup>38</sup>, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp<sup>†</sup>, A. Tapper, M. Vazquez Acosta, T. Virdee, S.C. Zenz

*Imperial College, London, United Kingdom*

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

*Brunel University, Uxbridge, United Kingdom*

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika, T. Scarborough, Z. Wu

*Baylor University, Waco, USA*

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

*The University of Alabama, Tuscaloosa, USA*

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

*Boston University, Boston, USA*

J. Alimena, E. Berry, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, N. Dhir, A. Ferapontov, A. Garabedian, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Sagir, T. Sinthuprasith, T. Speer, J. Swanson

*Brown University, Providence, 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, Davis, Davis, USA*

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

*University of California, Los Angeles, USA*

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Iova Rikova, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, S. Sumowidagdo, S. Wimpenny

*University of California, Riverside, Riverside, USA*

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, Y. Tu, A. Vartak, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

D. Barge, J. Bradmiller-Feld, C. Campagnari, T. Danielson, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, W. To, C. West, J. Yoo

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

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

*California Institute of Technology, Pasadena, USA*

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

*Carnegie Mellon University, Pittsburgh, USA*

J.P. Cumalat, W.T. Ford, A. Gaz, M. Krohn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, S.R. Wagner

*University of Colorado at Boulder, Boulder, USA*

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

*Cornell University, Ithaca, USA*

D. Winn

*Fairfield University, Fairfield, USA*

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, 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, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Kwan<sup>†</sup>, 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, O. Prokofyev, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang

*Fermi National Accelerator Laboratory, Batavia, USA*

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, M. Carver, D. Curry, S. Das, M. De Gruttola, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, K. Matchev, H. Mei, P. Milenov<sup>55</sup>, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, M. Snowball, D. Sperka, J. Yelton

*University of Florida, Gainesville, USA*

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

*Florida International University, Miami, USA*

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

*Florida State University, Tallahassee, USA*

M.M. Baarmand, M. Hohlmann, H. Kalakhety, F. Yumiceva

*Florida Institute of Technology, Melbourne, 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, M. Zakaria

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

B. Bilki<sup>56</sup>, W. Clarida, K. Dilsiz, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>57</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>49</sup>, A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, K. Yi

*The University of Iowa, Iowa City, USA*

I. Anderson, B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, M. Swartz, M. Xiao

*Johns Hopkins University, Baltimore, USA*

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

*The University of Kansas, Lawrence, USA*

I. Chakaberia, A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, N. Skhirtladze, I. Svintradze

*Kansas State University, Manhattan, USA*

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, USA*

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

*University of Maryland, College Park, USA*

A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, D. Velicanu, J. Veverka, T.W. Wang, B. Wyslouch, M. Yang, M. Zanetti, V. Zhukova

*Massachusetts Institute of Technology, Cambridge, USA*

B. Dahmes, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, S. Nourbakhsh, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz

*University of Minnesota, Minneapolis, USA*

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, USA*

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

*University of Nebraska-Lincoln, Lincoln, USA*

J. Dolen, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S. Rappoccio

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

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

*Northeastern University, Boston, USA*

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

*Northwestern University, Evanston, USA*

A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>30</sup>, T. Pearson, M. Planer, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

*University of Notre Dame, Notre Dame, USA*

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

*The Ohio State University, Columbus, USA*

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland<sup>2</sup>, C. Tully, J.S. Werner, A. Zuranski

*Princeton University, Princeton, USA*

E. Brownson, S. Malik, H. Mendez, J.E. Ramirez Vargas

*University of Puerto Rico, Mayaguez, USA*

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

*Purdue University, West Lafayette, USA*

N. Parashar, J. Stupak

*Purdue University Calumet, Hammond, USA*

A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B. Michlin, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

*Rice University, Houston, USA*

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

*University of Rochester, Rochester, USA*

R. Ciesielski, L. Demortier, K. Goulios, C. Mesropian

*The Rockefeller University, New York, USA*

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

K. Rose, S. Spanier, A. York

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>58</sup>, A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>59</sup>, V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, I. Suarez, A. Tatarinov, K.A. Ulmer

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

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

*Texas Tech University, Lubbock, USA*

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

*Vanderbilt University, Nashville, USA*

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, E. Wolfe, J. Wood

*University of Virginia, Charlottesville, USA*

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

*Wayne State University, Detroit, USA*

D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, E. Friis, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, C. Lazaridis, A. Levine, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, D. Taylor, C. Vuosalo, N. Woods

*University of Wisconsin, Madison, USA*

<sup>†</sup> Deceased.

<sup>1</sup> Also at Vienna University of Technology, Vienna, Austria.

<sup>2</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

- <sup>3</sup> Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
- <sup>4</sup> Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.
- <sup>5</sup> Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
- <sup>6</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil.
- <sup>7</sup> Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.
- <sup>8</sup> Also at Université Libre de Bruxelles, Bruxelles, Belgium.
- <sup>9</sup> Also at Joint Institute for Nuclear Research, Dubna, Russia.
- <sup>10</sup> Also at Suez University, Suez, Egypt.
- <sup>11</sup> Also at Cairo University, Cairo, Egypt.
- <sup>12</sup> Also at Fayoum University, El-Fayoum, Egypt.
- <sup>13</sup> Also at British University in Egypt, Cairo, Egypt.
- <sup>14</sup> Now at Ain Shams University, Cairo, Egypt.
- <sup>15</sup> Also at Université de Haute Alsace, Mulhouse, France.
- <sup>16</sup> Also at Brandenburg University of Technology, Cottbus, Germany.
- <sup>17</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- <sup>18</sup> Also at Eötvös Loránd University, Budapest, Hungary.
- <sup>19</sup> Also at University of Debrecen, Debrecen, Hungary.
- <sup>20</sup> Also at University of Visva-Bharati, Santiniketan, India.
- <sup>21</sup> Now at King Abdulaziz University, Jeddah, Saudi Arabia.
- <sup>22</sup> Also at University of Ruhuna, Matara, Sri Lanka.
- <sup>23</sup> Also at Isfahan University of Technology, Isfahan, Iran.
- <sup>24</sup> Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
- <sup>25</sup> Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- <sup>26</sup> Also at Università degli Studi di Siena, Siena, Italy.
- <sup>27</sup> Also at Centre National de la Recherche Scientifique (CNRS)–IN2P3, Paris, France.
- <sup>28</sup> Also at Purdue University, West Lafayette, USA.
- <sup>29</sup> Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- <sup>30</sup> Also at Institute for Nuclear Research, Moscow, Russia.
- <sup>31</sup> Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- <sup>32</sup> Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- <sup>33</sup> Also at California Institute of Technology, Pasadena, USA.
- <sup>34</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- <sup>35</sup> Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- <sup>36</sup> Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- <sup>37</sup> Also at University of Athens, Athens, Greece.
- <sup>38</sup> Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- <sup>39</sup> Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- <sup>40</sup> Also at Gaziosmanpasa University, Tokat, Turkey.
- <sup>41</sup> Also at Adiyaman University, Adiyaman, Turkey.
- <sup>42</sup> Also at Mersin University, Mersin, Turkey.
- <sup>43</sup> Also at Cag University, Mersin, Turkey.
- <sup>44</sup> Also at Piri Reis University, Istanbul, Turkey.
- <sup>45</sup> Also at Anadolu University, Eskisehir, Turkey.
- <sup>46</sup> Also at Ozyegin University, Istanbul, Turkey.
- <sup>47</sup> Also at Izmir Institute of Technology, Izmir, Turkey.
- <sup>48</sup> Also at Necmettin Erbakan University, Konya, Turkey.
- <sup>49</sup> Also at Mimar Sinan University, Istanbul, Turkey.
- <sup>50</sup> Also at Marmara University, Istanbul, Turkey.
- <sup>51</sup> Also at Kafkas University, Kars, Turkey.
- <sup>52</sup> Also at Yildiz Technical University, Istanbul, Turkey.
- <sup>53</sup> Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- <sup>54</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- <sup>55</sup> Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- <sup>56</sup> Also at Argonne National Laboratory, Argonne, USA.
- <sup>57</sup> Also at Erzincan University, Erzincan, Turkey.
- <sup>58</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>59</sup> Also at Kyungpook National University, Daegu, Korea.