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Measurement of the $Z \to \mu^+\mu^-$ angular coefficients in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ as functions of transverse momentum and rapidity

The CMS Collaboration*

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Abstract

A measurement of the eight angular polarization coefficients, A_0 to A_7, in the cross section for the Drell–Yan production of two muons is presented. The analysis is based on proton-proton (pp) collision data recorded with the CMS detector at the LHC at a center-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $140\,\text{fb}^{-1}$. The coefficients are determined double differentially in eight intervals of transverse momentum and two intervals of rapidity of the muon pair $\mu^+\mu^-$. The results are presented for the $\mu^+\mu^-$ invariant mass range 81–101 GeV and are compared with theoretical predictions calculated at next-to-next-to-leading order in perturbative quantum chromodynamics. The measurement provides relevant information about the underlying partonic dynamics and the Z boson production mechanisms.

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*See Appendix B for the list of collaboration members

1 Introduction

Processes with dilepton final states play a key role in collider experiments, providing clean experimental signatures and precise probes of the underlying dynamics of particle interactions. Particularly, the Drell–Yan (DY) process ($pp \to \gamma^*/Z \to \ell^+\ell^-$, where pp stands for proton-proton collisions and ℓ represents the e, μ, and τ leptons) [1] is sensitive to the electroweak (EW) γ^*/Z couplings and also provides unique information about lepton-hadron correlations [2, 3]. Such correlations are essential for understanding the dynamics of the initial-state partons and the effects of quantum chromodynamics (QCD), offering a window into parton distribution functions (PDFs) [4–6] and their connection with the angular structure of the final states. Within the parton model, this connection is encoded in eight angular polarization coefficients A_i ($i = 0, \ldots, 7$).

We consider the DY process in the Collins–Soper (CS) frame [7], where the z axis bisects the angle between the momentum vectors of the colliding protons, with the positive direction pointing closer to the momentum direction of the lepton pair, i.e. of the γ^*/Z boson in the laboratory frame. The x axis lies in the same plane as the momenta of the colliding protons, but orthogonal to the z axis. The y axis is then defined to complete the right-handed system. To be consistent with previous measurements [8, 9], the momentum of the beam proton closest in rapidity to the γ^*/Z boson is considered the "target momentum" in our measurement.

The differential cross section depends on the azimuthal angle ϕ^* and polar angle θ^* as

$$\begin{aligned}\frac{\mathrm{d}^5\sigma}{\mathrm{d}m_{\ell\ell}\mathrm{d}y^{\ell\ell}\mathrm{d}p_{\mathrm{T}}^{\ell\ell}\mathrm{d}\theta^*\mathrm{d}\phi^*} \propto \frac{\mathrm{d}^3\sigma^{\mathrm{unp}}}{\mathrm{d}m_{\ell\ell}\mathrm{d}y^{\ell\ell}\mathrm{d}p_{\mathrm{T}}^{\ell\ell}}\Big[&(1+\cos^2\theta^*) + \frac{A_0}{2}(1-3\cos^2\theta^*) \\ &+ A_1\sin(2\theta^*)\cos\phi^* + \frac{A_2}{2}\sin^2\theta^*\cos(2\phi^*) + A_3\sin\theta^*\cos\phi^* \\ &+ A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\Big],\end{aligned} \tag{1}$$

where σ^{unp} is unpolarized cross section and Figure 1 illustrates the definition of the ϕ^* and θ^* angles in the CS frame.

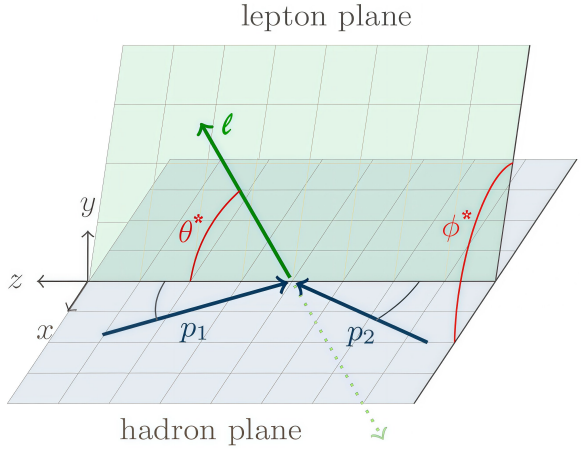

Figure 1: The definition of the CS frame and angles ϕ^* and θ^* of the negatively charged lepton produced in the γ^*/Z decay. The p_1 and p_2 vectors indicate the directions of the incoming proton's momenta in the dilepton rest frame and ℓ indicates the momentum of the negatively charged lepton [10].

The angular polarization coefficients A_i are functions of the lepton pair kinematic variables: transverse momentum $p_{\mathrm{T}}^{\ell\ell}$, rapidity $y^{\ell\ell}$, and invariant mass $m_{\ell\ell}$. Importantly, these coefficients

correspond to orthogonal angular terms in Eq. (1), which define modulations in the angular distribution of the leptons. The coefficients encode contributions of different polarization states of the γ^*/Z boson reflecting processes occurring at the parton level. In calculations at leading order (LO) in QCD, all are expected to be close to zero at $p_{\mathrm{T}}^{\ell\ell} \approx 0$, except for A_4, which describes the magnitude of asymmetry of the $\cos\theta^*$ distribution around zero. This phenomenon is also known as the forward-backward asymmetry (A_{FB}) and is a consequence of the parity violating nature of the EW decay of the γ^*/Z boson to a lepton pair. The coefficients A_0 and A_2 parametrize the longitudinal (L) polarization fraction of the γ^*/Z boson and the interference between its transverse (T) polarization states, respectively. The Lam–Tung relation $A_0 - A_2 = 0$ [11] holds at leading order in perturbative QCD as a consequence of helicity conservation and the vector nature of the mediating boson. Deviations from this relation can occur because of higher-order QCD radiation, noncollinear parton dynamics, and other effects resulting from the intrinsic transverse momentum of the interacting partons [12–15]. The coefficient A_1 encodes the interference between longitudinal and transverse polarization states. The A_3 and A_4 coefficients are based on the axial and vector EW couplings of quarks and leptons. The coefficient A_4 is used for precise measurements of the squared sine of the effective EW mixing angle $\sin^2\theta_W^{\mathrm{eff}}$ [16–18]. The A_5, A_6, and A_7 coefficients define the contribution of T-odd asymmetries to the total cross section and may be non-zero in one-loop processes at next-to-next-to-leading order (NNLO) in QCD [19, 20].

Some of the coefficients (A_0, A_2, A_3, and A_4) were measured for the first time in $\mathrm{p\overline{p}}$ collisions at a center-of-mass energy of 1.96 TeV at the Fermilab Tevatron by the CDF Collaboration [17]. More recent A_i measurements were performed by the CMS [8] and ATLAS [9] Collaborations based on the LHC Run 1 data. The amount of data collected at $\sqrt{s} = 8$ TeV allowed measuring A_0, A_1, A_2, A_3, and A_4 in the Z pole region as functions of Z boson rapidity and transverse momentum, and made it possible to unequivocally establish a violation of the Lam–Tung relation. Moreover, ATLAS performed measurements using the combined $\mathrm{e^+e^-}$ and $\mu^+\mu^-$ sample that indicated evidence of non-zero A_5, A_6, and A_7 with a significance of three standard deviations. In 2022, the LHCb Collaboration published the first measurement of the coefficients A_0 to A_4 in the dimuon channel in the forward rapidity region ($y^{\mu\mu} > 2$) with dimuon transverse momentum $p_{\mathrm{T}}^{\mu\mu} < 100$ GeV [21]. To date, all the measurements agree with theoretical calculations at NNLO precision in QCD.

This Letter presents a measurement of the full set of angular polarization coefficients A_0 to A_7 in the DY dimuon channel process ($\mathrm{pp} \to \mathrm{Z} \to \mu^+\mu^-$) using LHC pp collision data collected by the CMS experiment at $\sqrt{s} = 13$ TeV in 2016–2018. The data sample corresponds to an integrated luminosity of 140 fb^{-1}. The results are compared with NNLO QCD predictions as a function of the dimuon rapidity and transverse momentum for $|y^{\mu\mu}| < 2.4$ and $p_{\mathrm{T}}^{\mu\mu} < 400$ GeV.

2 The CMS detector and event selection

The CMS apparatus [22] is a multipurpose, nearly hermetic detector, designed to trigger on [23, 24] and identify electrons, muons, photons, and charged hadrons [25–27]. A global particle-flow (PF) algorithm [28] reconstructs all individual particle candidates in an event, combining information provided by the all-silicon tracker and by the crystal electromagnetic, and a brass and scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. 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. The single-muon trigger efficiency exceeds 90% over the full η range, and the efficiency

to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution, for muons with p_T up to 100 GeV, of 1% in the barrel and 3% in the endcaps [26].

Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4 μs [23]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing and reduces the event rate to a few kHz before data storage [24, 29].

For this analysis, events with two tracks reconstructed as μ^+ and μ^- using the PF algorithm are selected. Both muons are required to be isolated from other particles originating from the same primary vertex, which means that the ratio of the scalar sum of p_T of all other reconstructed physics objects within a cone $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.4$ around the muon track to the muon p_T^μ must be less than 0.15. Here, $\Delta\phi$ and $\Delta\eta$ are the distances in the ϕ and η coordinates, respectively. The events are recorded using a single-muon requirement in the HLT, where at least one isolated muon track with $p_T^\mu > 24$ GeV (for the 2016 and 2018 data taking periods) or $p_T^\mu > 27$ GeV (for the 2017 data taking period) and $|\eta^\mu| < 2.4$ is reconstructed in the event. To reduce the γ^* contribution, the invariant mass of the dimuon must satisfy $81 < m_{\mu\mu} < 101$ GeV. The requirement $|y^{\mu\mu}| < 2.4$ is also applied because of the acceptance of the detector. Moreover, an additional requirement $p_T^\mu > 26$ (20) GeV for the leading (subleading) muon is applied for the 2016 and 2018 samples, and $p_T^\mu > 29$ (20) GeV for the 2017 sample. This selection is introduced to ensure an efficient and uniform response of the trigger in the p_T^μ region close to the trigger p_T threshold.

3 Simulation and corrections

To simulate the signal process, the POWHEG v2.0 + MiNNLO [30, 31] generator interfaced with PYTHIA 8.240 [32] and PHOTOS ++ [33] is used. By interfacing with PHOTOS ++, quantum electrodynamics (QED) final state radiation (FSR) is considered at leading logarithmic precision, including matrix-element corrections and the effect of lepton pair production. The PDF set used is NNPDF3.1 [34] with the strong interaction coupling constant set to $\alpha_S(m_Z) = 0.118$, where m_Z is the mass of the Z boson. The Z boson event samples simulate all contributions to the dilepton final state, including those from virtual photons. For the Z boson production, the (G_μ, $\sin^2\theta_W^{\text{eff}}$, m_Z) EW input scheme is used, where G_μ is the Fermi constant extracted from the muon lifetime. Additionally, predictions for the angular coefficients are also calculated with MADGRAPH5_aMC@NLO v5.2.2.2 [35] (with the NNPDF3.1 PDF set) at next-to-leading order (NLO) using the FxFx jet merging scheme [36] with up to two partons in the matrix element calculations.

In this analysis, all background processes are modeled using NLO Monte Carlo (MC) event generators. The diboson processes (WW, WZ, and ZZ) are simulated with POWHEG [31] and MADGRAPH5_aMC@NLO, while the $tW^\pm$ process is generated with POWHEG. The W+jets contribution is found to be negligible according to the MADGRAPH5_aMC@NLO prediction. The MADGRAPH5_aMC@NLO generator is also used to simulate the DY $\to \tau^+\tau^-$ and $t\bar{t}$ processes for the 2017 and 2018 data sets. For the 2016 data set, the $t\bar{t}$ process is simulated with POWHEG [31] interfaced with HERWIG [37] using the CH3 tune [38]. For all other simulated samples in this work, parton showering, hadronization, the underlying event, and QED final-state radiation are modeled with PYTHIA 8 using the CP5 tune [39], with the hard primordial-k_T

parameter set to 2.225 GeV, as determined from a dedicated optimization using the $p_{\mathrm{T}}^{\mu\mu}$ measurement of Ref. [40]. Multiple pp interactions in the same or neighboring bunch crossings (pileup) are simulated with PYTHIA 8. Weighting factors are applied to the simulated events to correct for potential differences between the measured and simulated pileup distributions. Finally, all generated events are processed through a GEANT4-based detector simulation [41].

The background-to-signal ratio increases from approximately 0.03% at $p_{\mathrm{T}}^{\mu\mu} < 10$ GeV to about 2.9% at $p_{\mathrm{T}}^{\mu\mu} > 200$ GeV. The background from dimuon final states produced in diboson processes (WW, WZ, and ZZ) is dominant over the phase space of the measurement, contributing up to 2.8% of the selected events at high $p_{\mathrm{T}}^{\mu\mu}$ (> 200 GeV). For $p_{\mathrm{T}}^{\mu\mu} < 200$ GeV, the background from $\mathrm{t\bar{t}}$ decays is of comparable magnitude to the diboson contribution. In the low $p_{\mathrm{T}}^{\mu\mu}$ region (< 20 GeV), the $\mathrm{t\bar{t}}$ background becomes about 0.003–0.03%, comparable to the contribution from muons originating from τ lepton decays in the DY $\to \tau^+\tau^-$ process.

To account for the differences in the efficiencies between data and simulation, scale factors are derived and applied on an event-by-event basis. The efficiencies for trigger, muon identification, and muon isolation are measured using a "tag-and-probe" method [26] for both data and simulation as functions of the muon η and p_{T}. The application of the efficiency correction can modify the event weight by up to 10%. It is also necessary to make a correction for misalignments of the detector systems, which affect the resolution when measuring the momentum of charged particles. Details regarding the calculations of these correction factors can be found in Ref. [42].

In a small fraction of the collected events, an imperfect synchronization of the L1 trigger (associated with the limited time resolution of the muon detectors) resulted in an incorrect assignment of the bunch crossing, so that some tracks were associated with the previous bunch crossing. The probability of this "prefiring" effect does not exceed 1.5% [43] and depends on the muon η and p_{T}. It is measured differentially in these variables to properly model this dependence. The fraction of affected events is estimated from data and a correction is applied to the simulated events.

To avoid discrepancies with data in the shape of the Z boson kinematic distributions related to the model used by the MC generator, simulated events are reweighted in eight bins of $p_{\mathrm{T}}^{\mu\mu}$ and two bins of $y^{\mu\mu}$ (see binning in Section 4). For each $y^{\mu\mu}$ bin, the background contribution is subtracted from the $p_{\mathrm{T}}^{\mu\mu}$ distribution of data events. Both distributions, $p_{\mathrm{T}}^{\mu\mu}$ (data$-$background) and $p_{\mathrm{T}}^{\mu\mu}$ (DY $\to \mu\mu$ simulation after reconstruction), are normalized to unity. Then, correction weights are defined for each ($y^{\mu\mu}$, $p_{\mathrm{T}}^{\mu\mu}$) bin as the ratio of bin contents of these normalized histograms. The weights are applied to MC events according to the values of $y^{\mu\mu}$ and $p_{\mathrm{T}}^{\mu\mu}$ of the dimuon at the generator level before FSR (pre-FSR), after the other corrections are performed. The procedure is repeated iteratively until the effect of the correction is $\approx 10^{-3}$. The effect of the reweighting is most significant for $p_{\mathrm{T}}^{\mu\mu}$ bins up to 35 GeV and can reach 6% of the bin content.

Distributions as functions of $\cos\theta^*$ and ϕ^* for data and MC events, after all mentioned corrections are applied, are presented in Fig. 2. Discrepancies are at the 1% level, consistent with the systematic uncertainty discussed in Section 5.

4 Extraction of A_i

The angular coefficients are measured in two bins of the dimuon absolute rapidity, $|y^{\mu\mu}| = 0$–1 and 1–2.4, and eight bins of $p_{\mathrm{T}}^{\mu\mu}$ with edges at 0, 10, 20, 35, 55, 80, 120, 200, and 400 GeV.

At the pre-FSR level, the angular distribution of dimuon events in the CS frame $\mathrm{D}(\cos\theta^*, \phi^*)$

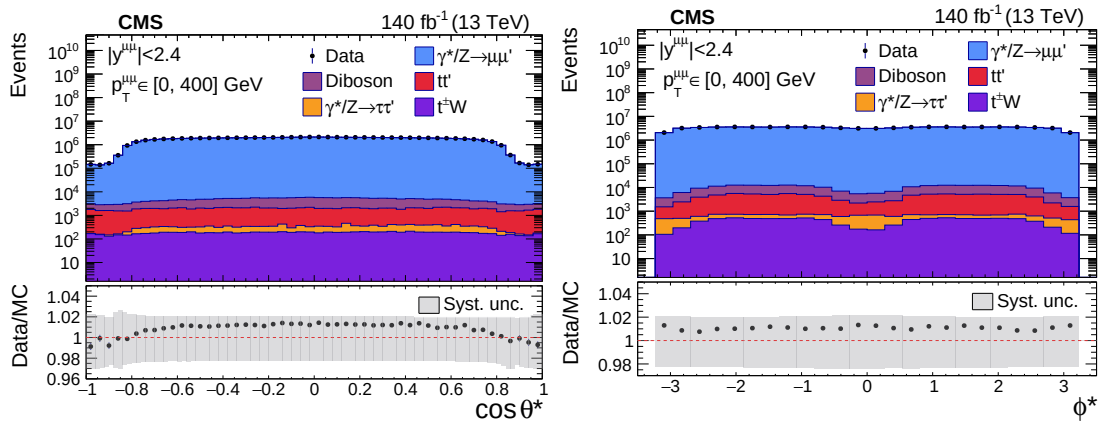

Figure 2: Distributions of events as functions of $\cos\theta^*$ (left) and ϕ^* (right), averaged over $p_{\mathrm{T}}^{\mu\mu}$ and $y^{\mu\mu}$. The measured distributions are represented by the black markers. The simulated contributions (from the signal and background processes) are shown by the colored histograms. The data/MC ratios are presented in the lower panels. The gray bands around unity represent the total systematic uncertainties.

is described by Eq. (1). However, the measured distribution is constructed from reconstructed final-state muons passing the event selection described in Sec. 2. Consequently, the observed angular distribution $\mathrm{D}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}})$ is affected by final-state radiation, detector acceptance and resolution, and migration of events between neighboring $p_{\mathrm{T}}^{\mu\mu}$ bins. Therefore, the observed distribution cannot be described directly by Eq. (1), and a template method is employed to extract the angular coefficients.

In each $(p_{\mathrm{T}}^{\mu\mu}, |y^{\mu\mu}|)$ interval, Eq. (1) can be written as

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\theta^*\mathrm{d}\phi^*} \propto \sum_{i=0}^{8} P_i, f_i(\theta^*, \phi^*), \tag{2}$$

where $f_i(\theta^*, \phi^*)$ are the trigonometric polynomials (basis function) corresponding to the angular coefficients in Eq. (1). The parameters P_i are related to the angular coefficients through $A_i = P_i/P_8$, where P_8 corresponds to the unpolarized cross section proportional to $(1+\cos^2\theta^*)$. For each basis function $f_i(\theta^*, \phi^*)$, a detector-level template $T_i^{\mathrm{MC}}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}})$ is constructed from simulated events. The intrinsic angular coefficients of the generator model, P_i^{ref}, are determined from angular moments following Ref. [2]. Each simulated event is assigned a weight

$$w_i = \frac{f_i(\theta^*, \phi^*)}{\sum_{j=0}^{8} P_j^{\mathrm{ref}} f_j(\theta^*, \phi^*)}, \tag{3}$$

The denominator removes the dependence on the polarization model implemented in the event generator, while the numerator projects the event onto the corresponding basis function $f_i(\theta^*, \phi^*)$. The weights are computed from the pre-FSR kinematics, whereas the templates are filled using the corresponding reconstructed events after the full detector simulation, event reconstruction, and application of all analysis corrections. The resulting detector-level angular distributions define the templates $T_i^{\mathrm{MC}}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}})$.

Under the assumption that final-state radiation and detector effects are accurately modeled by simulation, the measured angular distribution $\mathrm{D}^{\mathrm{data}}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}})$ can be represented as

$$\mathrm{D}^{\mathrm{data}}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}}) \approx \sum_{i=0}^{8} P_i\, T_i^{\mathrm{MC}}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}}) + \mathrm{D}^{\mathrm{bkg}}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}}), \tag{4}$$

where $\mathrm{D}^{\mathrm{bkg}}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}})$ denotes the contribution from background processes.

The coefficients P_i are extracted using a two-dimensional binned maximum-likelihood fit. Distributions $\mathrm{D}^{\mathrm{data}}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}})$, and $\mathrm{D}^{\mathrm{bkg}}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}})$, and all templates $T_i^{\mathrm{MC}}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}})$ are divided into $14 \times 14 = 196$ bins of equal size in $(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}})$. The fit is performed with MINUIT [44] using Poisson likelihoods independently in each $(p_{\mathrm{T}}^{\mu\mu}, |y^{\mu\mu}|)$ interval.

Because of the finite detector acceptance, the templates are not strictly orthogonal, leading to correlations among the fitted parameters. The largest correlations are observed between P_0, P_2, and P_8, reaching values of about 0.7 in some kinematic regions, while correlations involving the remaining coefficients are typically below 0.2.

The quality of the fit is assessed using the Pearson χ^2 test, including both statistical and systematic uncertainties (Sec. 5). Across all kinematic intervals, the χ^2 per degree of freedom is in the range 0.9–1.2, indicating a good description of the data.

The extraction procedure is validated using the $\mathrm{D}^{\mathrm{MC}}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}})$ distribution of simulated events instead of $\mathrm{D}^{\mathrm{data}}(\cos\theta^*_{\mathrm{obs}}, \phi^*_{\mathrm{obs}})$ in Eq. 4. The fitted coefficients are found to be consistent with the reference values within the statistical precision of the comparison, demonstrating that the effects of final-state radiation, detector acceptance, and event migration are well accounted by the template method. The fraction of events reconstructed in a $p_{\mathrm{T}}^{\mu\mu}$ bin different from their true bin is below 7% for the binning used in the measurement and has a negligible impact on the extracted coefficients.

5 Systematic uncertainties

To estimate the systematic uncertainty in the measurement, each source of a systematic effect is independently varied within its own uncertainty and the corresponding variation in the A_i value is evaluated. The difference between the varied A_i value and its baseline value is taken as the uncertainty from the considered source. The following effects are taken into account: experimental uncertainties (pileup reweighting, efficiency of trigger, efficiencies of muon identification and isolation, detector misalignment, luminosity measurement uncertainty [45, 46], and prefiring), theoretical cross section uncertainties for signal and background processes, uncertainties from the limited number of events in the MC samples, and the shape of $p_{\mathrm{T}}^{\mu\mu}$ distribution. The uncertainty related to the chosen PDF and the strong coupling $\alpha_{\mathrm{S}}(m_{\mathrm{Z}})$ value is evaluated following the PDF4LHC prescription [47] using a set of symmetric Hessian eigenvectors including $\alpha_{\mathrm{S}}(m_{\mathrm{Z}})$ variations. To estimate the effect of missing higher orders in perturbative QCD, the factorization scale μ_{F} and the renormalization scale μ_{R} are varied independently by factors of 0.5 and 2, excluding the extreme case where both scales are varied in opposite directions. The maximum variation of the predicted coefficients from these scale variations is taken as the uncertainty. The uncertainties from the latter two sources are also calculated for the reported MC predictions and found to change the values of the predicted coefficients by less than 10^{-4}.

The contribution of an A_i uncertainty source can vary depending on the coefficient and the kinematic range. The most significant uncertainties for A_0, A_1, A_2 come from the efficiency corrections. The size of the simulated event sample contributes significantly to the all coefficient uncertainties for $p_{\mathrm{T}}^{\mu\mu} > 80\,\mathrm{GeV}$, reaching the value of 97% from total systematic uncertainty on the A_6 coefficient in the bin $p_{\mathrm{T}}^{\mu\mu} \in [120, 200]\,\mathrm{GeV}$. The coefficients A_3 and A_4 are also sensitive to the PDF+$\alpha_{\mathrm{S}}(m_{\mathrm{Z}})$ uncertainty. The total systematic uncertainty is calculated as the sum in quadrature of the individual uncertainties, separately for positive and negative effects. The

uncertainty in the $A_0 - A_2$ difference, that tests the Lam–Tung relation, is calculated as the quadrature sum of the A_0 and A_2 uncertainties with the correlation between these coefficients taken into account.

6 Results

Figures 3–6 present the measured A_0 to A_7 angular coefficients, in the CS frame, for dimuons with invariant mass $81 < m_{\mu\mu} < 101\,\text{GeV}$, in two $|y^{\mu\mu}|$ bins, while Fig. 7 presents the corresponding $A_0 - A_2$ values. The POWHEG+MiNNLO and MADGRAPH5_aMC@NLO predictions are also shown in the figures. The measured values are provided in Tables A.1–A.3 and in the HEPData record of this analysis [48].

The A_0 values from data and POWHEG+MiNNLO simulation agree within systematic and statistical uncertainties for low- and high-$p_{\mathrm{T}}^{\mu\mu}$ bins, whereas in the intermediate $p_{\mathrm{T}}^{\mu\mu}$ range we observe a discrepancy of about three standard deviations. The MADGRAPH5_aMC@NLO predictions significantly underestimate A_0 in the range $10 < p_{\mathrm{T}}^{\mu\mu} < 35\,\text{GeV}$. The measured A_2 values coincide with the predicted POWHEG+MiNNLO and MADGRAPH5_aMC@NLO values at low $p_{\mathrm{T}}^{\mu\mu}$, but are slightly overestimated by the MC for $p_{\mathrm{T}}^{\mu\mu} > 50\,\text{GeV}$. In the 10–35 GeV $p_{\mathrm{T}}^{\mu\mu}$ range, the POWHEG+MiNNLO predictions are in good agreement with the measured $A_0 - A_2$ values, while the MADGRAPH5_aMC@NLO predictions show a significant discrepancy. For $p_{\mathrm{T}}^{\mu\mu} > 35\,\text{GeV}$, instead, both MC predictions equally underestimate the measurement. The distribution of A_1 is significantly overestimated by POWHEG+MiNNLO for $p_{\mathrm{T}}^{\mu\mu} < 35\,\text{GeV}$ in the $1 < |y^{\mu\mu}| < 2.4$ region, and also overestimated by MADGRAPH5_aMC@NLO predictions in both rapidity regions at low $p_{\mathrm{T}}^{\mu\mu}$. The coefficients A_5, A_6, and A_7 have values of the order of 10^{-3} and are consistent with zero within uncertainties in most of the bins in data and both MC simulations. The most significant deviation from zero of the measured values for these coefficients, across all bins, is at 2.8 standard deviations for A_6 in the bin $55 < p_{\mathrm{T}}^{\mu\mu} < 80\,\text{GeV}$, $1.2 < |y^{\mu\mu}| < 2.4$. In general, the agreement between data and both MC simulations is good for the coefficients A_3–A_7. Nevertheless, in most cases the POWHEG+MiNNLO predictions are closer to the data, which likely indicates the importance of including higher-order QCD corrections. The observed discrepancy between the measurement and the MADGRAPH5_aMC@NLO prediction for the A_0 and A_1 coefficients at $p_{\mathrm{T}}^{\mu\mu} < 35\,\text{GeV}$ may be associated with the choice of the jet merging scale at 30 GeV, which affects the matching between matrix-element and parton shower emissions in the low-$p_{\mathrm{T}}^{\mu\mu}$ region and with the choice of the parton shower simulation. A more detailed study is required to establish its origin.

The systematic uncertainty is dominant for coefficients A_0 and A_1 for $p_{\mathrm{T}}^{\mu\mu} < 55\,\text{GeV}$, and for coefficients A_2, A_3, and A_4 for $p_{\mathrm{T}}^{\mu\mu} < 200\,\text{GeV}$. For the Lam–Tung relation, the systematic uncertainty is larger than the statistical in all $p_{\mathrm{T}}^{\mu\mu}$ bins except the highest two. For the other cases, the statistical uncertainty dominates.

The angular polarization coefficients measured at $\sqrt{s} = 13\,\text{TeV}$ are also consistent with the values measured by the ATLAS and CMS Collaborations at $\sqrt{s} = 8\,\text{TeV}$ [8, 9]. The sixfold larger integrated luminosity of the data and the higher production cross section has reduced the statistical uncertainty significantly. The deviations of the A_6 coefficient from zero, observed by ATLAS in the $1 < |y^{\mu\mu}| < 2.4$ range at $p_{\mathrm{T}}^{\mu\mu} > 50\,\text{GeV}$, are also visible at $\sqrt{s} = 13\,\text{TeV}$, but their magnitudes are noticeably smaller.

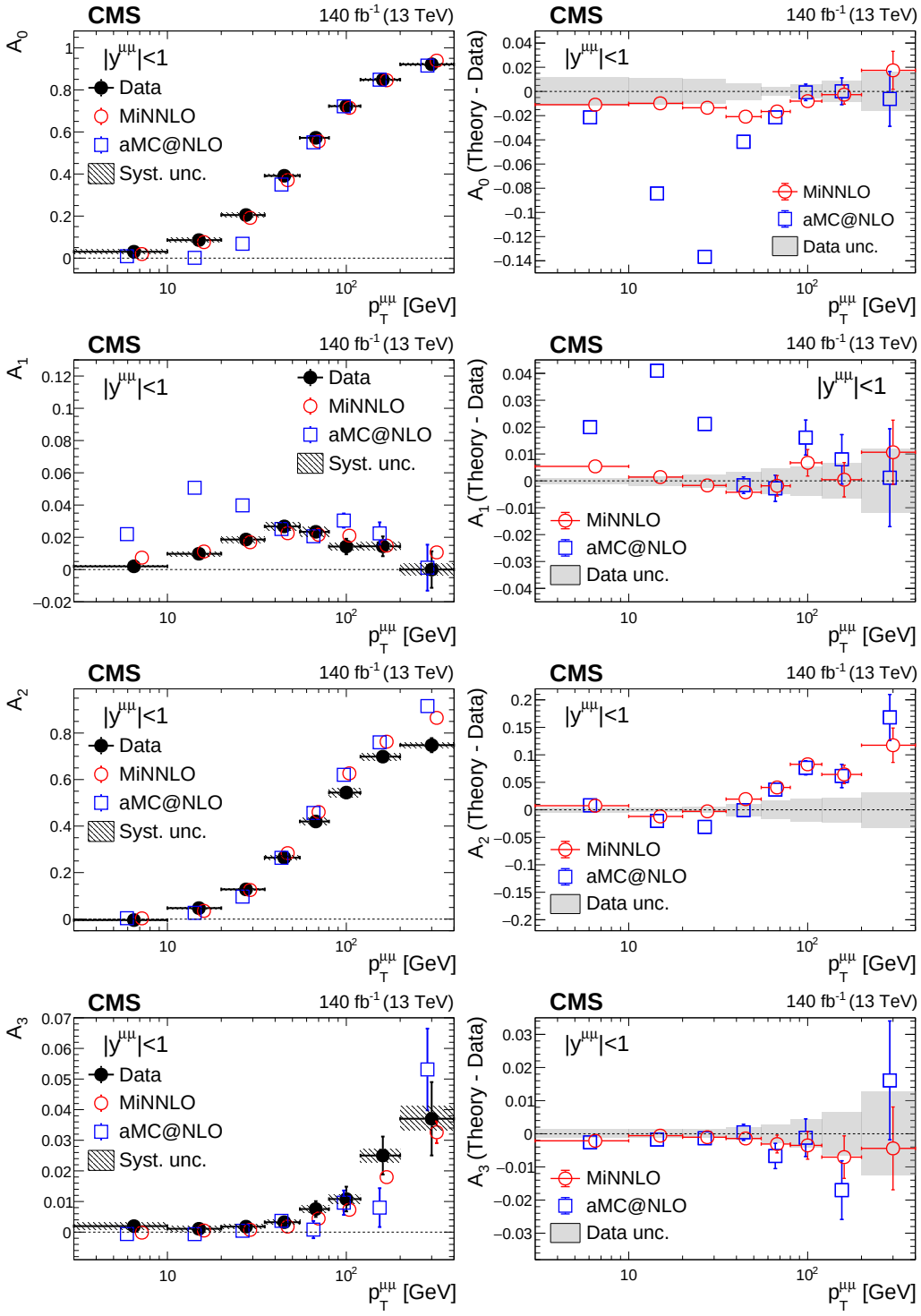

Figure 3: Left: Polarization coefficients A_0 to A_3 measured in the CS frame in bins of $p_{\mathrm{T}}^{\mu\mu}$ for $|y^{\mu\mu}| < 1$. The data points are shown as black circles. The POWHEG+MiNNLO and the MadGraph5_aMC@NLO predictions are represented by the red circles and blue squares, respectively, slightly displaced horizontally for improved visibility. The vertical bars (hatched boxes) represent the statistical (systematic) uncertainties. The theoretical uncertainties of the predictions are negligible and not shown. Right: Difference between the predicted and measured values. The gray area around zero represents the total uncertainty of the measurement, while the vertical bars represent the statistical uncertainties of the predictions.

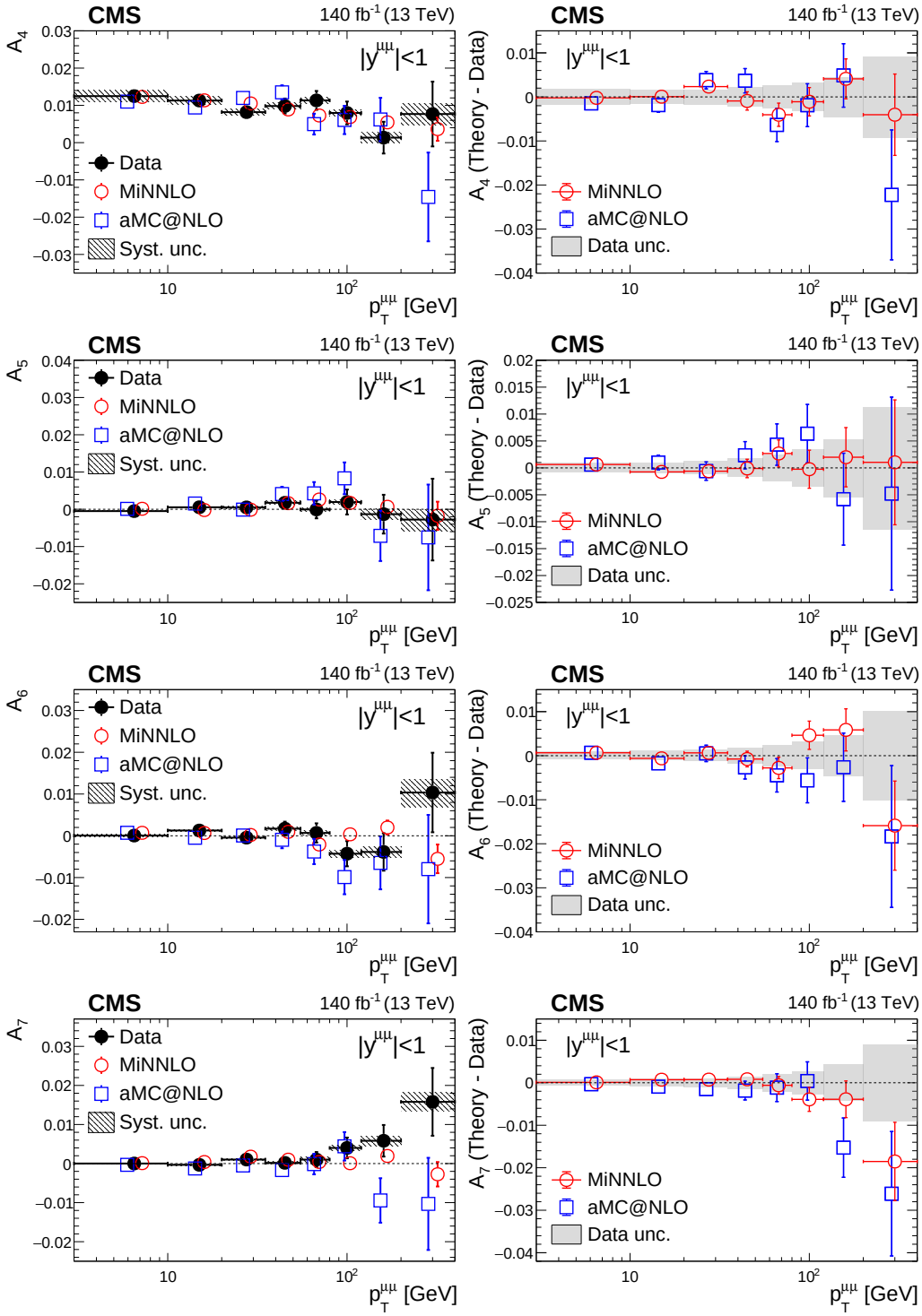

Figure 4: Same as Fig. 3, for the polarization coefficients A_4 to A_7.

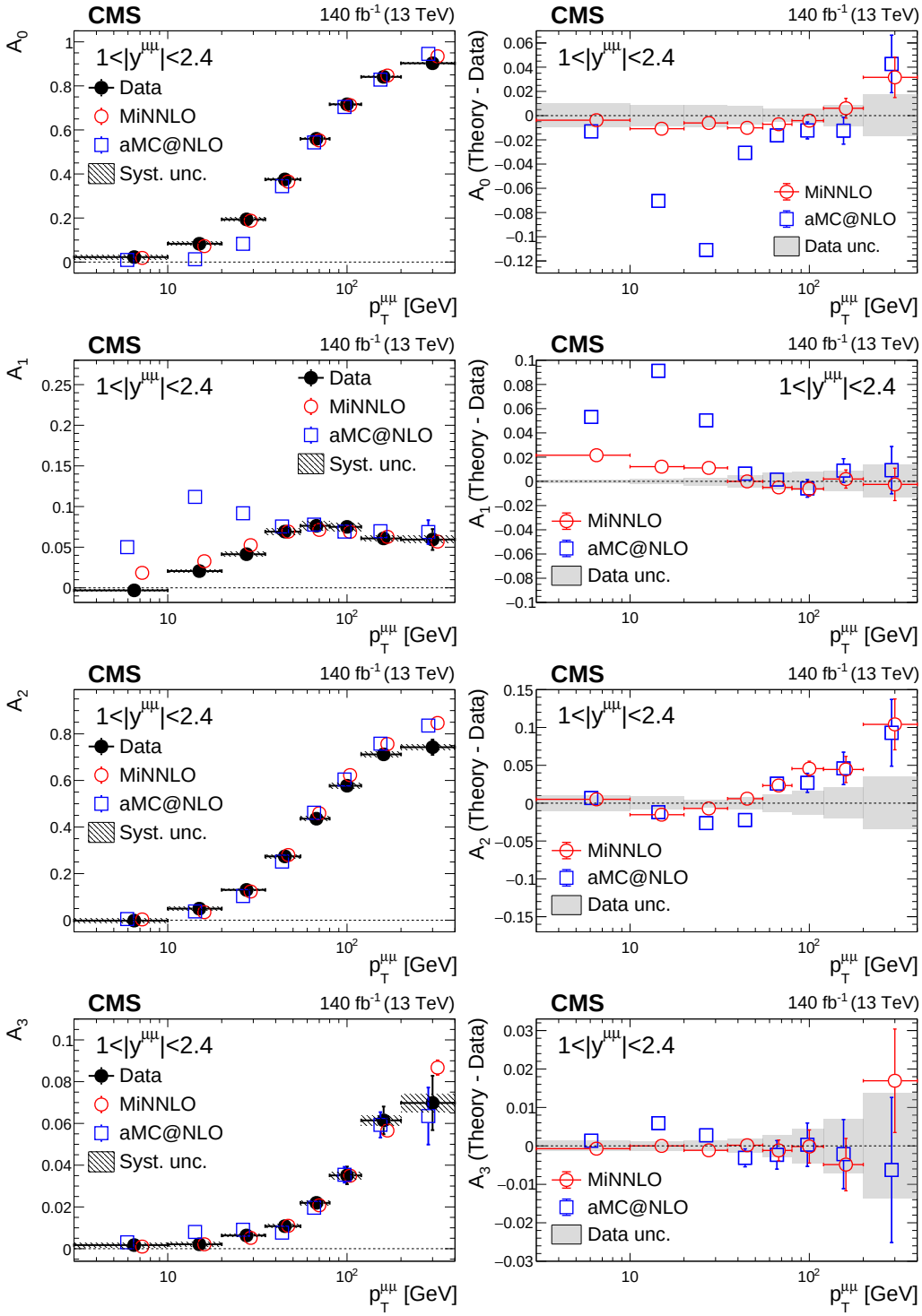

Figure 5: Same as Fig. 3, for the $1 < |y^{\mu\mu}| < 2.4$ bin.

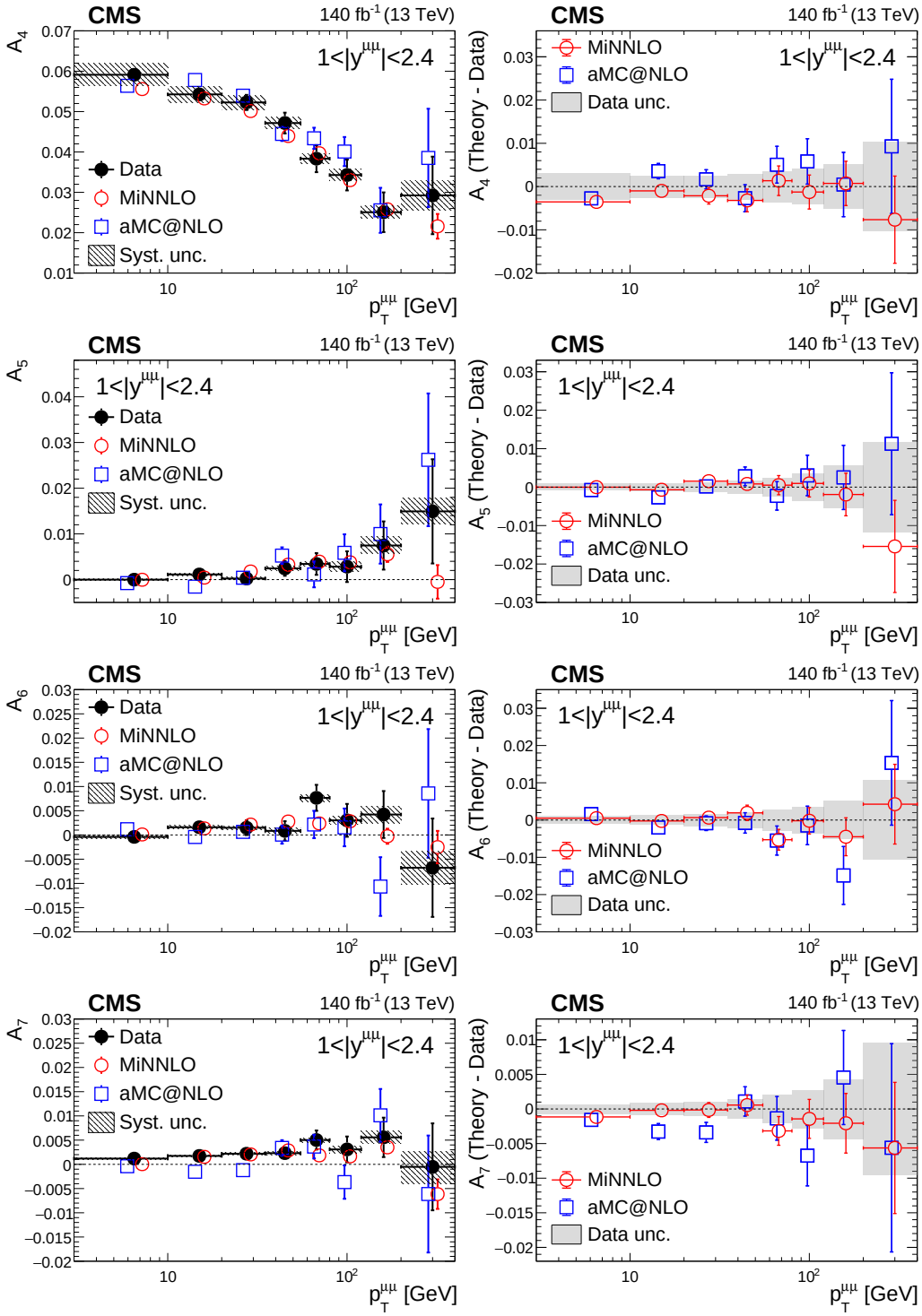

Figure 6: Same as Fig. 4, for the $1 < |y^{\mu\mu}| < 2.4$ bin.

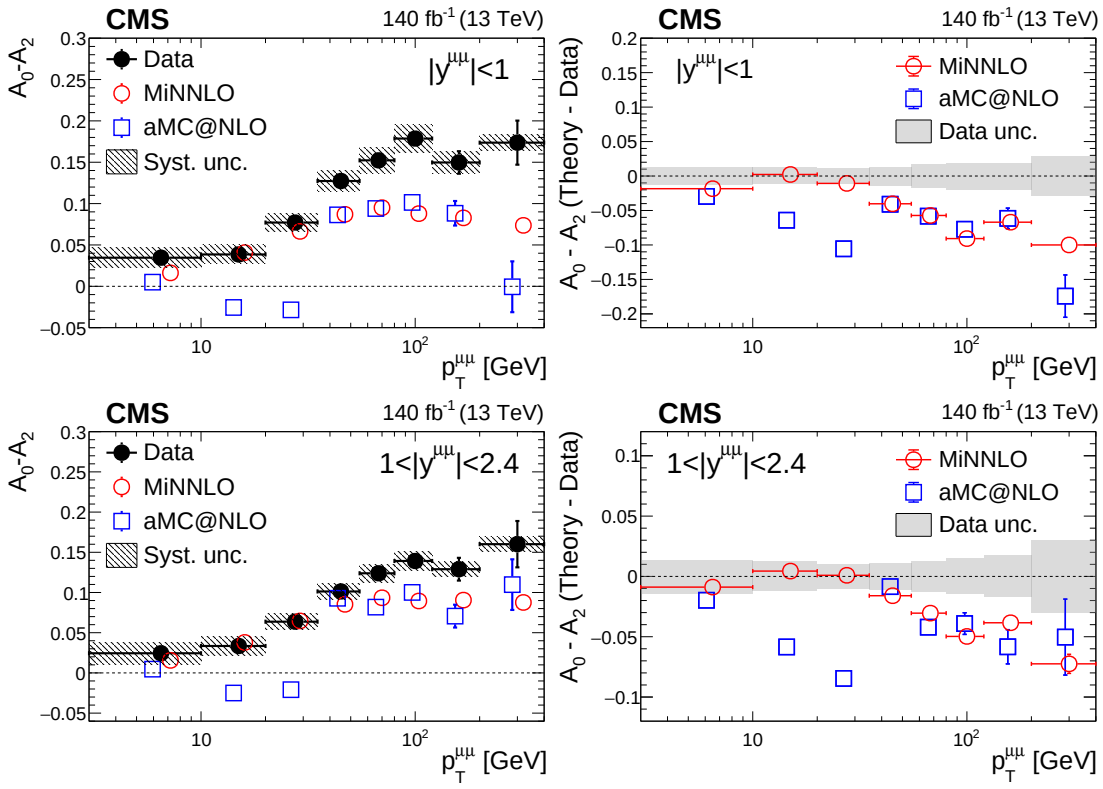

Figure 7: Left: Difference $A_0 - A_2$ measured in the CS frame in bins of $p_{\mathrm{T}}^{\mu\mu}$ for $|y^{\mu\mu}| < 1$ (upper) and $1 < |y^{\mu\mu}| < 2.4$ (lower). Right: Corresponding differences between the predicted and measured values.

7 Summary

The first measurement of the full set of angular polarization coefficients A_0–A_7 in the Drell–Yan dimuon channel in the central rapidity range $0 < |y^{\mu\mu}| < 2.4$ and $p_{\mathrm{T}}^{\mu\mu} < 400\,\mathrm{GeV}$ at $\sqrt{s} = 13\,\mathrm{TeV}$ is presented. The coefficients were determined double differentially in bins of transverse momentum and rapidity of the dimuon in the 81–101 GeV invariant mass range. The results are compared with state-of-the-art theoretical predictions at next-to-next-to-leading order in QCD and show consistency within uncertainties in most of the phase space.

The presented results provide a comprehensive characterization of the angular structure of dilepton production and offer stringent constraints on theoretical descriptions of electroweak vector boson production mechanisms and underlying partonic dynamics [5, 6]. The achieved precision and multidimensional binning establish a valuable benchmark for future phenomenological studies and for testing higher-order calculations [19, 20].

The most significant uncertainties vary across different coefficients and kinematic regions. The uncertainties on A_0, A_1, A_2 are mostly sensitive to the efficiency correction uncertainty while those on A_3 and A_4 also depend on the PDF+$\alpha_{\mathrm{S}}(m_{\mathrm{Z}})$ uncertainty. The statistics of simulated samples contribute to the uncertainty of all coefficients in the kinematic range $p_{\mathrm{T}}^{\mu\mu} > 80$ GeV.

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PID2023-147706NB-I00, PID2023-148896NB-I00, PID2023-146983NB-I00, PID2023-147115NB-I00, PID2023-148418NB-C41, PID2023-148418NB-C42, PID2023-148418NB-C43, PID2023-148418NB-C44, PID2024-158190NB-C22, RYC2021-033305-I, RYC2024-048719-I, CNS2023-144781, CNS2024-154769 and Plan de Ciencia, Tecnología e Innovación de Asturias, Spain; the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, the National Science, Research and Innovation Fund program IND_FF_68_369_2300_097, and the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B39G680009 (Thailand); the Eric & Wendy Schmidt Fund for Strategic Innovation through the CERN Next Generation Triggers project under grant agreement number SIF-2023-004; the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

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A Tables of angular polarization coefficients

This appendix collects tables listing the angular polarization coefficients A_0–A_7, as well as the $A_0 - A_2$ difference, measured in the CS frame, as a function of $p_{\mathrm{T}}^{\mu\mu}$ and in two $|y^{\mu\mu}|$ intervals. These numerical values correspond to the data points shown in Figs. 3–7.

Table A.1: Measured angular coefficients, in bins of $p_{\mathrm{T}}^{\mu\mu}$ (in GeV), for $|y^{\mu\mu}| < 1$.

$p_{\mathrm{T}}^{\mu\mu}$	0–10	10–20	20–35	35–55	55–80	80–120	120–200	200–400
A_0	0.030	0.086	0.205	0.392	0.572	0.723	0.848	0.922
Stat.	$\pm$0.001	$\pm$0.002	$\pm$0.002	$\pm$0.003	$\pm$0.003	$\pm$0.004	$\pm$0.008	$\pm$0.015
Syst.	$\pm$0.012	$\pm$0.011	$\pm$0.010	$\pm$0.006	$\pm$0.002	$^{+0.003}_{-0.004}$	$\pm$0.005	$\pm$0.006
A_1	0.0020	0.010	0.019	0.027	0.023	0.014	0.014	$<$0.0001
Stat.	$\pm$0.0009	$\pm$0.001	$\pm$0.002	$\pm$0.002	$\pm$0.004	$\pm$0.005	$\pm$0.006	$\pm$0.0113
Syst.	$\pm$0.0007	$\pm$0.001	$\pm$0.002	$\pm$0.003	$\pm$0.003	$\pm$0.003	$\pm$0.002	$^{+0.0038}_{-0.0035}$
A_2	$-$0.004	0.047	0.128	0.264	0.420	0.54	0.70	0.75
Stat.	$\pm$0.002	$\pm$0.002	$\pm$0.002	$\pm$0.003	$\pm$0.006	$\pm$0.01	$\pm$0.02	$\pm$0.03
Syst.	$\pm$0.004	$^{+0.004}_{-0.003}$	$\pm$0.005	$\pm$0.011	$\pm$0.016	$\pm$0.02	$\pm$0.02	$\pm$0.01
A_3	0.0020	0.0011	0.0018	0.0032	0.008	0.011	0.025	0.037
Stat.	$\pm$0.0007	$\pm$0.0008	$\pm$0.0011	$\pm$0.0016	$\pm$0.003	$\pm$0.004	$\pm$0.006	$\pm$0.012
Syst.	$\pm$0.0011	$\pm$0.0009	$\pm$0.0007	$\pm$0.0008	$\pm$0.001	$^{+0.002}_{-0.001}$	$\pm$0.002	$\pm$0.004
A_4	0.0125	0.011	0.0082	0.0098	0.0113	0.0080	0.001	0.008
Stat.	$\pm$0.0009	$\pm$0.001	$\pm$0.0015	$\pm$0.0020	$\pm$0.0025	$\pm$0.0031	$\pm$0.004	$\pm$0.009
Syst.	$\pm$0.0015	$\pm$0.001	$\pm$0.0008	$^{+0.0008}_{-0.0007}$	$\pm$0.0008	$\pm$0.0009	$\pm$0.002	$\pm$0.003
A_5	$-$0.0005	0.0005	0.0005	0.0017	$-$0.0001	0.0020	$-$0.001	$-$0.003
Stat.	$\pm$0.0008	$\pm$0.0009	$\pm$0.0012	$\pm$0.0016	$\pm$0.0024	$\pm$0.0033	$\pm$0.005	$\pm$0.011
Syst.	$\pm$0.0002	$\pm$0.0002	$\pm$0.0003	$^{+0.0005}_{-0.0004}$	$\pm$0.0005	$\pm$0.0007	$^{+0.001}_{-0.002}$	$\pm$0.003
A_6	0.0001	0.0013	$-$0.0004	0.0017	0.0007	$-$0.0043	$-$0.004	0.010
Stat.	$\pm$0.0009	$\pm$0.0011	$\pm$0.0013	$\pm$0.0017	$\pm$0.0023	$\pm$0.0030	$\pm$0.005	$\pm$0.010
Syst.	$^{+0.0003}_{-0.0002}$	$\pm$0.0003	$\pm$0.0003	$^{+0.0005}_{-0.0004}$	$^{+0.0006}_{-0.0005}$	$\pm$0.0008	$\pm$0.001	$^{+0.003}_{-0.004}$
A_7	$<$0.0001	$-$0.0003	0.0010	0.0002	0.0010	0.0040	0.006	0.016
Stat.	$\pm$0.0007	$\pm$0.0008	$\pm$0.0010	$\pm$0.0014	$\pm$0.0019	$\pm$0.0027	$\pm$0.004	$\pm$0.009
Syst.	$\pm$0.0002	$^{+0.0002}_{-0.0003}$	$\pm$0.0002	$^{+0.0003}_{-0.0004}$	$^{+0.0007}_{-0.0006}$	$\pm$0.0007	$\pm$0.001	$\pm$0.002

Table A.2: Measured angular coefficients, in bins of $p_{\mathrm{T}}^{\mu\mu}$ (in GeV), for $1 < |y^{\mu\mu}| < 2.4$.

$p_{\mathrm{T}}^{\mu\mu}$	0–10	10–20	20–35	35–55	55–80	80–120	120–200	200–400
A_0	0.023	0.083	0.194	0.375	0.560	0.717	0.841	0.903
Stat.	±0.002	±0.002	±0.003	±0.003	±0.004	±0.005	±0.008	±0.016
Syst.	±0.010	±0.008	±0.009	±0.007	±0.004	±0.003	±0.004	±0.006
A_1	-0.0031	0.021	0.041	0.069	0.076	0.075	0.061	0.059
Stat.	±0.0011	±0.001	±0.002	±0.003	±0.004	±0.006	±0.007	±0.013
Syst.	±0.0008	±0.002	±0.003	±0.004	±0.005	±0.005	±0.004	±0.005
A_2	-0.002	0.050	0.130	0.274	0.436	0.58	0.71	0.74
Stat.	±0.002	±0.002	±0.002	±0.003	±0.006	±0.01	±0.02	±0.03
Syst.	±0.010	$^{+0.009}_{-0.008}$	$^{+0.004}_{-0.005}$	±0.007	±0.010	±0.01	±0.01	±0.01
A_3	0.0017	0.0021	0.0063	0.0108	0.022	0.035	0.062	0.070
Stat.	±0.0008	±0.0009	±0.0011	±0.0016	±0.003	±0.004	±0.007	±0.013
Syst.	±0.0010	±0.0009	±0.0008	$^{+0.0008}_{-0.0009}$	±0.001	±0.002	±0.002	±0.004
A_4	0.059	0.054	0.052	0.047	0.038	0.034	0.025	0.029
Stat.	±0.001	±0.002	±0.002	±0.003	±0.003	±0.004	±0.005	±0.010
Syst.	±0.003	±0.002	±0.002	$^{+0.001}_{-0.002}$	±0.001	$^{+0.002}_{-0.001}$	±0.002	±0.004
A_5	<0.0001	0.0011	0.0002	0.0024	0.0034	0.003	0.008	0.015
Stat.	±0.0009	±0.0009	±0.0011	±0.0016	±0.0024	±0.003	±0.005	±0.011
Syst.	±0.0002	±0.0003	±0.0003	±0.0004	±0.0005	±0.001	±0.002	±0.003
A_6	-0.0004	0.0016	0.0015	0.0008	0.0077	0.0030	0.004	-0.007
Stat.	±0.0010	±0.0012	±0.0015	±0.0020	±0.0027	±0.0034	±0.005	±0.010
Syst.	±0.0003	±0.0004	±0.0004	±0.0005	$^{+0.0007}_{-0.0008}$	±0.0009	±0.002	±0.003
A_7	0.0012	0.0017	0.0022	0.0023	0.0050	0.0031	0.006	-0.0005
Stat.	±0.0007	±0.0008	±0.0010	±0.0014	±0.0020	±0.0027	±0.004	±0.0090
Syst.	±0.0002	±0.0002	±0.0002	±0.0003	$^{+0.0005}_{-0.0006}$	$^{+0.0007}_{-0.0008}$	±0.001	$^{+0.0031}_{-0.0034}$

Table A.3: Measured $A_0 - A_2$ difference in bins of $p_{\mathrm{T}}^{\mu\mu}$ (in GeV) and $|y^{\mu\mu}|$.

$p_{\mathrm{T}}^{\mu\mu}$	0–10	10–20	20–35	35–55	55–80	80–120	120–200	200–400
$\|y^{\mu\mu}\| < 1$								
$A_0 - A_2$	0.035	0.039	0.077	0.130	0.150	0.18	0.15	0.17
Stat.	±0.002	±0.003	±0.003	±0.004	±0.006	±0.01	±0.01	±0.03
Syst.	±0.012	$^{+0.012}_{-0.011}$	±0.011	±0.010	±0.020	±0.02	±0.01	±0.01
$1 < \|y^{\mu\mu}\| < 2.4$								
$A_0 - A_2$	0.024	0.034	0.064	0.100	0.120	0.14	0.13	0.16
Stat.	±0.002	±0.003	±0.004	±0.005	±0.006	±0.01	±0.01	±0.03
Syst.	±0.014	±0.012	±0.010	±0.010	±0.010	±0.01	±0.01	±0.01

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