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# Coherent photo-production of $\rho^0$ mesons in ultra-peripheral Pb-Pb collisions at the LHC measured by ALICE

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**Abstract.** We present the differential cross section for coherent $\rho^0$ photo-production at mid-rapidity ($-0.5 < y < 0.5$) measured by the ALICE experiment in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC, as well as the total $\rho^0$ cross section obtained by model-based extrapolation to all rapidities. These cross sections are compared to various model predictions, as well as to earlier measurements at RHIC. In addition, we present results on nuclear breakup in coincidence with coherent $\rho^0$ photo-production.

## 1 Introduction

Ultra-peripheral collisions (UPC) of lead nuclei are characterized by an impact parameter exceeding the sum of the two nuclear radii [1, 2]. The photon flux of heavy ions is enhanced by the square of the nucleus charge which allows us to study gamma-nucleus processes, such as the production of $\rho^0$ vector mesons decaying into two pions. Coherent processes are characterized by the emission of low transverse momentum ($p_T$) virtual photons coupling to almost all the nucleons. As a consequence, the pair of pions from the decay of the vector meson has low transverse momentum. This can be used to separate coherent production from non-coherent processes. Here we present the first measurement of coherent $\rho^0$ photo-production in Pb-Pb collisions at the LHC.

## 2 Used Pb-Pb data sets ( $\sqrt{s_{NN}} = 2.76$ TeV) and MC simulations

The ALICE experiment at the LHC [3], *cf.* Fig. 1, is well-suited for measuring ultra-peripheral processes at low invariant masses at mid-rapidity since its acceptance extends down to very low track momenta. The ALICE collaboration has implemented a dedicated UPC trigger, requiring activity at mid-rapidity, *e.g.* $N \geq 2$ hits in the second innermost layer of the Inner Tracking System (ITS) and $N \geq 2$ fired trigger pads in the time-of-flight detector (TOF); both VZERO detectors, VZERO-C ($2.8 < \eta < 5.1$), and VZERO-A ($-3.7 < \eta < -1.7$), are used as a veto.

With the UPC trigger described above, we have collected data corresponding to an integrated luminosity of approx. 0.2 $\mu$b$^{-1}$ and selected events with vertex $|v_z| < 10$ cm, exactly two tracks

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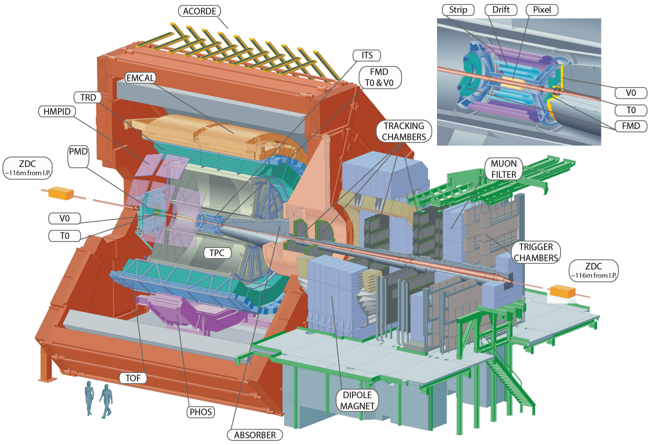

**Figure 1.** The ALICE experiment [3]. For our measurement we use the inner tracking system (ITS) consisting of silicon detectors, the Time Projection Chamber (TPC), the Time-of-Flight detector (TOF), the VZERO detectors, and for studying nuclear breakup in coincidence with $\rho^0$ production the two Zero-degree-Calorimeters (ZDC).

satisfying ALICE standard track cuts with two-pion rapidity $|Y(\pi\pi)| < 0.5$ and $p_T(\pi\pi) < 0.15$ GeV/$c$. The relative number of like-sign events which is a measure of background contamination, is found to be less than 2% for $M(\pi\pi) > 0.6$ GeV/$c^2$; we have subtracted this background from the invariant-mass spectrum to obtain the result shown in Fig. 2.

In order to correct for efficiency and acceptance, we have used a MC generator which is flat in invariant mass, *e.g.*, $M(\pi^+\pi^-) \in [2m_\pi,\ 1.5\,\mathrm{GeV}/c^2]$, $p_T(\pi^+\pi^-) \in [0,\ 0.15]\,\mathrm{GeV}/c$, $Y(\pi^+\pi^-) \in [-0.5,\ 0.5]$; for the the decay angle $\theta$, defined in the $\pi^+\pi^-$ rest-frame, we have used $\frac{\mathrm{d}\theta}{\mathrm{d}\cos\theta} \sim \sin^2\theta$ which is the leading term for vector mesons. The obtained efficiency×acceptance, $\epsilon_{M(\pi\pi)}$, is calculated for each bin in two-pion invariant mass, $M(\pi\pi)$, and then applied to the invariant-mass spectrum obtained from data. The advantage of using this flat MC generator over using, *e.g.*, STARLIGHT [4] is that for each bin in $M(\pi\pi)$ the same number of events are generated and as a consequence, the statistical errors do not increase away from the $\rho^0$ mass. We have checked that $\epsilon_{M(\pi\pi)}$ obtained from the flat MC simulation is consistent with $\epsilon_{M(\pi\pi)}$ obtained by using the STARLIGHT MC generator [4].

## 3 $\rho^0$ invariant-mass spectrum and cross section

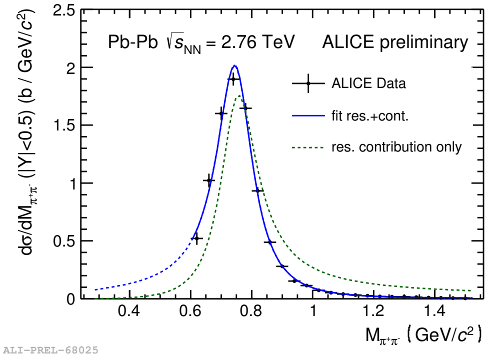

**Figure 2.** The two-pion invariant-mass spectrum corrected for efficiency and acceptance is shown. The blue, solid line shows the result of fitting the Söding function shown in equation (1) to the data points, while the green, dotted line indicates the resonant contribution, obtained by setting the amplitude $B$ for non-resonant pion pair production to zero.

The invariant-mass spectrum, corrected for efficiency and acceptance is shown in Fig. 2. We have fitted to this invariant-mass spectrum a function due to Söding [5] consisting of a relativistic Breit-

Wigner amplitude with a mass-dependent width $\Gamma(m_{\pi\pi})$ and of a constant amplitude $B$ describing non-resonant $\pi\pi$ production,

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\pi\pi}} = \left| A\, \frac{\sqrt{m_{\pi\pi} M_{\rho^0} \Gamma(m_{\pi\pi})}}{m_{\pi\pi}^2 - M_{\rho^0}^2 + i M_{\rho^0} \Gamma(m_{\pi\pi})} + B \right|^2 , \quad \Gamma(m_{\pi\pi}) = \Gamma_{\rho^0} \frac{M_{\rho^0}}{m_{\pi\pi}} \left( \frac{m_{\pi\pi}^2 - 4m_\pi^2}{M_{\rho^0}^2 - 4m_\pi^2} \right)^{3/2} . \tag{1}$$

Here, $M_{\rho^0}$ and $\Gamma_{\rho^0}$ denote the mass and width of $\rho^0$ and $m_\pi$ the pion mass.

The systematic errors are estimated by varying the track cuts and the interval in $M(\pi\pi)$ used in the fit. Other contributions to the systematic error include the error in signal extraction, luminosity determination, trigger efficiency, incoherent contribution and particle identification.

As a result, from the fits of equation (1) to the corrected invariant-mass distribution we obtain the mass and width of $\rho^0$ as well as the ratio $|B/A|$:

$$\begin{aligned} M(\rho^0) &= \left(761.6 \pm 2.3(\mathrm{stat.})^{+6.1}_{-3.0}(\mathrm{sys.})\right) \mathrm{MeV}/c^2, & (2)\\ \Gamma(\rho^0) &= \left(150.2 \pm 5.5(\mathrm{stat.})^{+12.0}_{-5.6}(\mathrm{sys.})\right) \mathrm{MeV}/c^2, & (3)\\ |B/A| &= \left(0.50 \pm 0.04(\mathrm{stat.})^{+0.10}_{-0.04}(\mathrm{sys.})\right)(\mathrm{GeV}/c^2)^{-1/2}. & (4) \end{aligned}$$

The obtained mass and width are found to be compatible to [8], where masses in the range of 769 – 775 MeV/$c^2$ and widths 148 – 152 MeV/$c^2$ are quoted.

Having obtained the invariant-mass spectrum we compute the cross section of $\rho^0$ production at mid-rapidity by integrating the resonant contribution ($B = 0$ in equation (1)) from the threshold ($2m_\pi$) to 1.5 GeV/$c^2$, as has been done before, *cf.* [6, 7]. The contribution of incoherently produced $\rho^0$ mesons is estimated by fitting STARLIGHT-generated templates to the two-pion transverse momentum spectrum and the subtracted from the cross section, *cf.* Fig. 3. While the incoherent template is consistent with our data, the coherent template is too narrow. A similar observation has been made by STAR [15] where it is argued that the larger width of the coherent peak can be described by using a larger nuclear radius.

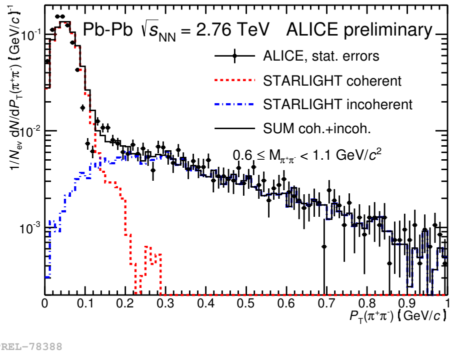

**Figure 3.** The transverse momentum of the two-pion system measured by ALICE is shown, together with templates for coherent and incoherent production generated by STARLIGHT [4].

The cross section for coherent photo-production of $\rho^0$ at mid-rapidity is measured to be:

$$\left.\frac{\mathrm{d}\sigma(\rho^0)^{\mathrm{coh.}}}{\mathrm{d}y}\right|_{|y|<0.5} = \left(420 \pm 10(\mathrm{stat.})^{+39}_{-55}(\mathrm{sys.})\right) \mathrm{mb}. \tag{5}$$

In order to obtain the total $\rho^0$ cross section, we have to extrapolate from mid-rapidity to all rapidities. Since this extrapolation is model-dependent, we have used the rapidity distributions of both

STARLIGHT [4] and GM [9] which are slightly different, in order to reduce the model-dependence and added the difference between these two extrapolations to the systematic error:

$$\sigma(\rho^0)^{\text{coh.}} = \left(4.3 \pm 0.1(\text{stat.})^{+0.6}_{-0.5}(\text{sys.})\right)\ \text{b}. \tag{6}$$

There are a number of predictions to which the cross sections obtained by ALICE can be compared to, *cf.* [4, 9–12]. Fig. 4 shows the new ALICE measurement (5),(6) together with model predictions, and with earlier measurements at lower center-of-mass energies. We find that our measurement is compatible to GM and to STARLIGHT, while the GDL1 prediction is about a factor of two above our measurement, similar to what has been seen in earlier measurements by the STAR experiment at RHIC energies.

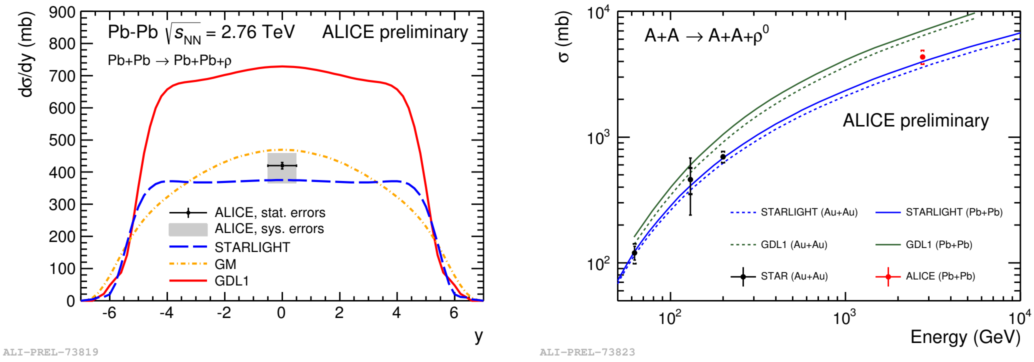

**Figure 4.** Comparison of the ALICE measurement to model predictions: GM [9], GDL1[10–12], STARLIGHT [4]. On the left plot, the cross section (5) at mid-rapidity is shown; the total cross section (6) is shown on the right plot, along with earlier measurements by STAR at lower center-of-mass energies [6, 13, 14].

## 4 Nuclear breakup in coincidence with UPC $\rho^0$ production

Neutrons generated by nuclear breakup can be detected in the two zero-degree calorimeters (ZDC), situated at about ±100 m from the interaction point. Due to the excellent energy resolution of the ALICE ZDCs, single neutrons can be detected with large (≈99%) efficiency [17]. This enables us to study nuclear breakup in coincidence with $\rho^0$ photo-production.

We considered the following four breakup modes which are according to the notation from [16]: 0N0N – no breakup, XN – one or both nuclei break up, 0NXN – one of the nuclei breaks up, and XNXN – both nuclei do break up. After subtracting the incoherent contribution for each breakup mode separately, we obtain the fractions shown in Table. 1. We have compared the obtained fractions with predictions and found that while both the STARLIGHT [4, 16] and the GDL1 [12] predictions are compatible with the obtained breakup fractions, GDL1 agrees better with the data.

## 5 Conclusions

The ALICE Collaboration has measured coherent $\rho^0$ photo-production in Pb-Pb collisions at the LHC. We have compared the measured cross section to a number of models and found that STARLIGHT and GM describe reasonably well the mid-rapidity cross section, one above and one below the ALICE

**Table 1.** Nuclear breakup in coincidence with coherent $\rho^0$ photo-production. The incoherent contribution is computed for each breakup mode separately and then subtracted. The resulting breakup fractions are compared to two model predictions *cf.* [12, 16].

| All events | 7293 | | STARLIGHT [4, 16] | GDL1 [12] |
|---|---|---|---|---|
| 0N0N | 6175 | $\left(84.7 \pm 0.4(\text{stat})^{+0.4}_{-1.9}(\text{sys})\right)\%$ | 79% ($-2.9\sigma$) | 84% ($-0.4\sigma$) |
| XN | 1174 | $\left(16.1 \pm 0.4(\text{stat})^{+2.2}_{-0.5}(\text{sys})\right)\%$ | 21% ($+2.2\sigma$) | 16% ($-0.2\sigma$) |
| 0NXN | 958 | $\left(13.1 \pm 0.4(\text{stat})^{+0.9}_{-0.3}(\text{sys})\right)\%$ | 16% ($+2.9\sigma$) | 12% ($-2.2\sigma$) |
| XNXN | 231 | $\left(3.2 \pm 0.2(\text{stat})^{+0.4}_{-0.1}(\text{sys})\right)\%$ | 5.2% ($+4.5\sigma$) | 3.7% ($+1.1\sigma$) |

measurement, whereas the GDL1 model over-predicts the measured cross section approximately by a factor of two.

Using the Zero-degree calorimeters, we were able to study nuclear breakup in coincidence with coherent $\rho^0$ photo-production. We have compared the measured breakup fractions to STARLIGHT and GDL1 predictions and found that while GDL1 agrees better with our measurements, both predictions are compatible with our measurements.

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