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Observation of Centrality-Dependent Acoplanarity for Muon Pairs Produced via Two-Photon Scattering in Pb + Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS Detector

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This Letter presents a measurement of $\gamma\gamma \to \mu^+\mu^-$ production in Pb + Pb collisions recorded by the ATLAS detector at the Large Hadron Collider at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with an integrated luminosity of 0.49 nb^{-1}. The azimuthal angle and transverse momentum correlations between the muons are measured as a function of collision centrality. The muon pairs are produced from $\gamma\gamma$ through the interaction of the large electromagnetic fields of the nuclei. The contribution from background sources of muon pairs is removed using a template fit method. In peripheral collisions, the muons exhibit a strong back-to-back correlation consistent with previous measurements of muon pair production in ultraperipheral collisions. The angular correlations are observed to broaden significantly in central collisions. The modifications are qualitatively consistent with rescattering of the muons while passing through the hot matter produced in the collision.

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Ultrarelativistic heavy-ion collisions form hot strongly interacting matter known as the quark-gluon plasma (QGP) [1–4]. The characterization of the properties of the QGP provides unique insight into the dynamics of strongly coupled many-body systems and is a primary goal of the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) heavy-ion programs. A common method for studying complex physical systems involves the use of penetrating probes whose interactions with the system are well understood or calibrated. Examples of penetrating probes in heavy-ion collisions are high-energy quarks and gluons produced in initial hard-scattering processes [5,6]. Indeed, many measurements have shown striking modifications to dijet [7–9] or gamma-jet balance [10], the properties of jet-fragment distributions [11–16], and the production rates of high transverse-momentum (p_{T}) hadrons [17–19] or jets [20–23] as a result of the interactions of the parent quarks and gluons with the QGP medium. However, the physics of this phenomenon, known as jet quenching, is complex, in large part due to the multiparticle nature of the parton showers that produce the observed jets.

An alternative, simpler, penetrating probe is provided by $\gamma\gamma \to \ell^+\ell^-$ processes that occur at non-negligible rates in ultrarelativistic heavy-ion collisions due to the intense electromagnetic fields generated by ions [24–26]. The associated photons have small transverse momenta—typically less than 10 MeV—and large longitudinal momenta and energies [27,28]. For example, in $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV Pb + Pb collisions at the LHC, the photon energy spectra and the resulting lepton p_{T} distributions extend to about 50 GeV. Because of the low transverse momenta of the photons, the leptons are produced nearly back to back in azimuth and with nearly identical transverse momenta. Photon-induced scattering processes in heavy-ion collisions are typically studied in so-called ultraperipheral collisions (UPCs) [29,30] for which the impact parameter between the colliding nuclei is larger than twice the nuclear radius, such that there is no hadronic interaction between the nuclei. UPC events are used to study exclusive vector-meson production in photon-nucleus collisions [31–37], lepton-pair production in photon-photon collisions [36], and recently, light-by-light scattering [38].

Although photon-induced reactions are typically measured in UPCs, they have also been observed in hadronic collisions of heavy ions [39,40], and theoretical advances in describing such processes have been made [41]. In such events, the photon fluxes are largest just outside the nuclear overlap region. It is expected that charged leptons produced in this region interact with the electric charges in the QGP that is formed, which may modify the leptons' momenta. While the effects of electromagnetic interactions are much weaker than the strong interactions responsible for jet quenching, the initial angles and momenta of the produced leptons are sufficiently well correlated that modifications much smaller than those associated with jet quenching are observable. One potential source of modification arises as

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small momentum transfers to the leptons due to electromagnetic interactions may result in the broadening of the momentum and angular correlations of the lepton pair, in analogy with the original picture of jet energy loss proposed by Bjorken [42]. Such broadening should be largest in central collisions, where the degree of overlap between the colliding nuclei is greatest and the transverse size and lifetime of the plasma are largest. Unlike jet observables [7–9,43], measurements using lepton pairs in this fashion have not been explored previously. Jets are multiparticle systems consisting of a shower of quarks and gluons. Measurements of the modification of these showers provide detailed information about the microscopic structure of the QGP over a range of length scales but at the expense of introducing significant complexity to the problem. The interaction of lepton pairs with the medium is much simpler, and thus measurements using such pairs are a critical baseline for understanding jet quenching.

This Letter reports a measurement by ATLAS of the angular and momentum correlations of muon pairs produced via photon-photon scattering in 5.02 TeV Pb + Pb collisions using data with an integrated luminosity of 0.49 nb^{-1} recorded during the 2015 Pb + Pb operation of the LHC. The $\gamma\gamma \to \mu^+\mu^-$ pairs are distinguishable from muon pairs arising from other production mechanisms through their angular and momentum correlations, which are quantified using the pair acoplanarity, α, and asymmetry, A, defined as

$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}, \qquad A \equiv \left| \frac{p_\mathrm{T}^+ - p_\mathrm{T}^-}{p_\mathrm{T}^+ + p_\mathrm{T}^-} \right|,$$

where $\phi^\pm$ represent the azimuthal angles and $p_\mathrm{T}^\pm$ the magnitudes of the transverse momenta of the two muons. The distributions of these quantities from $\gamma\gamma \to \mu^+\mu^-$ pairs are extremely peaked near zero due to the small transverse momentum of the $\gamma\gamma$ system. Background at small α and A, resulting from semileptonic decays of heavy-flavor (HF) hadrons, is subtracted using a template fit method exploiting the fact that these hadrons often decay after traveling a significant distance from the interaction point. Other background contributions such as Drell-Yan and Υ production and dissociative processes [44] are observed to be negligible over the narrow range of α and A considered here. The α and A distributions are presented for different intervals of Pb + Pb collision centrality. A broadening observed in the α distributions is characterized using a fitting procedure that provides a transverse momentum scale, $k_\mathrm{T}^\mathrm{rms}$.

The data are recorded with the ATLAS detector [45] using its calorimeter, inner detector, muon spectrometer, trigger, and data acquisition systems [46]. The calorimeter system consists of a liquid-argon (LAr) electromagnetic calorimeter covering $|\eta| < 3.2$, a steel-scintillator sampling hadronic calorimeter covering $|\eta| < 1.7$, a LAr hadronic calorimeter covering $1.5 < |\eta| < 3.2$, and a forward calorimeter (FCal) covering $3.2 < |\eta| < 4.9$. Charged-particle tracks are measured over the range $|\eta| < 2.5$ using the inner detector, which is composed of silicon pixel detectors in the innermost layers, followed by silicon microstrip detectors and a straw-tube transition-radiation tracker ($|\eta| < 2.0$), all immersed in a 2 T axial magnetic field. The muon spectrometer system comprises separate trigger and high-precision tracking chambers, covering $|\eta| < 2.4$ and $|\eta| < 2.7$, respectively, measuring the deflection of muons in a magnetic field provided by superconducting air-core toroid magnets.

Events used in this measurement are selected by a trigger requiring at least two muons [47], each having $p_\mathrm{T} > 4$ GeV. Events are further required to have a reconstructed primary vertex, built from at least two tracks with $p_\mathrm{T} > 0.4$ GeV. The collision centrality is determined by analyzing the total transverse energy measured in the FCal in minimum-bias Pb + Pb collisions and dividing the distribution into centrality intervals corresponding to successive quantiles of the total [48]. The intervals used in this measurement are 0%–10%, 10%–20%, 20%–40%, 40%–80%, and > 80%, which are ordered from the most central (highest transverse energy) to most peripheral. The > 80% interval includes the 80%–100% centrality interval as well as UPC events, which contain most of the muon pairs measured in that interval.

The detector response to signal muon pairs is evaluated using Monte Carlo (MC) samples of $\mathrm{Pb} + \mathrm{Pb} \to \mathrm{Pb}^{(*)}\gamma\gamma\mathrm{Pb}^{(*)} \to \mathrm{Pb}^{(*)}\mu^+\mu^-\mathrm{Pb}^{(*)}$ events, produced with the STARLIGHT event generator [28,49], which utilizes the equivalent photon approximation; the transverse momentum distributions of the incoming photons are determined by the nuclear form factor, resulting in $\gamma\gamma$ collision systems with small transverse momenta. A separate MC sample of background muon pairs resulting from heavy-flavor decays was produced using PYTHIA 8.185 [50] with the A14 set of tuned parameters [51] and NNPDF2.3 LO parton distribution functions [52]. Both samples were passed through a GEANT 4 [53] simulation of the detector and overlaid on minimum-bias Pb + Pb data. The resulting events were reconstructed in the same manner as the data.

The analysis is performed by considering all oppositely charged muon pairs in the events meeting the trigger and event selection requirements. The muons are identified by matching tracks in the muon spectrometer to tracks in the inner detector. Each muon is required to have $p_\mathrm{T} > 4$ GeV and $|\eta| < 2.4$ [54,55]. An invariant mass requirement of $4 < m_{\mu^+\mu^-} < 45$ GeV is applied to suppress the contribution from hadron (primarily J/ψ) decays and Z boson decays to muon pairs. In order to account for inefficiency introduced by the trigger and reconstruction, each muon is weighted by $w = (\varepsilon_\mathrm{trig}\varepsilon_\mathrm{reco})^{-1}$ when constructing the distributions. Both efficiencies are functions of the muon p_T and η and are obtained from studies of $J/\psi \to \mu^+\mu^-$ decays [56,57]. The efficiencies rise rapidly as a function of p_T

before reaching constant values of approximately 0.8 to 0.95 for $p_T > 5$ GeV, depending on the η value. Systematic uncertainties due to the efficiency corrections are evaluated by varying each efficiency by its uncertainty. These variations have little impact on the measurement since they largely cancel out in final observables, which are normalized by the total yield.

The α and A distributions include significant background from HF decays. The background α and A distributions are each obtained from data by making selections on the other variable to suppress the $\gamma\gamma$ contribution. Specifically, the background α distribution is constructed by requiring $A > 0.06$, and the background A distribution is obtained by requiring $\alpha > 0.015$. These selections were found not to significantly alter the distributions in the HF MC sample. In order to minimize the influence of statistical fluctuations, both the background α and A distributions were assumed to be smooth functions, determined by fitting them with second-order polynomials. Systematic uncertainties in the shapes of these distributions are evaluated by propagating statistical uncertainties obtained from the fits including covariance between the parameters. The systematic uncertainty of the background shape is evaluated by performing the fits with linear and constant functions.

The normalization of the background α and A distributions is determined using a template-fitting procedure. The quadrature sum $d_{0\mathrm{pair}} \equiv d_0^+ \oplus d_0^-$ is constructed for each muon pair, where $d_0^\pm$ are the transverse impact parameters of the track trajectories of the individual muons relative to the collision vertex. The template fitting is performed over the signal-enriched kinematic range $\alpha < 0.015$ and $A < 0.06$. The $d_{0\mathrm{pair}}$ distributions are fit using the function $\mathcal{F}(d_{0\mathrm{pair}}) \equiv f\mathcal{S}(d_{0\mathrm{pair}}) + (1-f)\mathcal{B}(d_{0\mathrm{pair}})$, where $\mathcal{S}$ and $\mathcal{B}$ are the $\gamma\gamma$ signal and HF background distributions, respectively, to obtain the signal fraction, f. The $\mathcal{S}$ distributions are determined primarily by multiple scattering and detector resolution, and are obtained from the STARLIGHT MC sample. The $\mathcal{B}$ distributions have long tails as one or both of the HF hadrons may travel a significant distance before decaying. These $\mathcal{B}$ distributions are obtained from data by requiring that $A > 0.15$ and $\alpha > 0.02$. Since the signal process populates only small values of A and α, the $\mathcal{B}$ distributions obtained in this way are dominated by the HF contribution in the data. In the 40%–80% and >80% centrality intervals, the distributions from the HF MC sample were used, as the data did not contain enough events after applying these selections to construct a template. An example of the template fitting for the 0%–10% centrality interval is shown in the left panel of Fig. 1. Uncertainties in the signal fractions resulting from the $\mathcal{S}$ shape are obtained by modifying the fit function, $\mathcal{F}_{\mathrm{sys}}(d_{0\mathrm{pair}}) \equiv f\mathcal{S}(cd_{0\mathrm{pair}}) + (1-f)\mathcal{B}(d_{0\mathrm{pair}})$, where c is an additional free parameter in the fitting that enables scaling of the $\mathcal{S}$ distributions along the $d_{0\mathrm{pair}}$ axis; this variation accounts for possible inaccuracies in the d_0 resolution in the STARLIGHT MC sample. Uncertainties due to the $\mathcal{B}$ template are evaluated by varying the requirements on α and A in the definition of the background region. The signal fraction in the 0%–10% interval is $f = 0.51 \pm 0.03$, and generally increases in more peripheral collisions, becoming consistent with no background contribution in the most peripheral interval, >80%.

The α and A distributions are obtained from the data by restricting the range of the other variable: $A < 0.06$ and $\alpha < 0.015$, respectively. Both the data obtained in this fashion and the background distributions are shown in the center and right panels of Fig. 1 respectively, for the 0%–10% centrality interval.

The background-subtracted distributions $(1/N_s)dN_s/d\alpha$ and $(1/N_s)dN_s/dA$ measured in different centralities in the data are shown in Fig. 2 in the top and bottom rows, respectively. Each distribution is normalized to unity over its measured range. The > 80% distribution is plotted in each panel for comparison. The systematic uncertainties affecting the background normalization and shape are not shown in this figure. These uncertainties are generally

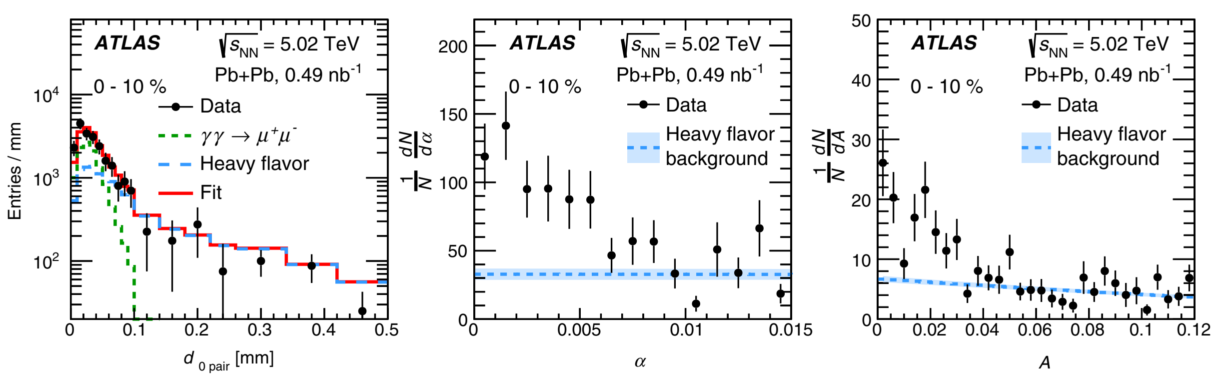

FIG. 1. Template fits (left) to the $d_{0\mathrm{pair}}$ distributions are shown for the 0–10% interval. The α (center) and A (right) distributions are shown before background subtraction (points). These distributions are normalized to unity over their measured range. In the central and right plots, the background contributions with normalization fixed by the template fitting are indicated by the dashed line with the uncertainties represented by the shaded band.

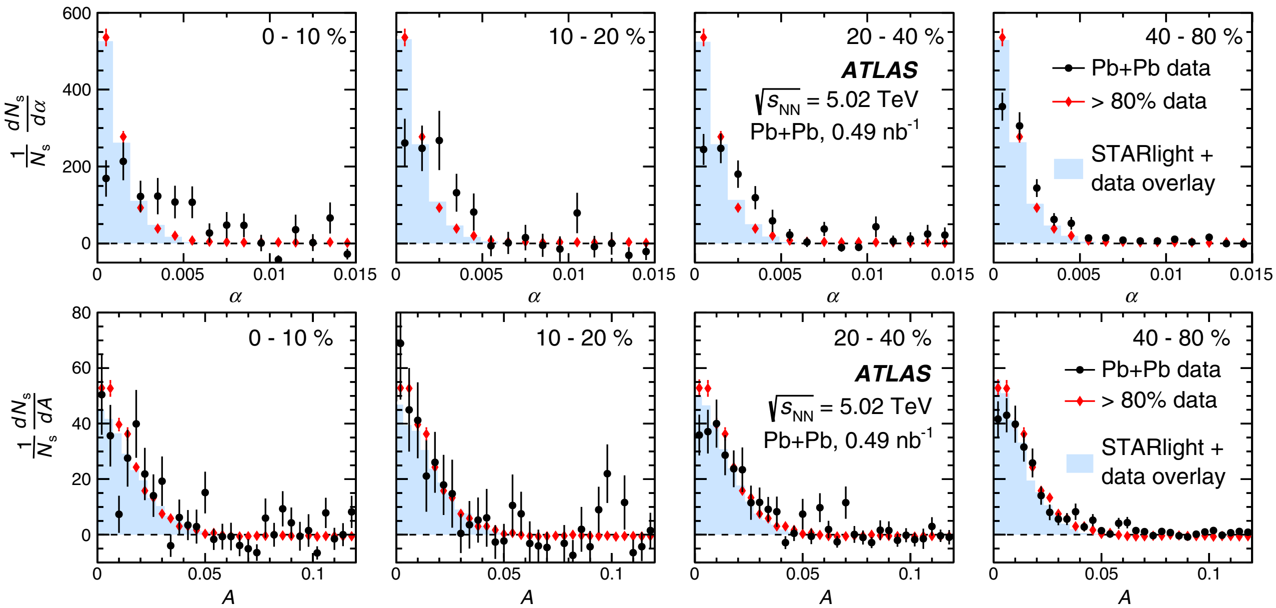

FIG. 2. The background-subtracted distributions are shown for α (upper row) and A (lower row). Each distribution is normalized to unity over its measured range. Moving from left to right, the data (circles) are shown for increasingly peripheral collisions (lower degree of overlap, higher percentile). The distributions obtained from the MC simulation ($\gamma\gamma \to \mu^+\mu^-$ generated by STARLIGHT and overlaid on data) are shown for the corresponding centrality interval as a filled histogram. The distribution measured in the most peripheral collisions, the $>$ 80% interval (diamonds) is repeated in each panel to facilitate a direct comparison. The error bars include the statistical and systematic uncertainties. Uncertainties related to the background normalization are not shown.

negligible compared with the statistical uncertainties indicated by the error bars, and they exhibit strong correlations as a function of α and A. After background subtraction, both data distributions are consistent with zero at the largest values of α and A considered in the measurement. This feature indicates that other sources of background, such as Drell-Yan and Υ production and dissociative processes, which are essentially constant over the measurement range, are not a significant contribution. A clear, centrality-dependent broadening is seen in the acoplanarity distributions when compared to the $>$ 80% interval. No such effect is seen for the asymmetry distributions. The corresponding distributions from the $\gamma\gamma \to \mu^+\mu^-$ MC samples are also shown. The MC α distributions show almost no centrality dependence, indicating that the broadening evident in the data is notably larger than that expected from detector effects. Although the A distributions from the MC sample broaden slightly in more central collisions, they are intrinsically much broader than the corresponding α distributions.

In order to quantify the broadening observed in the α distributions, the unsubtracted distributions are fit to a Gaussian function plus the normalized background distribution. The fit functions are shown with the solid curves in Fig. 3 and the values of the width, σ, are listed in Table I. The σ values increase by more than a factor of 2 between the most peripheral interval and the most central interval. Similar fits are performed for the A distributions and the resulting σ values are listed in Table I. Unlike the α

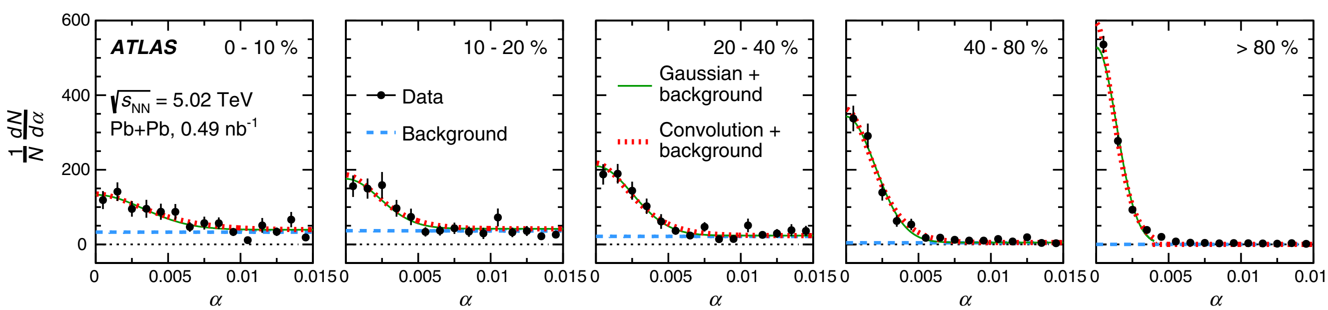

FIG. 3. Results of fits to the muon pair α distributions using the sum of Gaussian and background functions. A standard Gaussian function is shown as a solid curve while the dotted curve shows a Gaussian function in α convolved with the measured $p_{\mathrm{T\,avg}}$ distribution. The background distributions are indicated by the dashed lines.

TABLE I. Values of the parameters obtained by applying the Gaussian and convolution fits to the α distributions shown in Fig. 3 for different intervals of centrality. Also shown are the average number of participants, $\langle N_{\text{part}}\rangle$; the rms $p_{\text{T avg}}$, $p_{\text{T avg}}^{\text{rms}}$, used to relate the σ parameter to $k_{\text{T}}^{\text{rms}}$ in the Gaussian fitting procedure; and the σ parameter obtained from applying the Gaussian fitting to the A distributions.

Centrality	$\langle N_{\text{part}}\rangle$	$p_{\text{T avg}}^{\text{rms}}$ [GeV]	$\sigma_A(\times 10^3)$	Gaussian fit $\sigma_\alpha(\times 10^3)$	$k_{\text{T}}^{\text{rms}}$ [MeV]	Convolution fit $k_{\text{T}}^{\text{rms}}$ [MeV]
0–10%	359 ± 2	7.0 ± 0.1	$17.9^{+1.0}_{-0.9}$	3.3 ± 0.4	66 ± 10	70 ± 10
10–20%	264 ± 3	7.7 ± 0.4	$13.6^{+1.2}_{-1.0}$	2.3 ± 0.3	40 ± 7	42 ± 7
20–40%	160 ± 3	7.4 ± 0.3	$17.2^{+0.4}_{-0.4}$	2.5 ± 0.2	48 ± 6	44 ± 5
40–80%	47 ± 2	6.8 ± 0.3	$16.1^{+0.1}_{-0.1}$	2.0 ± 0.1	35 ± 4	32 ± 2
$> 80\%$		7.0 ± 0.3	$15.5^{+0.1}_{-0.1}$	1.40 ± 0.03		

distributions, no significant broadening of the A distributions can be inferred.

Assuming that the broadening of the α distributions results from a physical process that transfers a *small* amount of transverse momentum, $|\vec{k}_{\text{T}}| \ll p_{\text{T}}^{\pm}$, to each muon then the variance of the α distribution can be approximated as

$$\langle \alpha^2 \rangle = \langle \alpha^2 \rangle_0 + \frac{1}{\pi^2} \frac{\langle \vec{k}_{\text{T}}^2 \rangle}{\langle p_{\text{T avg}}^2 \rangle}, \quad (1)$$

where $p_{\text{T avg}}$ is the average of ${p_{\text{T}}}^+$ and ${p_{\text{T}}}^-$ and $\langle \alpha^2 \rangle_0$ is the intrinsic mean square acoplanarity resulting from both the production process itself and the angular resolution in the muon measurement.

Taking $\langle \alpha^2 \rangle_0$ to be the σ^2 of the Gaussian fit in the $> 80\%$ interval, an estimate of the root mean square (rms) of $|\vec{k}_{\text{T}}|$, $k_{\text{T}}^{\text{rms}}$, is evaluated in each centrality interval using the measured value of the rms value of $p_{\text{T avg}}$, and substituting σ^2 of the Gaussian fit in that centrality interval for $\langle \alpha^2 \rangle$. For the 0–10% centrality interval this procedure gives $k_{\text{T}}^{\text{rms}} = 66 \pm 10$ MeV.

The variance of the A distribution obeys a relation similar to Eq. (1) but with $1/\pi^2$ substituted by $1/4$. If the values obtained above for $k_{\text{T}}^{\text{rms}}$ are used in that equation an increase of only about 0.001 in the rms of A is expected between $> 80\%$ and 0%–10% collisions. The insensitivity of the asymmetry to the broadening observed in the acoplanarity distributions can be understood as resulting from the roughly 5 times larger intrinsic width of the A distribution. This larger width is consistent with, and can be attributed to, the momentum resolution of the ATLAS inner detector [58].

This fitting procedure provides a direct relationship between the widths of the α distributions and the $k_{\text{T}}^{\text{rms}}$ but does not fully account for the shape of the $p_{\text{T avg}}$ distributions. This limitation is addressed by an alternative procedure, in which the unsubtracted α distributions are fit as above but replacing the Gaussian function with a function produced by convolving the measured $p_{\text{T avg}}$ distribution in each centrality interval with a Gaussian function in α of width $\sqrt{(k_{\text{T}}^{\text{rms}})^2 + k_{\text{T0}}^2}/\pi p_{\text{T avg}}$. The parameter k_{T0} is obtained from the fit to the data in the $> 80\%$ centrality interval. The results of these fits are also shown in Fig. 3, and the obtained $k_{\text{T}}^{\text{rms}}$ values are shown in Fig. 4 as a function of $\langle N_{\text{part}}\rangle$, the average number of participant nucleons in each centrality interval obtained from a Glauber model analysis [48]. Also shown in Fig. 4 are estimates for $k_{\text{T}}^{\text{rms}}$ obtained by applying Eq. (1) to the results of the Gaussian acoplanarity fits. The two methods yield results that are consistent within their uncertainties. With both methods, the extracted $k_{\text{T}}^{\text{rms}}$ is observed to grow from more peripheral to more central collisions, or equivalently, from smaller to larger $\langle N_{\text{part}}\rangle$. In the 0%–10% centrality interval $k_{\text{T}}^{\text{rms}} = 70 \pm 10$ MeV. Variations of the $p_{\text{T avg}}$-convolution fitting are also performed allowing an additional background contribution consistent with Drell-Yan and dissociative processes. The extracted $k_{\text{T}}^{\text{rms}}$ agree with those reported here well within the uncertainties

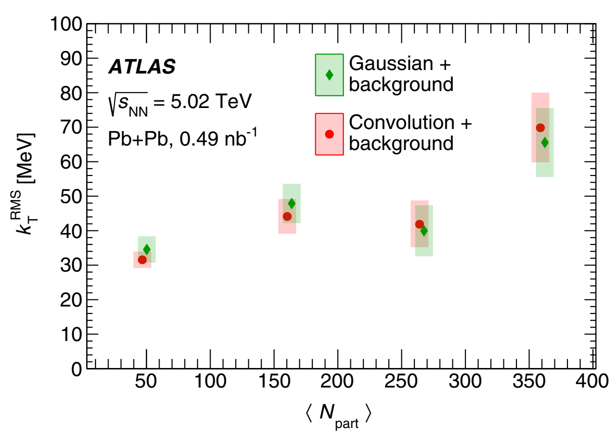

FIG. 4. The $k_{\text{T}}^{\text{rms}}$ values obtained from the fits shown in Fig. 3 as a function of $\langle N_{\text{part}}\rangle$. The shaded bands indicate the total uncertainty accounting for both the systematic and statistical uncertainties in the α distributions and background. The data points have been horizontally offset for visualization purposes, and the horizontal sizes of the error bands are arbitrary.

associated with the background subtraction. Although the discussion here formulates the broadening as momentum transfer applied to each muon, the analysis does not assume that such final-state effects are the only possible mechanism, and the physical interpretation of the $k_{\mathrm{T}}^{\mathrm{rms}}$ values is not limited to this paradigm. More generally, the $k_{\mathrm{T}}^{\mathrm{rms}}$ values provide an estimate of a transverse momentum scale associated with a physical mechanism absent in the typical description of coherent $\gamma\gamma$ processes in heavy-ion collisions, in which the $\gamma\gamma$ system has much less initial transverse momentum.

In conclusion, this Letter reports a measurement of muon pair production in Pb + Pb collisions in which the pairs are produced electromagnetically through the process $\gamma\gamma \to \mu^+\mu^-$. Contributions from heavy-flavor decays are removed and the resulting α and A distributions exhibit a strong correlation attributable to the small transverse momentum of the initial $\gamma\gamma$ system. The α distributions are observed to broaden in increasingly central collisions. No such broadening is seen in the A distributions, where the sensitivity is limited by momentum resolution. A transverse momentum scale quantifying the magnitude of the broadening, relative to > 80% collisions, is extracted from the α distributions. In the 0%–10% centrality interval, that scale, assumed to be the rms momentum transfer to each final-state muon in the transverse plane, is $k_{\mathrm{T}}^{\mathrm{rms}} = 70 \pm 10$ MeV.

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