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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

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A B S T R A C T

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.

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

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

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$\overline{\text{p}}$ interactions for q_T up to 55 GeV [2]. The angular coefficients in pp collisions are expected to differ from those in p$\overline{\text{p}}$ collisions for several reasons. For p$\overline{\text{p}}$ collisions, the Z boson production occurs predominantly via the q$\overline{\text{q}}$ annihilation process, whilst the contribution of the qg Compton process is larger in pp collisions than p$\overline{\text{p}}$ 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 ∼80% at $q_T > 100$ GeV. For the q$\overline{\text{q}}$ 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

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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 ~0.1% at low q_T to ~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.

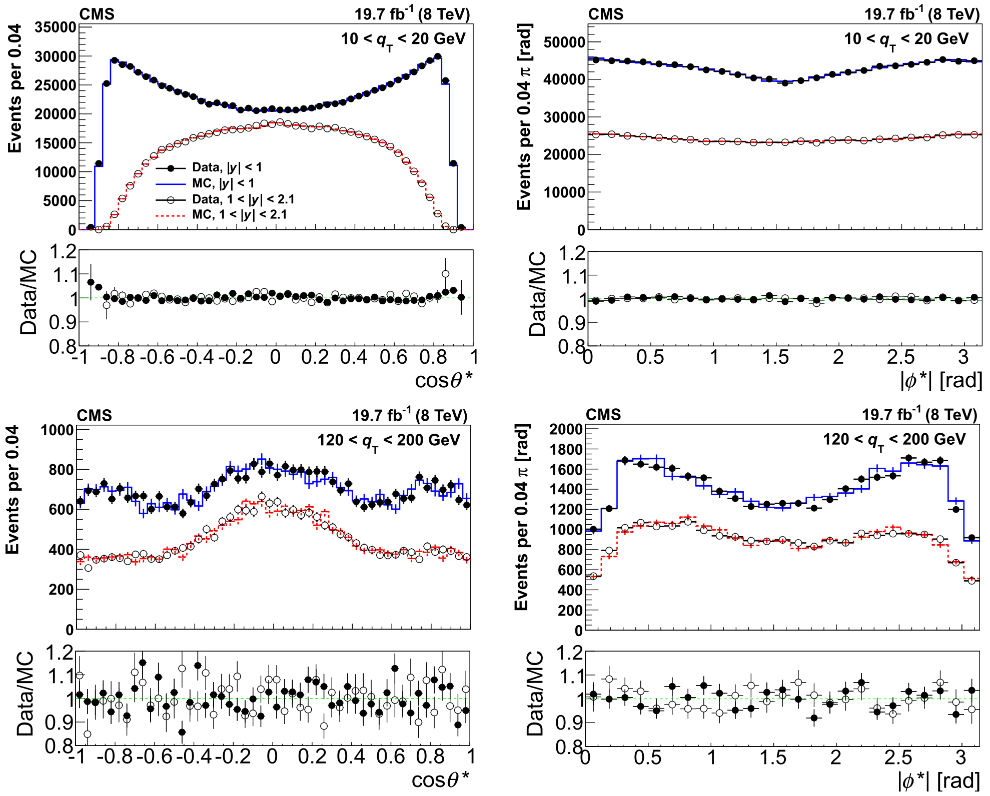

Fig. 1. A few examples of the observed 1D angular distributions in $\cos\theta^*$ (left) and $|\phi^*|$ (right) compared to the MC simulation using the best fit values of the angular coefficients. The top (bottom) plots show the distributions for $10 < q_T < 20$ GeV ($120 < q_T < 200$ GeV), a region 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 ±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 eμ sample by 10% and the yields of WZ and ZZ events by 50%. The statistical 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 $O(\alpha_{QED})$ 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

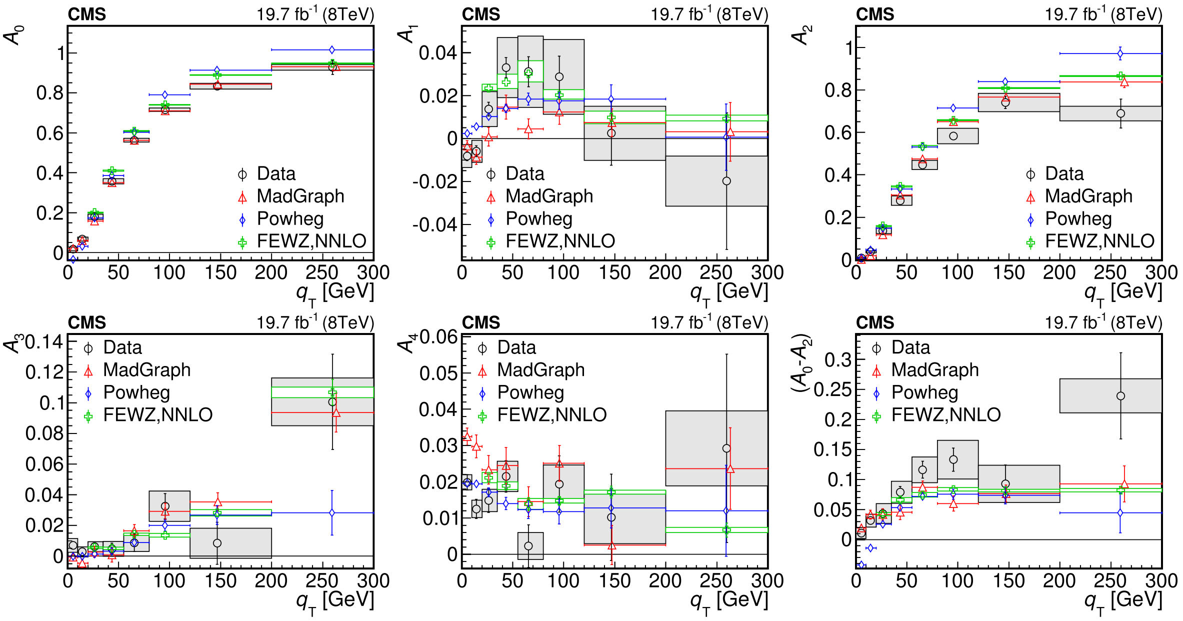

Fig. 2. Comparison of the five angular coefficients A_i and $A_0 - A_2$ measured in the Collins–Soper frame in bins of q_T for $|y| < 1$. The circles show the measured results. The vertical bars represent the statistical uncertainties and the boxes the systematic uncertainties of the measurement. The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

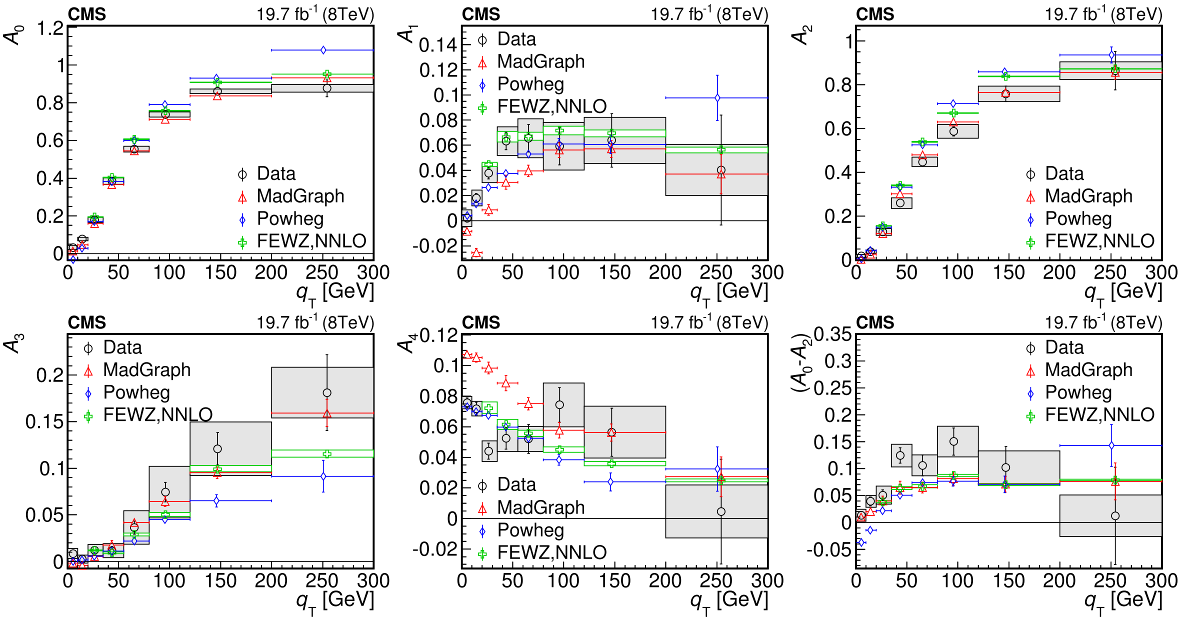

Fig. 3. Comparison of the five angular coefficients and $A_0 - A_2$ under the same conditions as Fig. 2, for the rapidity bin $1 < |y| < 2.1$.

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 $p\overline{p}$ collisions at the Tevatron. The larger contribution from the qg 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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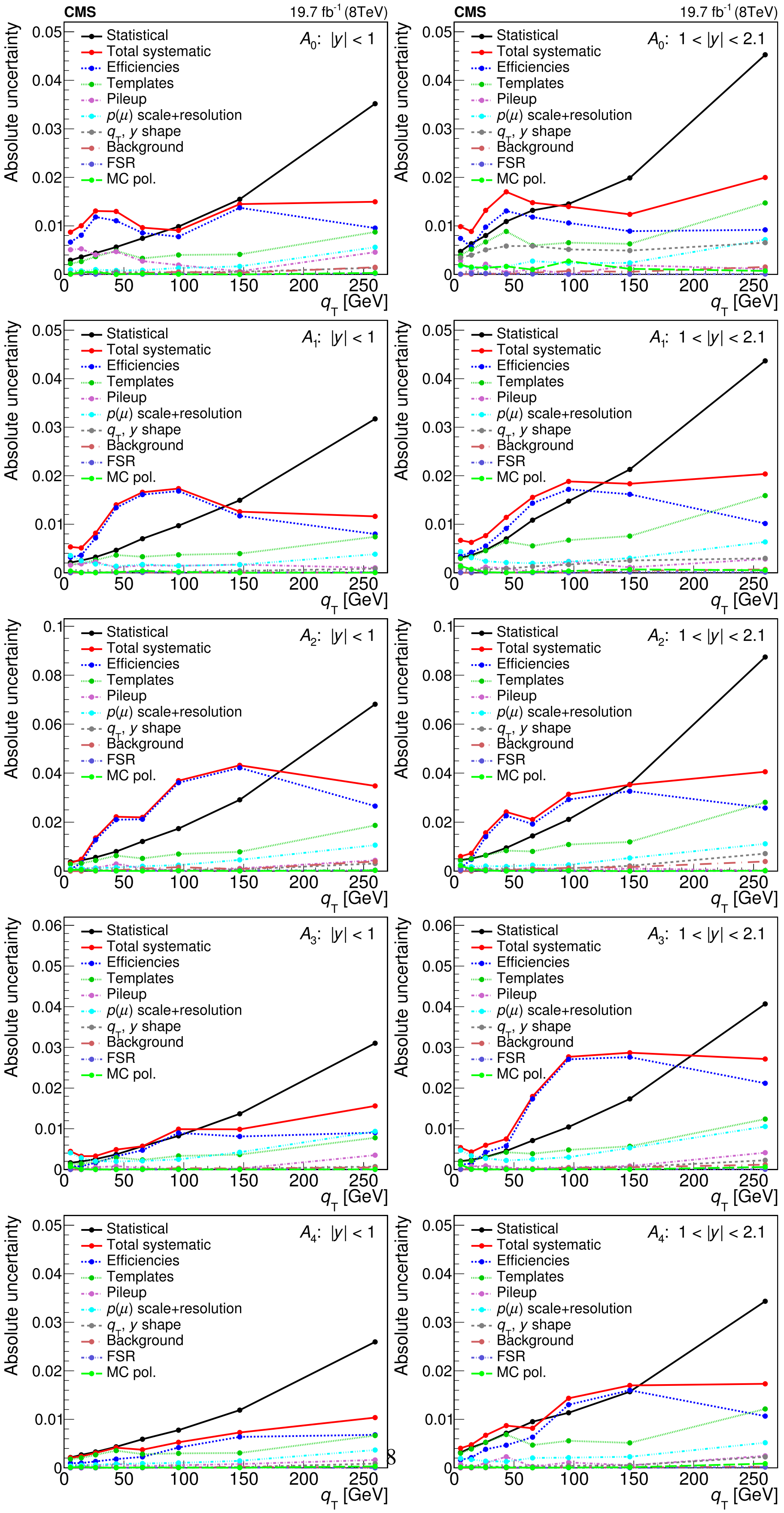

Fig. 4. Absolute uncertainties in the five angular coefficients A_0 to A_4. Each figure shows the q_T dependence in the indicated ranges of $|y|$.

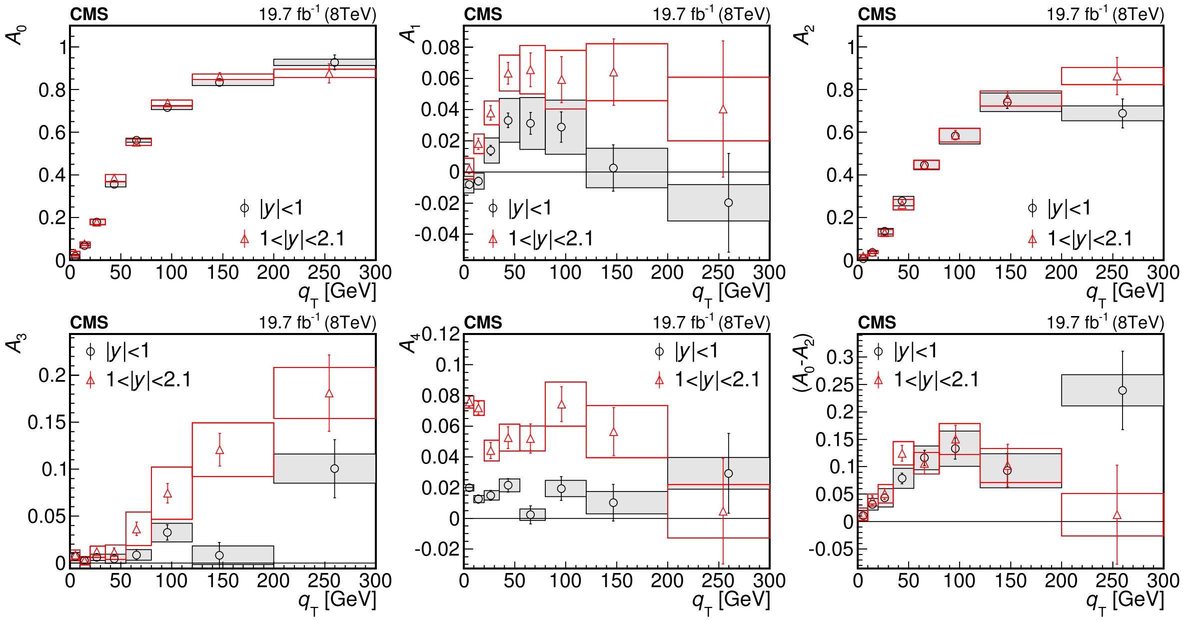

Fig. 5. Comparison of the five angular coefficients A_i and $A_0 - A_2$ measured in the Collins–Soper frame in bins of q_T between $|y| < 1$ (circles) and $1 < |y| < 2.1$ (triangles). The vertical bars represent the statistical uncertainties and the boxes the systematic uncertainties of the measurement.

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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