Photoproduction of K^+K^- Pairs in Ultraperipheral Collisions

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K^+K^- pairs may be produced in photonuclear collisions, either from the decays of photoproduced $\phi(1020)$ mesons or directly as nonresonant K^+K^- pairs. Measurements of K^+K^- photoproduction probe the couplings between the $\phi(1020)$ and charged kaons with photons and nuclear targets. The kaon-proton scattering occurs at energies far above those available elsewhere. We present the first measurement of coherent photoproduction of K^+K^- pairs on lead ions in ultraperipheral collisions using the ALICE detector, including the first investigation of direct K^+K^- production. There is significant K^+K^- production at low transverse momentum, consistent with coherent photoproduction on lead targets. In the mass range $1.1 < M_{KK} < 1.4$ GeV/c^2 above the $\phi(1020)$ resonance, for rapidity $|y_{KK}| < 0.8$ and $p_{T,KK} < 0.1$ GeV/c, the measured coherent photoproduction cross section is $\mathrm{d}\sigma/\mathrm{d}y = 3.37 \pm 0.61(\mathrm{stat}) \pm 0.15(\mathrm{syst})$ mb. The center-of-mass energy per nucleon of the photon-nucleus (Pb) system $W_{\gamma\mathrm{Pb},n}$ ranges from 33 to 188 GeV, far higher than previous measurements on heavy-nucleus targets. The cross section is larger than expected for $\phi(1020)$ photoproduction alone. The mass spectrum is fit to a cocktail consisting of $\phi(1020)$ decays, direct K^+K^- photoproduction, and interference between the two. The confidence regions for the amplitude and relative phase angle for direct K^+K^- photoproduction are presented.

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Introduction.—High-energy photoproduction is an important technique for studying hadronic interactions. Ultraperipheral collisions (UPCs) of relativistic ions are a tool for studying photonuclear interactions at energies far higher than those available elsewhere [1–4]. The electromagnetic field of one nucleus forms an intense virtual-photon beam that can interact with nuclei from the opposing beam. UPC interactions occur when the impact parameter (b) between the two nuclei is large enough—e.g., b is greater than the sum of the nuclear radii—so that no obscuring hadron-hadron interactions occur.

A photon can fluctuate into a quark-antiquark pair (dipole) that scatters elastically from a target nucleus, emerging as a real vector meson [5]. The elastic scattering is mediated by the Pomeron, which is a colorless object and to lowest order, composed of two gluons. The exchange involves the quantum numbers of the vacuum, so following the vector meson dominance model, the outgoing meson has the same quantum numbers $J^{PC} = 1^{--}$ as the incident photon [6]. Alternatively, the photon can fluctuate directly into a virtual meson pair, like $\pi^+\pi^-$ or K^+K^-. One of the mesons can then scatter elastically from the target, making the pair real. For midrapidity kaons in ALICE, the kaon-proton center-of-mass energy is 50 GeV, far higher than can be studied elsewhere. Exclusive K^+K^- production can also occur via two-photon [7] or in double-Pomeron interactions [8], but this is the first observation in the photon-Pomeron channel.

Since the channels are indistinguishable, meson pairs from the decay of vector mesons [$\rho^0 \to \pi^+\pi^-$ or $\phi(1020) \to K^+K^-$] can interfere with the directly produced pairs. The production amplitude has two terms: The resonance is described using a Breit-Wigner distribution expressed in the Jackson form, with amplitude A_ϕ, and there is, in addition, a continuum component with amplitude B_{KK} [9–11], giving

$$\frac{d\sigma}{dM_{KK}} = \left| A_\phi \frac{\sqrt{M_{KK} M_\phi \Gamma_\phi}}{M_{KK}^2 - M_\phi^2 + i M_\phi \Gamma_\phi} + B_{KK} \right|^2, \quad (1)$$

where $M_\phi = 1019.416 \pm 0.016$ MeV/c^2 [12] and Γ_ϕ are the $\phi(1020)$ mass and mass-dependent width, respectively, with

$$\Gamma_\phi = \Gamma_0 \frac{M_\phi}{M_{KK}} \left(\frac{M_{KK}^2 - 4M_K^2}{M_\phi^2 - 4M_K^2} \right)^{3/2}. \quad (2)$$

Here, $\Gamma_0 = 4.249 \pm 0.013$ MeV/c^2 is the native $\phi(1020)$ width, and $M_K = 493.677 \pm 0.016$ MeV/c^2 is the kaon mass [12]. Both A_ϕ and B_{KK} are complex, but only their

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relative phase matters. By taking A_ϕ to be real, the relative phase is encoded in B_{KK}. Far above the $\phi(1020)$ resonance (many Γ_0), the mass-dependent width rises, and the cross section declines smoothly. One difference between the K^+K^- and $\pi^+\pi^-$ systems is that the branching ratio $\phi(1020) \to K^+K^-$ is only 49.1% [12], while the ρ^0 almost always decays to $\pi^+\pi^-$. This branching ratio is included in A_ϕ, Ryskin and Shabelski considered the direct dikaon contribution to the total dikaon cross section and concluded that it should be small and with a relative phase angle near zero [13]. A later calculation predicted that the dikaon system should behave similarly to the dipions, with a small correction to the width to account for three-body $\phi(1020)$ decays [11].

The transverse momentum p_T of the meson depends on the production mechanism, so it is important in selecting coherent photoproduction events, where a dipole or virtual meson pair scatters from the target nucleus. The meson p_T is the vector sum of the photon p_T and the Pomeron p_T, which usually dominates [14]. For coherent production, its scale is controlled by the form factor of the target nucleus. Destructive interference between the amplitudes for production on the two nuclei can reduce the cross section at low p_T, especially near midrapidity [14,15]. In incoherent production, when a dipole or virtual meson pair scatters from a single nucleon, the typical p_T is larger, around a few hundred MeV/c. Although Pomeron-Pomeron interactions can also produce exclusive K^+K^- pairs [8], because of the short range of the strong force, these reactions cannot be coherent over the entire nuclei and, so, will not produce a peak at low p_T and do not contribute to the current coherent measurement.

Previously, $\phi(1020)$ photoproduction has been studied at fixed-target experiments [6,16] and the HERA ep collider [17–19]. However, the direct K^+K^- contribution has not yet been observed. The H1 Collaboration searched for skewing in the ϕ Breit-Wigner peak due to direct K^+K^- production (in electroproduction) but found no evidence for it [19]. In contrast, the $\rho^0 +$ direct $\pi^+\pi^-$ state has been studied in both UPCs [20–25] and, at lower energy, at fixed-target experiments [6]. The $\pi^+\pi^-$ mass spectra are well fit by the sum of amplitudes for ρ^0 and direct $\pi^+\pi^-$, with a high-statistics fit exhibiting additional interference from $\omega \to \pi^+\pi^-$ [22,26]. Higher-mass $\pi^+\pi^-$ states have also been seen [23,27,28].

This Letter reports on exclusive photoproduction of the K^+K^- final state, from the decay of the $\phi(1020)$ and direct production. The data cover the mass region $1.1 < M_{KK} < 1.4$ GeV/c^2. This is significantly above the $\phi(1020)$ peak, with the lower mass limit at about $M_\phi + 18\Gamma_0$.

The cross sections are measured at the center-of-mass energy per nucleon of the photon-nucleus (Pb) system $W_{\gamma\mathrm{Pb},n}$, where $W_{\gamma\mathrm{Pb},n}$ varies from 33 to 188 GeV, depending on M_{KK} and rapidity. This range of energies is more than an order of magnitude higher than previous studies using heavy-nucleus targets [6,16].

Detector and data.—The results presented in this Letter are based on the data collected in 2015 by the ALICE experiment [29,30], with Pb-Pb collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. A dedicated trigger was used to select candidate UPC events [23], rejecting any activity within the time windows for nominal beam-beam interactions, using the scintillator detectors V0 [31] and AD [32,33] located at large positive and negative pseudorapidity. In addition, the trigger required that the silicon pixel detector (SPD), the two innermost layers of the inner tracking system (ITS) [34], measured at least two short track segments with a large opening angle in azimuth.

The time projection chamber (TPC) covering the pseudorapidity acceptance of $|\eta| < 0.9$ was used for charged particle tracking and vertexing together with the ITS as well as for particle identification based on the specific ionization energy loss, $\mathrm{d}E/\mathrm{d}x$ [35].

Analysis procedure.—The analysis selected events with exactly two good tracks. The tracks were required to have at least 50 hits (clusters) in the TPC, at least one hit in each of the two layers of the SPD, and to have the distance-of-closest approach to the event vertex of less than $0.0182 + 0.035/p_T^{1.01}$ cm in the transverse plane and less than 2 cm along the beam direction. The two selected tracks having opposite charge are reconstructed as K^+K^- pair candidates under the kaon mass hypothesis. As there are no same-charge pairs passing the particle identification criteria, the contribution of uncorrelated background could be ignored in this analysis.

Kaons are identified based on the $\mathrm{d}E/\mathrm{d}x$ measurement in the TPC. The selection criteria are applied to the variable n_{σ_i}, the deviation of the measured signal from the expected signal in units of the $\mathrm{d}E/\mathrm{d}x$ measurement uncertainty for each particle hypothesis i. Since the ratio of signal K^+K^- pairs to background $\pi^+\pi^-$ pairs is less than 0.1%, stringent particle identification criteria are introduced. First, the tracks in each pair are required to satisfy $|n_{\sigma_K}| < 3$. In addition, the tracks which are compatible within $2n_{\sigma_{\pi,\mu,e}}$ are excluded to reject $\pi^+\pi^-$ pairs as well as dilepton pairs from the $\gamma\gamma \to l^+l^-$ process.

The contamination of the K^+K^- pair candidates by the misidentified particles is estimated from the two-dimensional n_{σ_K} distribution of the two tracks in each pair. While the signal K^+K^- pairs have a two-dimensional Gaussian-like distribution centered at (0,0), background pairs are clustered at nonzero values. For $1.1 < M_{KK} < 1.4$ GeV/c^2, the contamination is negligible as the signal and background distributions are well separated from each other. At higher masses, the expected difference in $\mathrm{d}E/\mathrm{d}x$ between kaons and lighter particles decreases, so they become indistinguishable in some n_{σ_K} regions. Therefore, the invariant mass range above 1.4 GeV/c^2 is not used in the analysis. For pairs with $M_{KK} < 1.1$ GeV/c^2, the kaons lose energy rapidly and do not reach the sensitive region of the ALICE detector.

Measurement of the cross section.—The invariant mass differential cross section of exclusive K^+K^- photoproduction is obtained by correcting the number of K^+K^- candidates (N_{KK}) found in the rapidity interval of $|y_{KK}| < 0.8$ and in the p_T interval of $p_{T,KK} < 0.1$ GeV/c by acceptance and efficiency ($\mathcal{A} \times \varepsilon$):

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}M_{KK}\mathrm{d}y_{KK}} = \frac{N_{KK} \times f_{\mathrm{pileup}}}{(\mathcal{A} \times \varepsilon) \times \mathcal{L} \times \Delta M_{KK} \times \Delta y_{KK}}. \quad (3)$$

The $\mathcal{A} \times \varepsilon$ is computed using a dedicated Monte Carlo simulation with STARlight [36] for the K^+K^- pairs from direct production and $\phi(1020)$ decays.

The generated K^+K^- pairs are transported through the detector setup using a GEANT3 model [37] to simulate a realistic detector response. The corresponding integrated luminosity ($\mathcal{L}$) for the data sample is 0.406 $\mu\mathrm{b}^{-1}$ with a relative systematic uncertainty of 2.6% [38]. Some events are lost due to pileup, when another interaction creates a signal in one of the veto detectors. The pileup events mainly come from two-photon production of e^+e^- pairs, and their effect is taken into account with an additional correction factor, $f_{\mathrm{pileup}} = 11.1 \pm 3.8\%$ [23]. Similarly, the p_T^2 -differential cross section of exclusive K^+K^- photoproduction in $1.1 < M_{KK} < 1.4$ GeV/c^2 is measured:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{T,KK}^2\mathrm{d}y_{KK}} = \frac{N_{KK} \times f_{\mathrm{pileup}}}{(\mathcal{A} \times \varepsilon) \times \mathcal{L} \times \Delta p_{T,KK}^2 \times \Delta y_{KK}}. \quad (4)$$

Systematic uncertainties.—The systematic uncertainties of the measured cross section are estimated for the track selection criteria (1.5%) and the track matching between ITS and TPC (4%) as well as for the acceptance and efficiency (1%), without dependence on $p_{T,KK}$, y_{KK}, and M_{KK} [23]. Uncertainties of 1% and 3.8% are included for the trigger efficiency and for the pileup correction, respectively [23]. The uncertainty of the luminosity (2.6%) results from the uncertainty of the reference luminosity in the cross section of 2.5% [38] and an additional 0.4% uncertainty on the live time of readout detectors used for the trigger.

The systematic uncertainty of the kaon identification is estimated as a function of $p_{T,KK}$ and M_{KK} to account for the track momentum dependence in the kaon identification performance. The expected signal of TPC $\mathrm{d}E/\mathrm{d}x$ for each particle hypothesis is varied in the MC simulations by the maximum difference of the signal in data and MC simulations. Then, n_{σ_i} and the corresponding kaon identification efficiency are recalculated. The resulting uncertainty is negligible for $1.1 < M_{KK} < 1.2$ GeV/c^2 and amounts to 3.9% and 6.5% for $1.2 < M_{KK} < 1.3$ GeV/c^2 and $1.3 < M_{KK} < 1.4$ GeV/c^2, respectively. The systematic uncertainty increases slowly as a function of $p_{T,KK}$ from 3.4% for $p_{T,KK} < 0.025$ GeV/c to 4.9% for $0.1 < p_{T,KK} < 0.2$ GeV/c. Over most of the kinematic range, this is the largest single systematic uncertainty.

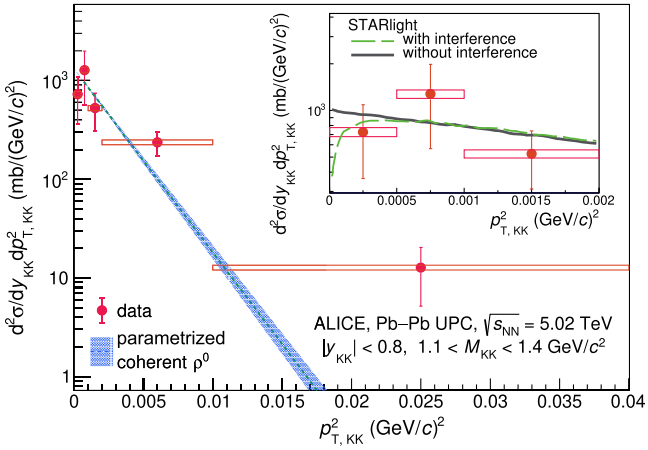

FIG. 1. Differential cross section as a function of $p_{T,KK}^2$ for exclusive K^+K^- photoproduction in Pb-Pb UPCs at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and $|y_{KK}| < 0.8$. The vertical lines and boxes across the data points represent statistical and systematic uncertainties, respectively. The dashed blue line and band are the result of a fit to an exponential with the fixed slope parameter $b = 428 \pm 6(\mathrm{stat}) \pm 15(\mathrm{syst})$ $(\mathrm{GeV}/c)^{-2}$, from a previous result on ρ^0 production [39] (see the text for details). The inset shows two curves from STARlight with and without interference between the two photon directions [14,36].

Results.—Figure 1 shows the p_T^2 spectrum of the selected K^+K^- events. Most of the cross section is concentrated below $p_{T,KK}^2 < 0.01(\mathrm{GeV}/c)^2$, consistent with coherent photoproduction. Some events are seen at higher values of $p_{T,KK}^2$; these may be from incoherent production. The coherent data are well described with an exponential shape $\mathrm{d}^2\sigma/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}^2 = a\exp(-bp_T^2)$, where the slope parameter b is fixed to that measured for coherent ρ^0 photoproduction on lead, $b = 428 \pm 6(\mathrm{stat}) \pm 15(\mathrm{syst})$ $(\mathrm{GeV}/c)^{-2}$ [39]. The figure inset shows an expanded view of the low p_T^2 region and compares the data with two STARlight calculations, with and without an interference between photon emission from the two nuclei [14,36], which exhibit different trends only at very low p_T. The curve with interference is a slightly better match to the data.

The invariant mass-dependent cross section for coherent K^+K^- photoproduction is shown in Fig. 2. The data with $p_{T,KK}^2 > 0.01$ $(\mathrm{GeV}/c)^2$ are mostly from incoherent photoproduction and so are not included in the cross sections. The integrated cross section $\mathrm{d}\sigma/\mathrm{d}y_{KK} = 3.37 \pm 0.61(\mathrm{stat}) \pm 0.15(\mathrm{syst})$ mb is measured in the mass range $1.1 < M_{KK} < 1.4$ GeV/c^2 for rapidity $|y_{KK}| < 0.8$ and $p_{T,KK}^2 < 0.01$ $(\mathrm{GeV}/c)^2$. K^+K^- pairs could be produced by other reactions, such as $\gamma\gamma \to f_2(1270) \to K^+K^-$, but calculations indicate that the expected cross section for this process [40] estimated using STARlight [41] is a negligible fraction of the K^+K^- photoproduction cross section as illustrated in Fig. 2.

The measured cross section is fitted to a combination of $\phi(1020) \to K^+K^-$ and direct K^+K^- production according

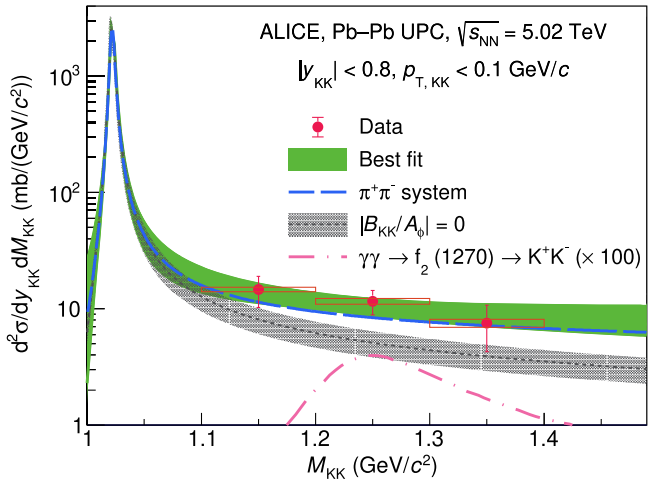

FIG. 2. Differential cross section of coherent K^+K^- photoproduction as a function M_{KK} in Pb-Pb UPCs at $\sqrt{s_{\rm NN}} = 5.02$ TeV in $|y_{KK}| < 0.8$. The vertical lines and boxes along the data points represent statistical and systematic uncertainties, respectively. The green solid line presents the best-fit result of $|B_{KK}/A_\phi| = 0.28$ $(\mathrm{GeV}/c^2)^{-1/2}$ and $\varphi = 0.06$ rad together with the 1σ bounds of the fit in a green band. The blue dashed curve shows the best fit with $|B_{\pi\pi}/A_\rho| = 0.54$ $(\mathrm{GeV}/c^2)^{-1/2}$ [23] and $\varphi = 1.46$ rad (the best-fit values for ρ plus direct $\pi^+\pi^-$) [22]. The black dotted line represents the curves under the hypothesis of $|B_{KK}/A_\phi| = 0$, showing only the $\phi(1020) \to K^+K^-$ contribution. The gray band indicates the impact of the systematic uncertainty from the $\phi(1020)$ meson cross section, showing a 25% variation.

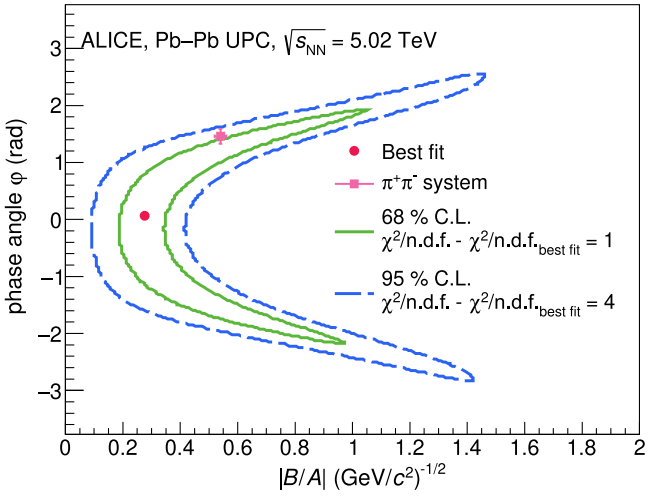

FIG. 3. Confidence regions for the relative fraction of direct K^+K^- contribution with respect to the amplitude of $\phi(1020) \to K^+K^-$ ($|B_{KK}/A_\phi|$) and the relative phase angle between $\phi(1020) \to K^+K^-$ and direct K^+K^- (φ). The best fit is shown as a red dot at $|B_{KK}/A_\phi| = 0.28$ $(\mathrm{GeV}/c^2)^{-1/2}$ and $\varphi = 0.06$ rad found with $\chi^2/\mathrm{n.d.f.}_{\rm best\ fit} = 0.3$, while a pink square at the $|B_{\pi\pi}/A_\rho| = 0.54 \pm 0.01(\mathrm{stat}) \pm 0.02(\mathrm{syst})$ $(\mathrm{GeV}/c^2)^{-1/2}$ [23] and relative phase angle $\varphi = 1.46 \pm 0.11(\mathrm{stat}) \pm 0.07(\mathrm{syst})$ rad [22] indicates the best-fit values for ρ plus direct $\pi^+\pi^-$. The green solid line and blue dashed line represent the boundary of 68% and 95% confidence regions, respectively.

to Eq. (1). The amplitude of $\phi(1020) \to K^+K^-$ (A_ϕ) was calculated from previous photoproduction measurements on protons [16,17,42] and a Glauber calculation [41], with a branching ratio of $\phi(1020) \to K^+K^-(49.2 \pm 0.5\%)$ [12]. The reference $\phi(1020)$ cross sections did not include a direct K^+K^- contribution. This could have had a small effect on the measured A_ϕ.

A 25% uncertainty in A_ϕ is estimated to account for the uncertainty in the previous measurements [16,17] and the uncertainty in the Glauber approach [43]. STARlight predictions for ρ^0 production under similar circumstances were 15%–20% below the data [23], while predictions for J/ψ production were about 15%–50% above the data, depending on rapidity [44]. The latter is not surprising, since STARlight does not include gluon shadowing. The $\phi(1020)$ is intermediate in mass, but closer to the ρ^0, so a $\pm 25\%$ uncertainty in the cross section seems conservative for the $\phi(1020)$.

The black dotted line and surrounding shaded region in Fig. 2 show the ϕ-only prediction, with the 25% uncertainty. The measured cross section is about 2.1σ above the expected $\phi(1020) \to K^+K^-$ cross section in the range $1.1 < M_{KK} < 1.4$ GeV/c^2. Also shown, with a blue dashed line, is the prediction using the values $|B_{\pi\pi}/A_\rho| = 0.54 \pm 0.01(\mathrm{stat}) \pm 0.02(\mathrm{syst})$ $(\mathrm{GeV}/c^2)^{-1/2}$ [23] and relative phase angle $\varphi = 1.46 \pm 0.11(\mathrm{stat}) \pm 0.07(\mathrm{syst})$ rad [22] found for ρ^0 plus the direct $\pi^+\pi^-$ system. The resulting $\mathrm{d}^2\sigma/\mathrm{d}M_{KK}\mathrm{d}y_{KK}$ is slightly below, but consistent with, the data points. The best fit of Eq. (1) found the relative fraction of direct K^+K^- contribution with respect to A_ϕ to be $|B_{KK}/A_\phi| = 0.28$ $(\mathrm{GeV}/c^2)^{-1/2}$, with the relative phase angle between $\phi(1020) \to K^+K^-$ and direct K^+K^- 0.06 rad.

Figure 3 shows the confidence regions for $|B_{KK}/A_\phi|$ and φ. The horseshoe shape of the curves including the first investigation of direct K^+K^- production is because of the large correlations between the two parameters. If the interference is constructive, a small direct K^+K^- component is preferred, while a large K^+K^- component is better fit with destructive interference. The invariant mass-dependent cross section curves corresponding to the 68% confidence region are shown as a 1σ green band in Fig. 3, while the dashed blue band shows the 95% confidence level. We do not include the uncertainty on the cross section $\sigma[\gamma A \to \phi(1020)A]$ within the figure. As $\sigma[\gamma A \to \phi(1020)A]$ is reduced or increased, it moves the confidence region left or right, with relatively small changes to the shape. One standard deviation ($\pm 1\sigma$) changes in $\sigma[\gamma A \to \phi(1020)A]$ move $|B_{KK}/A_\phi|$ by about ± 0.15 $(\mathrm{GeV}/c^2)^{-1/2}$, respectively. The best-fit point for the $\pi\pi$ system is fully compatible with the current K^+K^- measurement.

Looking ahead, during LHC run 3, ALICE will collect a far larger data sample, due to the increased luminosity [45]

and continuous-readout data acquisition system [46,47], which eliminates the need for a restrictive, prescaled trigger. Improved precision measurement of coherent K^+K^- photoproduction by the reduction of statistical uncertainty and an improved tracking will make it possible to further disentangle the resonance and nonresonance contributions with their relative phase angle.

Conclusions.—We report the first study of coherent K^+K^- photoproduction in ultraperipheral collisions at $W_{\gamma\mathrm{Pb},n}$ from 33 to 188 GeV, in the range $1.1 < M_{KK} < 1.4\ \mathrm{GeV}/c^2$ and $|y_{KK}| < 0.8$. The $\mathrm{d}^2\sigma/\mathrm{d}p_{T,KK}^2\mathrm{d}y_{KK}$ is concentrated below $p_{T,KK}^2 < 0.01\ (\mathrm{GeV}/c)^2$, consistent with coherent photoproduction. The measured $\mathrm{d}^2\sigma/\mathrm{d}M_{KK}\mathrm{d}y_{KK}$ below $p_{T,KK}^2 < 0.01\ (\mathrm{GeV}/c)^2$ is about 2.1σ larger than what is expected from $\phi(1020)$ production alone estimated based on HERA data with a Glauber model calculation but is consistent with a mixture of $\phi(1020)$ and direct K^+K^- production. The fitted ratio of $\phi(1020)$ production to K^+K^- production is consistent with that seen for the ρ^0 and direct $\pi^+\pi^-$.

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