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Observation of forward neutron multiplicity dependence of dimuon acoplanarity in ultraperipheral PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

The CMS Collaboration

Abstract

The first measurement of the dependence of $\gamma\gamma \rightarrow \mu^+\mu^-$ production on the multiplicity of neutrons emitted very close to the beam direction in ultraperipheral heavy ion collisions is reported. Data for lead-lead interactions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, with an integrated luminosity of approximately 1.5 nb^{-1} , were collected using the CMS detector at the LHC. The azimuthal correlations between the two muons in the invariant mass region $8 < m_{\mu\mu} < 60$ GeV are extracted for events including zero, one, or at least two neutrons detected in the forward pseudorapidity range $|\eta| > 8.3$. The back-to-back correlation structure from leading-order photon-photon scattering is found to be significantly broader for events with a larger number of emitted neutrons from each nucleus, corresponding to interactions with a smaller impact parameter. This observation provides a data-driven demonstration that the average transverse momentum of photons emitted from relativistic heavy ions has an impact parameter dependence. These results provide new constraints on models of photon-induced interactions in ultraperipheral collisions. They also provide a baseline to search for possible final-state effects on lepton pairs caused by traversing a quark-gluon plasma produced in hadronic heavy ion collisions.

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1 The Lorentz-boosted electromagnetic (EM) fields surrounding relativistic heavy ions with large
 2 charges can be treated as a flux of quasireal photons [1, 2] with the flux intensity proportional
 3 to the square of the ion charge. Therefore, ions accelerated at colliders can interact when
 4 their impact parameter (b) is greater than twice the nuclear radius (R_A), via photon-photon
 5 and photon-nucleus processes, the so-called ultraperipheral collisions (UPCs) [3–8][3, 4, 6–8]
 6 . Photon-photon interactions ~~are fundamental processes that~~ can be used to test quantum
 7 electrodynamics (QED) and to search for physics beyond the standard model [9–16][5, 9–17]
 8 . Photon-nucleus interactions probe the gluon distribution at small Bjorken x in the nucleon or
 9 nucleus [11, 12, 18–25][11, 12, 18–25].

10 The momentum of emitted quasireal photons is predominantly along the beam direction and
 11 the transverse momentum (p_T) is small, ~~on the scale of ω/γ_L , where ω is the photon energy
 12 and γ_L is the Lorentz factor of the projectile and target nuclei in the lab frame typically less than
 13 30 MeV [6, 7].~~ Therefore, the lepton pairs produced from leading-order photon-photon scatter-
 14 ing ($\gamma\gamma \rightarrow \ell^+\ell^-$) possess small pair p_T and are nearly back-to-back in the azimuthal angle (ϕ).
 15 Recently, photon-photon [26, 27] and photon-nucleus [28, 29] processes have been observed at
 16 very low p_T in hadronic ($b < 2R_A$) heavy ion collisions. Interestingly, a broadening of lepton
 17 pair azimuthal angle correlations (or equivalently an increase of lepton pair p_T) is observed
 18 in hadronic collisions compared to that from UPCs [26, 27]. In hadronic events, a deconfined
 19 state of partonic matter, known as the quark-gluon plasma (QGP), can be formed. Therefore,
 20 final-state EM modifications of lepton pairs inside a QGP medium ~~(Coulomb rescattering or
 21 deflection by magnetic fields trapped in the QGP)~~ have been proposed as possible interpre-
 22 tations of the broadening effect [26, 27, 30]. The initial p_T of the lepton pairs depends on the
 23 overlap integral of the photon fluxes produced by the two nuclei, and as a result the average
 24 pair p_T ($\langle p_T \rangle$) could depend on the b between the two colliding ions. Although models of the
 25 flux of photons integrated over a given b range have large uncertainties [8, 31, 32], a QED calcu-
 26 lation [32] predicts larger $\langle p_T \rangle$ for smaller b values. Such a larger $\langle p_T \rangle$ in the initial state would
 27 broaden the pair angular correlation, which could explain the effects observed in more central
 28 hadronic collisions.

29 To disentangle possible contributions from initial- and final-state effects to the modifications
 30 observed in hadronic heavy ion collisions, an experimental handle on the b dependence of
 31 lepton pair production in UPCs is essential. The photon-photon interactions can occur in con-
 32 junction with the excitation of one or both of the ions via photon absorption into giant dipole
 33 resonances or higher excited states [6–8, 33, 34][6–8, 17, 33, 34]. The giant dipole resonances
 34 typically decay by emitting a single neutron, while higher excited states may emit two or more
 35 neutrons. These forward neutrons have very low relative momentum with respect to their
 36 parent ions, and therefore approximately retain the beam rapidity. The contribution of higher
 37 excitations becomes larger as b gets smaller [6–8][6–8, 17]. Therefore, the number of emitted
 38 neutrons detected in the forward region can be used to classify UPC events into different b
 39 ranges.

40 This letter reports the first measurement of the forward neutron multiplicity dependence of
 41 $\gamma\gamma \rightarrow \mu^+\mu^-$ production in the muon pair invariant mass region $8 < m_{\mu\mu} < 60$ GeV in lead-lead
 42 (PbPb) UPCs at a nucleon-nucleon center-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV, using data collected
 43 with the CMS detector during the 2018 LHC run. The PbPb sample that includes information
 44 about forward neutrons corresponds to an integrated luminosity of approximately 1.5 nb^{-1} .
 45 Azimuthal correlations of muon pairs, quantified by the acoplanarity, $\alpha = 1 - |\phi^+ - \phi^-|/\pi$,
 46 are presented for several different classes of neutron multiplicity detected in the forward pseu-
 47 dorapidity range $|\eta| > 8.3$. Here, ϕ^\pm represent the azimuthal angle of each muon in the lab
 48 frame. A larger average α for lepton pairs from leading-order $\gamma\gamma$ scatterings corresponds to

fewer back-to-back azimuthal correlations, and thus larger initial p_T of the interacting photons. The muon azimuthal angle is used instead of p_T because of its superior experimental resolution. The average invariant mass of muon pairs in various neutron multiplicity classes is also presented as a probe of the initial photon energy and its b dependence.

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, there are four subdetectors, including a silicon pixel and strip tracker detector, a lead-tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are detected in the range $|\eta| < 2.4$ in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching muons to tracks measured in the silicon tracker leads to a relative p_T resolution around 1% [35] and an azimuthal angle resolution better than 7×10^{-4} radians for a typical muon in this analysis. The CMS experiment has extensive forward calorimetry, including two steel and quartz-fiber Cherenkov hadron forward (HF) calorimeters that cover the range of $2.9 < |\eta| < 5.2$, which are used to reject hadronic PbPb collision events. Two zero degree calorimeters (ZDC) [36], made of quartz fibers and plates embedded in tungsten absorbers, are used to detect neutrons from nuclear dissociation events in the range $|\eta| > 8.3$. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [37].

Events used in this study were selected online using a hardware-based trigger system that requires at least one muon candidate coincident with a PbPb bunch crossing [38]. On the trigger level, there is no explicit selection on the minimum muon p_T and events with an energy deposit above the noise threshold in both HF calorimeters are vetoed. For the offline analysis, events have to pass a set of selection criteria designed to reject beam-related background processes (beam-gas collisions and beam scraping events) and hadronic collisions. Events are required to have a primary interaction vertex, formed by two or more tracks, within 20 cm from the CMS detector center along the beam axis. The cluster shapes in the pixel detector must be compatible with those expected from particles produced by a PbPb collision [39]. To suppress hadronic PbPb collisions, the largest energy deposits in the HF calorimeters are required to be below 7.3 and 7.6 GeV in the positive and negative rapidity sides, respectively, where these noise thresholds are determined from empty bunch crossing events. In addition, events must contain exactly two muon candidates and no additional tracks in the range $|\eta| < 2.4$. Selected events are then classified by neutron multiplicity, which is determined by the energies deposited in the ZDCs. For single neutrons, the relative energy resolution of the ZDCs is ~ 22 – 26% , while the detection efficiency is close to 100% in simulated events [36]. Based on neutron peaks observed in the total ZDC energy distribution (see Appendix A), events are divided into three neutron multiplicity classes (0n, 1n, and Xn with $X \geq 2$) on each side. The corresponding purities of selected neutron multiplicity classes are estimated by a multi-Gaussian function fit to the energy distribution. The purities are nearly 100% for the 0n and Xn classes ~~and~~, but only ~ 93 – 95% for the 1n class because of detector resolution effects. From the combinations of the number of neutrons in each ZDC separately, a total of six neutron multiplicity classes, labeled as 0n0n, 0n1n, 0nXn, 1n1n, 1nXn, and XnXn, are used in this study. The 0n0n class corresponds to no Coulomb break-up of either nucleus and the 1nXn class corresponds to one neutron emitted from one nucleus and at least two neutrons emitted from the other nucleus.

Muons are selected in the kinematic range of $p_T^\mu > 3.5$ GeV and $|\eta^\mu| < 2.4$. They are reconstructed using the combined information of the tracker and muon detectors (so-called "soft muons" defined in Ref. [35]). The opposite-sign distribution (signal and background) is re-

constructed by combining μ^+ and μ^- candidates, while the combinatorial background is estimated using events containing same-sign muons. One of the muon candidates in the opposite- or same-sign pair is required to match a trigger muon. The studied dimuon kinematic range is $8 < m_{\mu\mu} < 60 \text{ GeV}$ and $|y^{\mu\mu}| < 2.4$ to ensure high efficiency and also to suppress the contribution from photoproduced resonances (charmonia and Z bosons).

The detector reconstruction efficiency is estimated using a dedicated $\gamma\gamma \rightarrow \mu^+\mu^-$ Monte Carlo simulation sample produced by the STARLIGHT (v3.0) event generator [40] without restriction on the Coulomb break-up of either nucleus. Only $\ell^+\ell^-$ pairs from the leading-order $\gamma\gamma$ scattering are generated, and the calculation is performed by integrating over the entire b space for UPC events. No differential b dependence of the initial photon p_T is considered in STARLIGHT. The CMS detector response is simulated further using GEANT4 with these STARLIGHT generated events [41]. The muon trigger ($\epsilon_{\text{trig}}^{\mu}$) and reconstruction ($\epsilon_{\text{reco}}^{\mu}$) efficiencies are estimated as functions of p_T^{μ} , η^{μ} , and ϕ^{μ} . To correct for detector inefficiencies, each muon pair event is scaled by $(\epsilon_{\text{trig}}\epsilon_{\text{reco}})^{-1}$, where $\epsilon_{\text{trig}} = 1 - (1 - \epsilon_{\text{trig}}^{\mu+})(1 - \epsilon_{\text{trig}}^{\mu-})$ and $\epsilon_{\text{reco}} = \epsilon_{\text{reco}}^{\mu+}\epsilon_{\text{reco}}^{\mu-}$. The reconstruction and trigger efficiencies rapidly reach a plateau as functions of p_T with values of $\sim 95\text{--}99\%$ above $p_T^{\mu} \approx 6 \text{ GeV}$ for $|\eta^{\mu}| < 1.2$ and above $p_T^{\mu} \approx 4 \text{ GeV}$ for $1.2 < |\eta^{\mu}| < 2.4$. Systematic uncertainties associated with the efficiency corrections are negligible since they largely cancel out in the final observables, which are normalized by the total yield.

The cross section of single electromagnetic dissociation (EMD) [42, 43] of Pb nuclei in PbPb collisions was measured to be $187.4 \pm 0.2 \text{ (stat)}_{-11.2}^{+13.2} \text{ (syst) b}$ at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ [44]. It is expected to be even larger at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ given the stronger EM fields. Because of the large single-EMD cross section, a single measured $\gamma\gamma \rightarrow \mu^+\mu^-$ event may contain concurrent EMD PbPb events in the same bunch crossing. These concurrent events can emit neutrons and migrate the neutron multiplicity of a single $\gamma\gamma \rightarrow \mu^+\mu^-$ interaction to higher values. This EMD pileup effect is quantified by measuring the ZDC energy distributions from “zero bias” triggered events that require only the presence of both beams in the same bunch crossing. No valid collision vertex or track is allowed to be present in the event. The same HF veto thresholds as for the $\gamma\gamma \rightarrow \mu^+\mu^-$ events are applied. The neutron multiplicity classes in these selected zero-bias events are used to estimate the probability of a $\gamma\gamma \rightarrow \mu^+\mu^-$ event being assigned an incorrect neutron multiplicity because of pileup effects. By inverting a matrix of these migration probabilities, the true observable distributions are extracted from the measured data. In this study, about 11% of measured $\gamma\gamma \rightarrow \mu^+\mu^-$ events have neutron multiplicity migration caused by EMD pileup.

Figure 1 shows the corrected α distributions of $\mu^+\mu^-$ pairs in PbPb collisions within the kinematic range ($p_T^{\mu} > 3.5 \text{ GeV}$, $|\eta^{\mu}| < 2.4$, and $|y^{\mu\mu}| < 2.4$) for different neutron multiplicity classes. The α distributions are normalized to unit integral over their measured range ($(1/N_s)dN_s/d\alpha$, where N_s represents the signal yield). Each α spectrum is characterized by a narrow core close to zero and a long tail. The core component mostly originates from the leading-order $\gamma\gamma$ scattering, while in the tail component, higher-order $\gamma\gamma$ processes dominate. These higher-order processes include, e.g., extra photon radiation from the produced lepton(s), multiple-photon interactions, or scattering of (one or both) photons emitted from one of the protons inside the nucleus [5, 30]. The tail contribution in the XnXn class is larger than that in the 0n0n class. This is consistent with the expectation of larger contributions of higher-order $\gamma\gamma$ processes in UPC events that have smaller b and produce more neutrons in the forward region.

To investigate a possible b dependence of the initial photon p_T , the core contribution to the α distribution is decoupled from the tail contribution using a two-component empirical fit func-

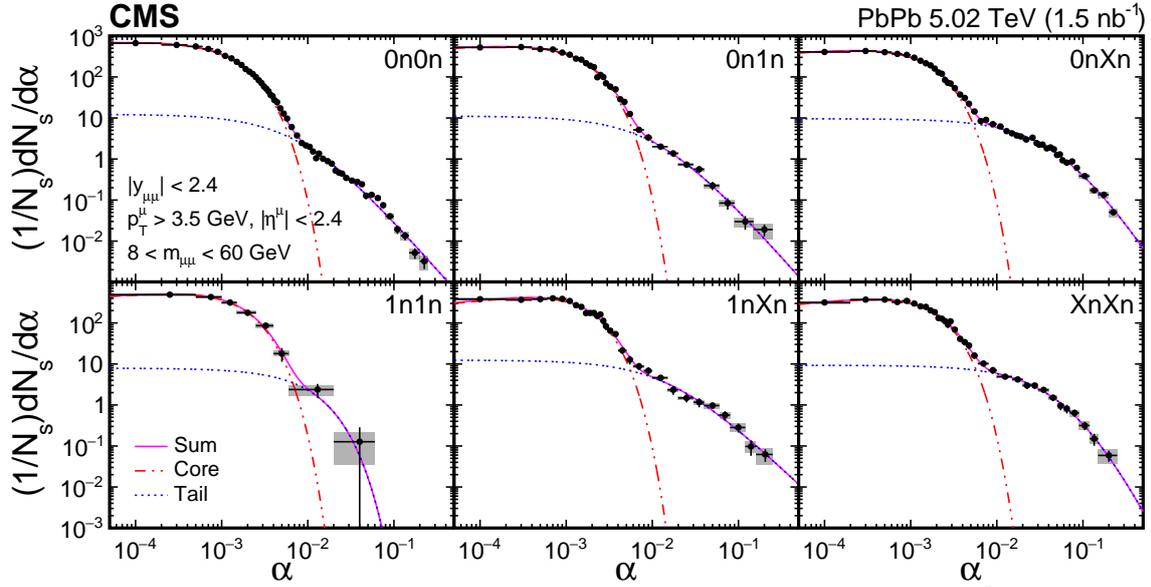


Figure 1: Neutron multiplicity dependence of acoplanarity distributions from $\gamma\gamma \rightarrow \mu^+\mu^-$ for $p_T^\mu > 3.5$ GeV, $|\eta^\mu| < 2.4$, $|y^{\mu\mu}| < 2.4$, and $8 < m_{\mu\mu} < 60$ GeV in ultraperipheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The α distributions are normalized to unit integral over their measured range. The dot-dot-dashed and dotted lines indicate the core and tail contributions, respectively, found using a fit to Eq. (1). The vertical lines on data points depict the statistical uncertainties, while the systematic uncertainties and horizontal bin widths are shown as gray boxes.

144 tion (where c_i and t_i are the fit parameters), as shown in Fig. 1,

$$\begin{aligned} \text{core} &: c_1 e^{-\alpha/c_2 + c_3 \alpha^{0.25}}, \\ \text{tail} &: t_1 [1 + (t_2/t_3)\alpha]^{-t_3}, \end{aligned} \quad (1)$$

145 except for the case of 1n1n, where a simple exponential function is used for the tail component,
 146 given the limited number of events. The core component is largely modeled by an exponential
 147 function with a correction term (c_3) to account for the small depletion in the very small α (e.g.,
 148 $< 5 \times 10^{-4}$) region, which tends to become more evident as the neutron multiplicity increases.
 149 This core functional form is validated by the STARLIGHT event generator and leading-order
 150 QED calculations, resulting in a $< 0.3\%$ discrepancy on the average acoplanarity from the fit
 151 and theoretical predictions. A binned χ^2 goodness-of-fit minimization is performed using the
 152 integral of the function across each bin to account for the finite binning effect of the histogram.
 153 The average acoplanarity of $\mu^+\mu^-$ pairs from the core component ($\langle \alpha^{\text{core}} \rangle$) is then calculated
 154 using the fit function, and therefore might depend on the choice of functional form.

155 The measured α distribution and $\langle \alpha^{\text{core}} \rangle$ of $\mu^+\mu^-$ pairs have several sources of systematic un-
 156 certainty arising from the contamination of hadronic collisions, the EMD pileup correction, the
 157 neutron multiplicity classification, and the fit procedure. The uncertainty of the hadronic con-
 158 tamination is estimated by removing the requirement that selected events only contain two
 159 muons and is found to be $< 1.1\%$. To estimate the systematic uncertainty associated with
 160 the HF noise threshold, the threshold to define the hadronic contamination is tightened to
 161 5 GeV for both UPCs and zero-bias triggered events. The difference from the nominal result
 162 is quoted as the systematic uncertainty and contributes $< 2.7\%$. The uncertainty arising from
 163 impure 1n class selection ($< 0.7\%$) is estimated by subtracting the contributions of 2n events

164 selected with tight energy requirements, according to the 2n contamination probability. The
 165 systematic uncertainty associated with contamination of photoproduced Y mesons ($\sim 0.6\%$)
 166 is estimated by comparing α distributions from STARLIGHT between pure $\gamma\gamma \rightarrow \mu^+\mu^-$ and
 167 $\gamma\gamma \rightarrow \mu^+\mu^-$ mixed with photoproduced coherent Y(1S), with the relative yield ratio of Y(1S)
 168 over $\gamma\gamma \rightarrow \mu^+\mu^-$ estimated by fitting the invariant mass distribution. The systematic uncer-
 169 tainty in $\langle\alpha^{\text{core}}\rangle$ associated with the binned χ^2 fit procedure is estimated by varying the bin
 170 width of α distributions, and is found to be less than 4%. The total systematic uncertainties
 171 are derived from a quadratic sum of all systematic sources and are found to be at most 5.1%
 172 in $\langle\alpha^{\text{core}}\rangle$. To measure $\langle m_{\mu\mu}\rangle$, a second order polynomial function is fit to the mass spectrum γ
 173 **excluding the mass region $9 < m_{\mu\mu} < 11 \text{ GeV}$,** (see Appendix A), to interpolate the contribution
 174 of $\gamma\gamma$ scattering to dimuon pair production over the Y mass region. The systematic uncertainty
 175 related to this procedure is estimated by comparing the nominal result to the one obtained by a
 176 third-order polynomial function fit. Together with the aforementioned systematic sources, the
 177 total systematic uncertainty in $\langle m_{\mu\mu}\rangle$ is below 1.8%, across all neutron multiplicity classes.

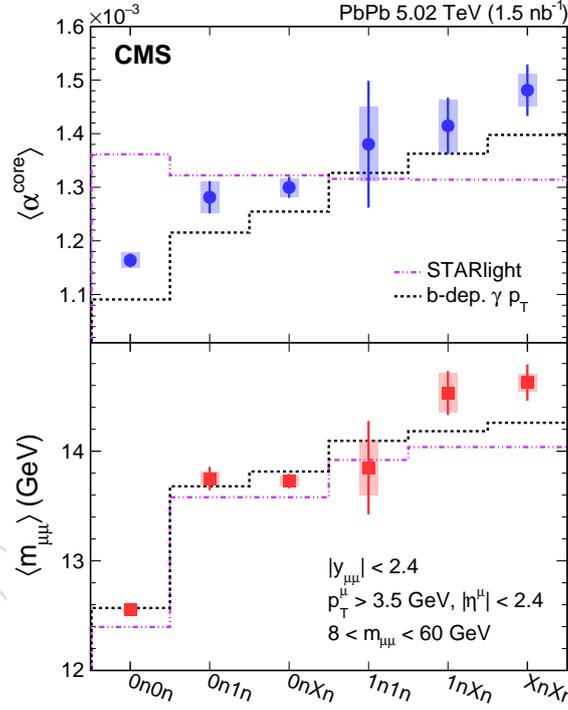


Figure 2: Neutron multiplicity dependence of $\langle\alpha^{\text{core}}\rangle$ (upper) and $\langle m_{\mu\mu}\rangle$ (lower) of $\mu^+\mu^-$ pairs in ultraperipheral PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$. The vertical lines on data points depict the statistical uncertainties, while the systematic uncertainties of the data are shown as shaded areas. **In the upper plot, the The** dashed-dot (redviolet) line shows the STARLIGHT prediction, and the dotted (black) line corresponds to the leading-order QED calculation of Ref. [45].

178 The neutron multiplicity dependence of $\langle\alpha^{\text{core}}\rangle$ for $\mu^+\mu^-$ pairs in ultraperipheral PbPb colli-
 179 sions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ is shown in Fig. 2 (upper), in the mass region $8 < m_{\mu\mu} < 60 \text{ GeV}$.
 180 A strong neutron multiplicity dependence of $\langle\alpha^{\text{core}}\rangle$ is clearly observed, while the $\langle\alpha^{\text{core}}\rangle$ pre-
 181 dicted by STARLIGHT is **almost** constant at a value of about 1.35×10^{-3} , shown as dashed-
 182 dotted line in Fig. 2 (upper). The $\langle\alpha^{\text{core}}\rangle$ for inclusive UPCs is measured to be $(1227 \pm 7 \text{ (stat)} \pm$
 183 $8 \text{ (syst)}) \times 10^{-6}$, about 10% lower than the STARLIGHT prediction. In general, the $\langle\alpha^{\text{core}}\rangle$ in
 184 data becomes larger as the emitted neutron multiplicity increases. A fit to the dependence of
 185 $\langle\alpha^{\text{core}}\rangle$ on the neutron multiplicity with a constant value is rejected with a p -value correspond-
 186 ing to 5.7 standard deviations. This observation demonstrates that initial photons producing

187 $\mu^+\mu^-$ pairs have a significant b dependence of their p_T , which impacts the p_T and acoplanarity
 188 of muon pairs in the final state. This initial-state contribution must be properly taken into ac-
 189 count when exploring possible final-state EM effects arising from a hot QGP medium formed
 190 in hadronic heavy ion collisions [26, 27]. A recent leading-order QED calculation [45], incor-
 191 porating a b dependence of the initial photon p_T [32], has provided results for all the reported
 192 neutron multiplicity classes. The average b values estimated in Ref. [45] range from about 112
 193 to 22 fm for the 0n0n to XnXn neutron multiplicity classes, respectively. The model calcula-
 194 tion can qualitatively describe the increasing trend of $\langle\alpha^{\text{core}}\rangle$ data with the neutron multiplicity,
 195 shown as the dotted line in Fig. 2 (upper). However, the data are systematically higher than
 196 the model calculation (plotted without uncertainties) by about 5%, which may be related to the
 197 presence in data of soft photon radiation from the muons [30].

198 A rapidity dependence of the α distribution is also investigated for 0n1n, 0nXn and 1nXn
 199 classes (see Appendix A) for dimuon rapidity in the same or opposite hemisphere corresponding
 200 to higher neutron multiplicities hemisphere containing larger (smaller) neutron multiplicity. In
 201 the 0nXn class, the tail contribution in the same rapidity hemisphere with Xn is significantly
 202 larger than that in the opposite rapidity hemisphere rapidity hemisphere with zero neutrons,
 203 suggesting contributions from different higher-order processes that correlate with the dimuon
 204 pair production. However, no rapidity dependence is observed for the $\langle\alpha^{\text{core}}\rangle$ values extracted
 205 from the fits using Eq. (1). This confirms the expectation that the $\langle\alpha^{\text{core}}\rangle$ is dominated by
 206 leading-order $\gamma\gamma \rightarrow \mu^+\mu^-$ scatterings.

207 In Fig. 2 (lower), the average invariant mass $\langle m_{\mu\mu} \rangle$ of all muon pairs passing the selection crite-
 208 ria, is shown as a function of the neutron multiplicity. A clear neutron multiplicity dependence
 209 of $\langle m_{\mu\mu} \rangle$ is observed, with the $\langle m_{\mu\mu} \rangle$ value measured in XnXn events being larger than that in
 210 0n0n events with a significance exceeding 5 standard deviations. This trend of $\langle m_{\mu\mu} \rangle$ can be
 211 qualitatively described by both model calculations. As the muon pair invariant mass is largely
 212 determined by the initial photon energy, this observation suggests that the energy of the pho-
 213 tons involved in UPCs is on average larger in collisions with smaller b , a conclusion similar to
 214 that previously drawn for the initial photon p_T .

215 In summary, the first measurements of $\gamma\gamma \rightarrow \mu^+\mu^-$ production as a function of forward neu-
 216 tron multiplicity in ultraperipheral lead-lead collisions at a nucleon-nucleon center-of-mass en-
 217 ergy of 5.02 TeV are reported. A significant broadening of back-to-back azimuthal correlations
 218 is seen, with respect to the leading-order $\gamma\gamma \rightarrow \mu^+\mu^-$ process, for increasing multiplicities of
 219 emitted forward neutrons. This observed trend is qualitatively reproduced by a leading-order
 220 quantum electrodynamics calculation, demonstrating the importance of an impact parameter
 221 dependent photon p_T . A similar trend of increasing average invariant mass of muon pairs
 222 with neutron multiplicity is also observed. These measurements provide the first experimental
 223 demonstration that the initial energy and transverse momentum of photons exchanged in ul-
 224 traperipheral heavy ion collisions depend on the impact parameter of the interaction. These
 225 results call for theoretical efforts to improve the precision in modeling photon-induced in-
 226 teractions. Future searches for electromagnetic interactions of leptons inside the quark-gluon
 227 plasma created in heavy ion collisions should incorporate a baseline where the initial broaden-
 228 ing effects presented in this Letter are properly taken into account.

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379 A ZDC energy distributions and rapidity dependence of acopla- 380 narity distributions and subtraction of Υ mesons

381 Figure A.1 (left) shows the correlation between energy distributions of the ZDC detectors, lo-
382 cated on the positive (Plus) and negative (Minus) directions with respect to the CMS interaction
383 point, for events selected in the analysis. Figure A.1 (right) shows the measured Minus ZDC
384 energy distribution together with a multi-Gaussian function fit.

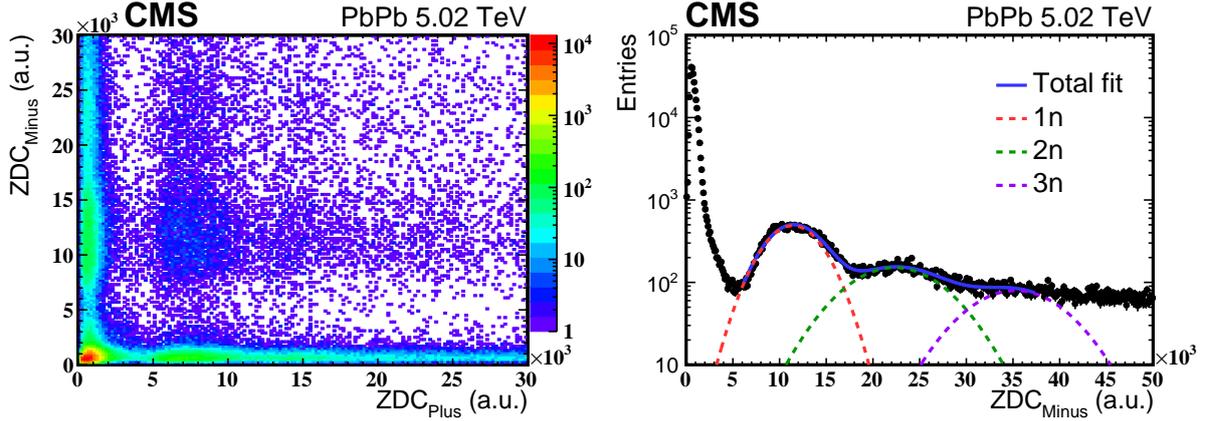


Figure A.1: The left panel shows the correlation between energy distributions of the Minus and Plus ZDC detectors (one entry per event), while the right panel shows a multi-Gaussian function fit to Minus ZDC energy distribution.

385 For the measured neutron multiplicity class with asymmetric neutron numbers, the dimuon
386 rapidity is divided into two hemispheres using the plane defined by $y = 0$. In each rapid-
387 ity hemisphere, the α distribution from $\gamma\gamma \rightarrow \mu^+\mu^-$ is normalized by the total yields in this
388 neutron multiplicity class ($(1/N_s)dN_s^{\text{rap}}/d\alpha$, where the N_s represents the total yields and N_s^{rap}
389 represents the yields in each rapidity hemisphere), as shown in Fig. A.2.

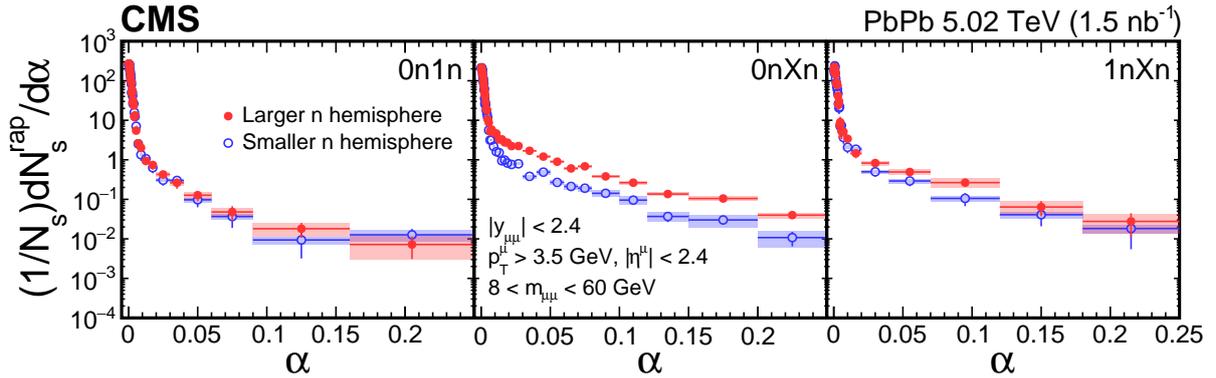


Figure A.2: Acoplanarity distributions of $\gamma\gamma \rightarrow \mu^+\mu^-$ events for three different neutron multiplicity classes with asymmetric neutron numbers. The solid red (open blue) symbols correspond to events where the dimuon rapidity is in the hemisphere containing larger (smaller) neutron multiplicity. The vertical lines on data points depict the statistical uncertainties while the systematic uncertainties are shown as shaded areas.

390 The yields of muon pairs from $\gamma\gamma$ scattering in the Υ mass region ($9 < m_{\mu\mu} < 11$ GeV) are
391 extracted by a binned χ^2 fit to the invariant mass spectrum, as shown in Fig. A.3. Each Υ state
392 is modeled by a Gaussian function. All the parameters of the $\Upsilon(1S)$ fit are left free. For the
393 $\Upsilon(2S)$ and $\Upsilon(3S)$ states, the yields are allowed to vary while the mean and width are fixed

394 to values found by multiplying those for $\Upsilon(1S)$ by the ratio of the published masses of the
 395 states [46]. The contribution of $\gamma\gamma$ scattering to dimuon pair production in the Υ mass region
 396 is extracted using a second order polynomial function.

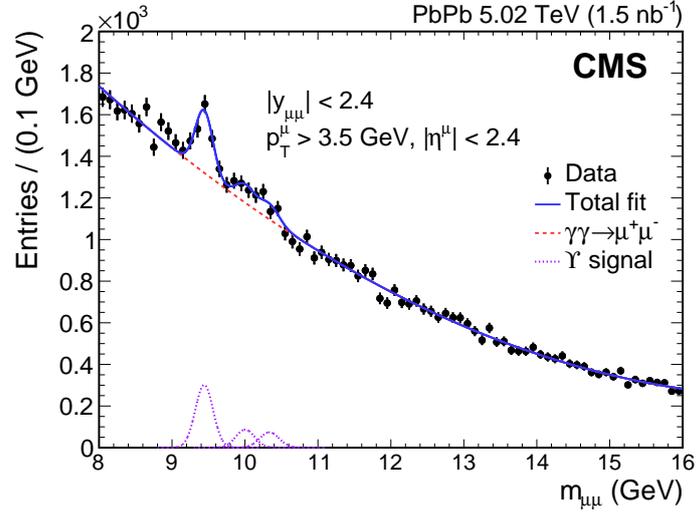


Figure A.3: The efficiency corrected invariant mass distribution of muon pairs in inclusive ultraperipheral PbPb collisions, for the kinematic range $p_T^\mu > 3.5 \text{ GeV}$, $|\eta^\mu| < 2.4$, and $|y^{\mu\mu}| < 2.4$. The result of the fit to the data is shown as solid blue line. The yields of muon pairs from $\gamma\gamma$ scattering in the Υ mass region are shown as dashed red line. The separate yields for each Υ state are shown as dotted violet lines.