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Khachatryan, V.

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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

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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 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.

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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, θ^* and ϕ^* 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 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.

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, 4.3×10^6

events with Z boson candidates remain for $|y| < 1.0$ and 2.5×10^6 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 η since the p_T dependence is weak. The trigger efficiency is determined in bins of p_T and η , separately for μ^+ and μ^- . The identification efficiency is measured in bins of p_T and η . 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 ϕ^* . The efficiency of the isolation requirement for the leading muon is measured as a function of p_T and η 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 ϕ^* , 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 ($\cos\theta^*$, ϕ^*) 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 ϕ^* , the absolute value $|\phi^*|$ is used. The fit is made in 12×12 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.

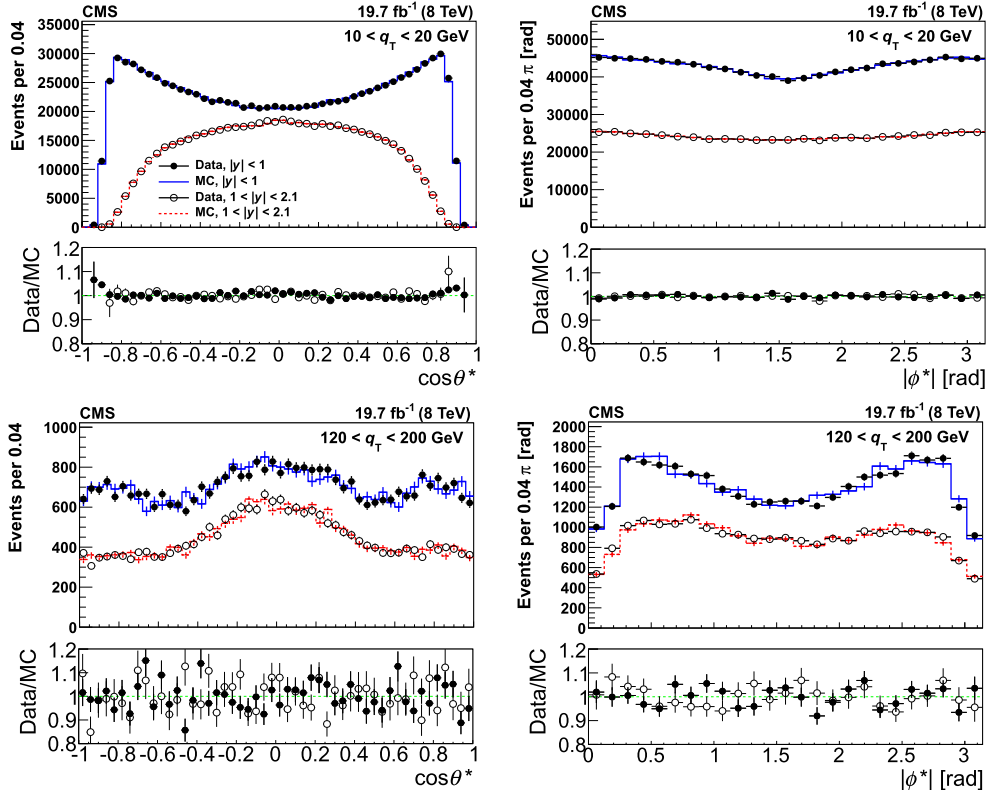


Fig. 1. A few examples of the observed 1D angular distributions in $\cos\theta^*$ (left) and $|\phi^*|$ (right) compared to the MC simulation using the best fit values of the angular coefficients. The top (bottom) plots show the distributions for $10 < q_T < 20$ GeV ($120 < q_T < 200$ GeV), a region 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

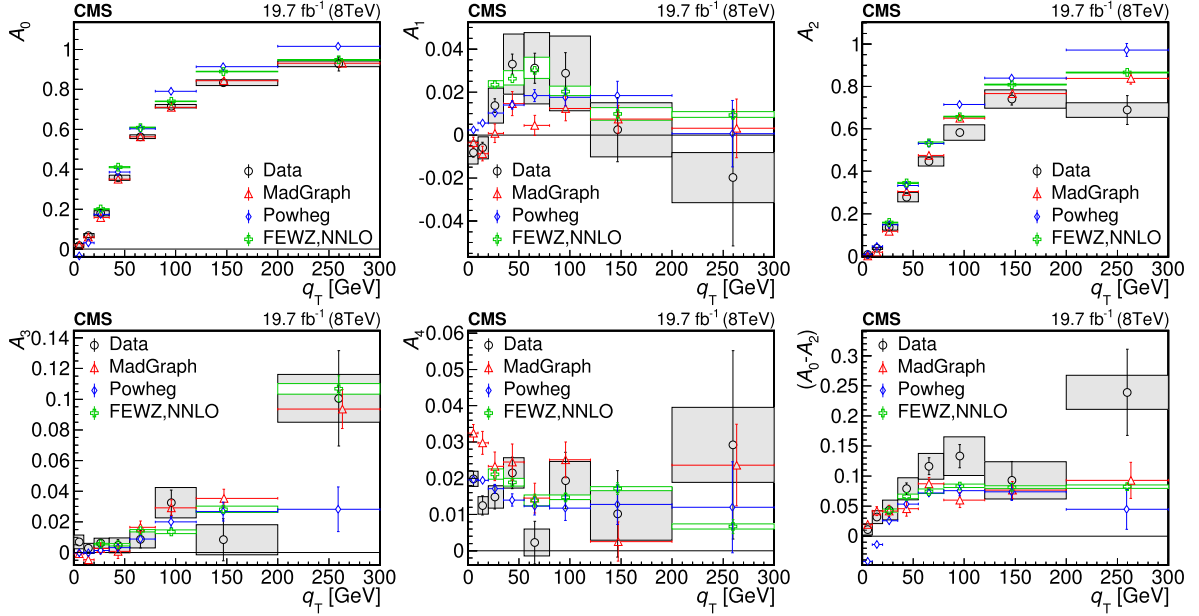


Fig. 2. Comparison of the five angular coefficients A_i and $A_0 - A_2$ measured in the Collins–Soper frame in bins of q_T for $|y| < 1$. The circles show the measured results. The vertical bars represent the statistical uncertainties and the boxes the systematic uncertainties of the measurement. The 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.

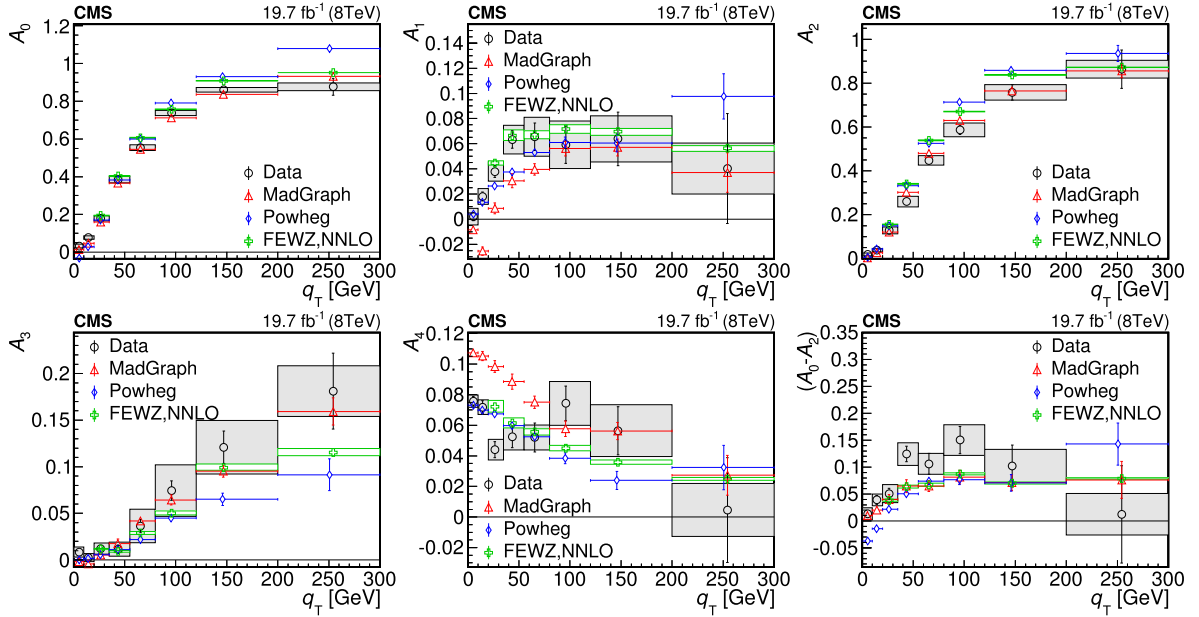


Fig. 3. Comparison of the five angular coefficients and $A_0 - A_2$ under the same conditions as Fig. 2, for the rapidity bin $1 < |y| < 2.1$.

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.

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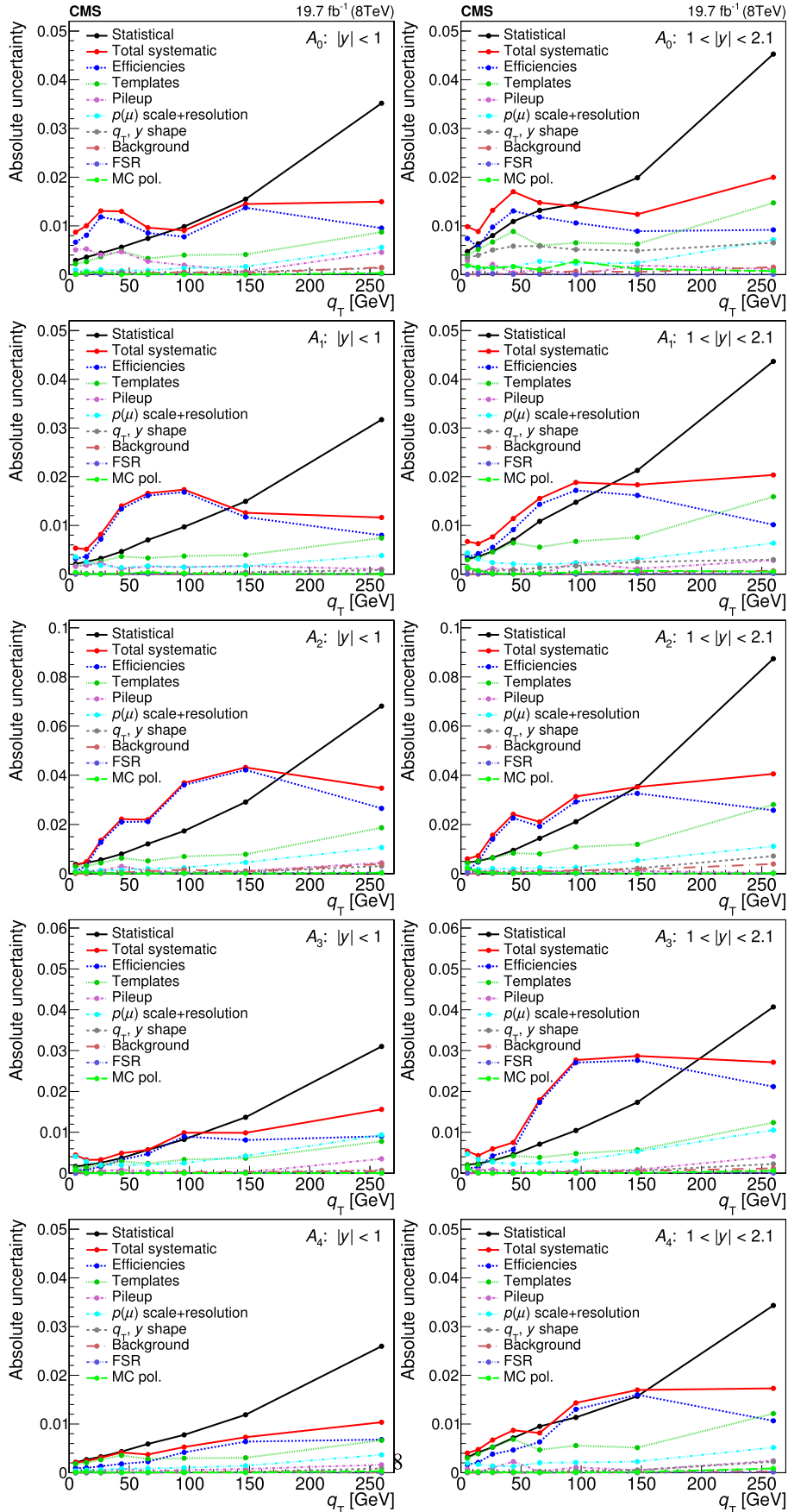


Fig. 4. Absolute uncertainties in the five angular coefficients A_0 to A_4 . Each figure shows the q_T dependence in the indicated ranges of $|\eta|$.

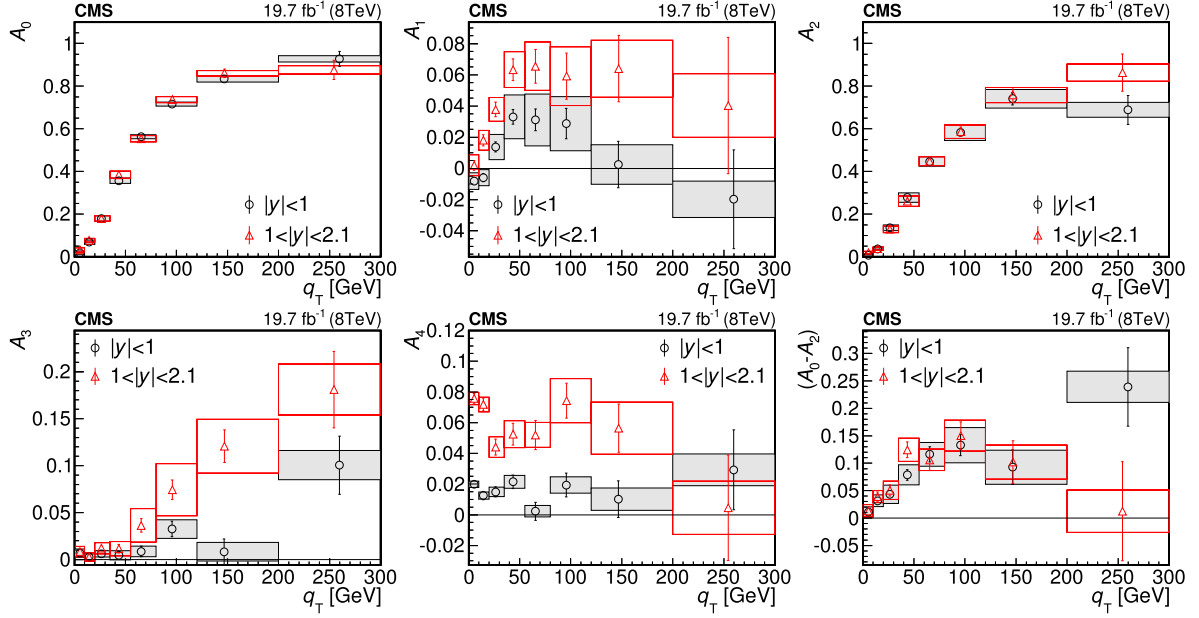


Fig. 5. Comparison of the five angular coefficients A_i and $A_0 - A_2$ measured in the Collins-Soper frame in bins of q_T between $|y| < 1$ (circles) and $1 < |y| < 2.1$ (triangles). The vertical bars represent the statistical uncertainties and the boxes the systematic uncertainties of the measurement.

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	± 0.003	± 0.009	-0.008	± 0.002	± 0.005	0.007	± 0.004	± 0.003
10–20	0.068	± 0.004	± 0.010	-0.006	± 0.003	± 0.005	0.037	± 0.004	± 0.005
20–35	0.179	± 0.004	± 0.013	0.014	± 0.003	± 0.008	0.136	± 0.006	± 0.014
35–55	0.357	± 0.006	± 0.013	0.033	± 0.005	± 0.014	0.278	± 0.008	± 0.022
55–80	0.563	± 0.007	± 0.010	0.031	± 0.007	± 0.017	0.447	± 0.012	± 0.022
80–120	0.716	± 0.010	± 0.009	0.029	± 0.010	± 0.017	0.583	± 0.017	± 0.037
120–200	0.834	± 0.015	± 0.014	0.002	± 0.015	± 0.013	0.741	± 0.029	± 0.043
>200	0.928	± 0.035	± 0.015	-0.020	± 0.032	± 0.012	0.689	± 0.068	± 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	± 0.002	± 0.004	0.020	± 0.002	± 0.002	0.011	± 0.005	± 0.009
10–20	0.003	± 0.002	± 0.003	0.013	± 0.003	± 0.002	0.032	± 0.006	± 0.011
20–35	0.006	± 0.003	± 0.003	0.015	± 0.003	± 0.003	0.043	± 0.007	± 0.016
35–55	0.005	± 0.004	± 0.005	0.021	± 0.004	± 0.004	0.079	± 0.010	± 0.018
55–80	0.009	± 0.006	± 0.006	0.002	± 0.006	± 0.004	0.116	± 0.014	± 0.022
80–120	0.033	± 0.008	± 0.010	0.019	± 0.008	± 0.005	0.133	± 0.019	± 0.032
120–200	0.008	± 0.014	± 0.010	0.010	± 0.012	± 0.007	0.093	± 0.031	± 0.031
>200	0.101	± 0.031	± 0.016	0.029	± 0.026	± 0.010	0.239	± 0.072	± 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	± 0.005	± 0.010	0.002	± 0.003	± 0.007	0.019	± 0.005	± 0.006
10–20	0.077	± 0.006	± 0.009	0.018	± 0.004	± 0.006	0.038	± 0.005	± 0.007
20–35	0.179	± 0.008	± 0.013	0.038	± 0.005	± 0.008	0.129	± 0.006	± 0.016
35–55	0.385	± 0.011	± 0.017	0.063	± 0.007	± 0.011	0.260	± 0.009	± 0.024
55–80	0.554	± 0.013	± 0.015	0.066	± 0.011	± 0.016	0.448	± 0.014	± 0.021
80–120	0.737	± 0.015	± 0.014	0.059	± 0.015	± 0.019	0.587	± 0.021	± 0.031
120–200	0.860	± 0.020	± 0.012	0.064	± 0.021	± 0.018	0.758	± 0.035	± 0.035
>200	0.876	± 0.045	± 0.020	0.040	± 0.044	± 0.020	0.864	± 0.087	± 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	± 0.002	± 0.005	0.076	± 0.003	± 0.004	0.013	± 0.007	± 0.011
10–20	0.003	± 0.002	± 0.004	0.072	± 0.004	± 0.005	0.039	± 0.008	± 0.011
20–35	0.012	± 0.003	± 0.006	0.044	± 0.005	± 0.007	0.051	± 0.010	± 0.017
35–55	0.012	± 0.005	± 0.008	0.052	± 0.007	± 0.009	0.124	± 0.014	± 0.021
55–80	0.036	± 0.007	± 0.018	0.052	± 0.009	± 0.008	0.106	± 0.019	± 0.019
80–120	0.074	± 0.010	± 0.028	0.074	± 0.011	± 0.014	0.150	± 0.025	± 0.028
120–200	0.121	± 0.017	± 0.029	0.056	± 0.016	± 0.017	0.102	± 0.039	± 0.031
>200	0.181	± 0.041	± 0.027	0.005	± 0.034	± 0.017	0.012	± 0.090	± 0.039

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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. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady², B. Rahbaran, H. Rohringer, J. Schieck, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

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. Villella

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. Perniè², 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. Beluffi³, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco⁴, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrkowski, A. Popov⁵, 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. Chinellato⁶, 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 Manganote⁶, A. Vilela Pereira

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

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

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

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

A. Aleksandrov, V. Genchev², 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. Plestina⁷, 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. Zhang⁸, 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.⁹

Charles University, Prague, Czech Republic

Y. Assran¹⁰, A. Ellithi Kamel¹¹, M.A. Mahmoud¹², A. Radi^{13,14}

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. Agram¹⁵, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹⁵, J.-C. Fontaine¹⁵, 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. Bernet⁷, G. Boudoul², E. Bouvier, S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo², 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. Tsamalaidze⁹

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. Zhukov⁵

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. Lingemann², 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. Borras, 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. Hempel¹⁶, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁶, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁶, R. Mankel, I. Marfin¹⁶, 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. Hartmann², T. Hauth, U. Husemann, I. Katkov⁵, A. Kornmayer², 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. Horvath¹⁷, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁸, A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karacsi¹⁹, 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. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik²⁰, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu²¹, G. Kole, S. Kumar, M. Maity²⁰, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage²²

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. Etesami²³, A. Fahim²⁴, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh²⁵, M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, C. Calabria^{a,b}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, S. My^{a,c}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b,2}, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,2}, R. Venditti^{a,b}, P. Verwilligen^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b}, R. Travaglini^{a,b}

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b}, G. Cappello^a, M. Chiorboli^{a,b}, S. Costa^{a,b}, F. Giordano^{a,2}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

^c CSFNSM, Catania, Italy

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

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

F. Ferro^a, M. Lo Vetere^{a,b}, E. Robutti^a, S. Tosi^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^{a,2}, R. Gerosa^{a,b,2}, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M.T. Lucchini^{a,b,2}, S. Malvezzi^a, R.A. Manzoni^{a,b}, A. Martelli^{a,b}, B. Marzocchi^{a,b,2}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, T. Tabarelli de Fatis^{a,b}

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

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,2}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,d,2}, M. Merola^a, P. Paolucci^{a,2}

^a INFN Sezione di Napoli, Napoli, Italy

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

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, R. Carlin^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, F. Montecassiano^a, M. Passaseo^a, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, P. Zotto^{a,b}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, Italy

M. Gabusi^{a,b}, A. Magnani^a, S.P. Ratti^{a,b}, V. Re^a, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^a, P. Vitulo^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b,2}, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b,2}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

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

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

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

^a INFN Sezione di Roma, Roma, Italy

^b Università di Roma, Roma, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, S. Casasso^{a,b,2}, M. Costa^{a,b}, R. Covarelli, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b,2}, C. Mariotti^a, S. Maselli^a, G. Mazza^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^a, M.M. Obertino^{a,c}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a, U. Tamponi^a

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

S. Belforte ^a, V. Candelise ^{a,b,2}, M. Casarsa ^a, F. Cossutti ^a, G. Della Ricca ^{a,b}, B. Gobbo ^a, C. La Licata ^{a,b},
M. Marone ^{a,b}, A. Schizzi ^{a,b}, T. Umer ^{a,b}, A. Zanetti ^a

^a INFN Sezione di Trieste, Trieste, Italy

^b 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 ²⁹, 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. Matveev³⁰, 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. Kim³¹, 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. Azarkin³², I. Dremin³², M. Kirakosyan, A. Leonidov³², G. Mesyats, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin³³, 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. Adzic³⁴, M. Ekmedzic, J. Milosevic, V. Rekoivic

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. Colafranceschi³⁵, 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. Rolandi³⁶, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁷, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsiros, G.I. Veres¹⁸, 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. Lustermann, 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. Starodumov³⁸, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler³⁹, 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. Bakirci⁴⁰, S. Cerci⁴¹, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal⁴², A. Kayis Topaksu, G. Onengut⁴³, K. Ozdemir⁴⁴, S. Ozturk⁴⁰, A. Polatoz, D. Sunar Cerci⁴¹, B. Tali⁴¹, H. Topakli⁴⁰, M. Vergili, C. Zorbilmez

Cukurova University, Adana, Turkey

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan⁴⁵, B. Isildak⁴⁶, G. Karapinar⁴⁷, K. Ocalan⁴⁸, S. Sekmen, U.E. Surat, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E.A. Albayrak⁴⁹, E. Gülmez, M. Kaya⁵⁰, O. Kaya⁵¹, T. Yetkin⁵²

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. Newbold⁵³, 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. Belyaev⁵⁴, 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. Lucas⁵³, L. Lyons, A.-M. Magnan, S. Malik, B. Mathias, J. Nash, A. Nikitenko³⁸, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp[†], 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. Dhingra, 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[†], 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. Milenov⁵⁵, 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. Bilki⁵⁶, W. Clarida, K. Dilsiz, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁵⁷, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁴⁹, 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. Musienko³⁰, 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. Stickland², 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. Bouhali⁵⁸, A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁹, 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

[†] Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

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