Photon-Induced Physics with Heavy-Ion Beams in ALICE

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The possibilities to study ultra-peripheral collisions, in particular exclusive vector meson production, with the ALICE detector is reviewed.

Photon-induced interactions have traditionally been studied with lepton beams in fixed target experiments and at colliders. But two–photon and photon–hadron interactions can occur also when the lepton beams are replaced by high energy protons or heavy ions\cite{1,2}. The electromagnetic interactions can be studied in ultra-peripheral collisions where the impact parameters are larger than the sum of the projectile radii and no hadronic interactions occur. This paper will discuss the possibilities for studying ultra-peripheral collisions in the ALICE experiment.

1. The ALICE Experiment

ALICE is an experiment at the CERN Large Hadron Collider (LHC) primarily designed to study the physics of strongly interacting matter in nucleus-nucleus collisions\cite{3,4}. The ALICE detector consists of a central barrel, a forward muon arm, and a set of smaller, forward detectors.

The central barrel, which covers the pseudorapidity range $|\eta| < 0.9$, has a charged particle tracking system consisting of an Inner Tracking System (ITS) in combination with a cylindrical Time-Projection Chamber (TPC). Particle identification is obtained from the energy loss in the tracking detectors in combination with information from a Time-of-Flight (TOF) detector, a Transition Radiation Detector (TRD), and an imaging Cherenkov detector (HMPID). In addition, the central barrel contains a high resolution Photon Spectrometer (PHOS) and an Electromagnetic Calorimeter (EMCAL). The HMPID, PHOS and EMCAL cover only parts of the central barrel acceptance.

The central barrel is designed to be able to handle multiplicities up to $dn_{ch}/d\eta = 8000$, a conservative estimate of the maximum multiplicities expected in central Pb+Pb collisions at the LHC. All charged tracks with transverse momenta ($p_T$) greater than 0.2 GeV/c can be reconstructed, with a momentum resolution changing from about 0.7% at $p_T = 1$ GeV/c to 3.5% at $p_T = 100$ GeV/c.

The muon arm covers the pseudorapidity range $-2.5 > \eta > -4.0$ and consists of an arrangement of absorbers, a large dipole magnet, ten planes of cathode pad tracking chambers, and four planes of resistive-plate triggering chambers. The muon arm is capable of reconstructing $J/\Psi$ and $\Upsilon$ vector mesons through their di–muon decay channel with transverse momenta down to $p_T = 0$ and with a resolution in invariant mass of 70 and 100 MeV/$c^2$, respectively.

Several smaller detectors are located at forward angles. These are the photon multiplicity detector (PMD), the forward multiplicity detector (FMD), the T0 and V0 detectors, and the Zero-Degree calorimeters (ZDC). The T0, Cherenkov radiation detectors, and V0, plastic scintillators, cover about 0.5 and 2.0 units of pseudorapidity, respectively, on each side of the interaction point.

Signals from the V0, T0, ITS (Si-Pixel), TOF, TRD, PHOS, EMCAL, and the muon trigger chambers are available in the lowest ALICE trigger level (Level 0). The ZDCs are located too far from the interaction point to be included in Level 0, but the information is available in the higher trigger levels.

An outline of the ALICE detector is shown in Fig. 1.
2. Ultra-Peripheral Collisions in ALICE

Ultra-peripheral collisions will have a very different topology compared with the central, hadronic interactions, which are the main focus of the ALICE experiment. The versatility of the ALICE detector should allow these interactions to be studied, however, but they will require different trigger and analysis techniques. Ultra-peripheral collisions can be studied both with heavy-ion and proton beams.

The photons from the electromagnetic field of one of the nuclei (or protons) can interact with the other nucleus in several ways. The interaction can be purely electromagnetic (two-photon interaction) or the photon can interact hadronically with the target nucleus (photomagnetic interaction). The photomagnetic interactions can either lead to the target nucleus breaking up (“inelastic”) or remaining intact (“elastic”). The photomagnetic interactions can be further subdivided depending on if the photon first fluctuates to a hadronic state (resolved interactions) or if it interacts as a bare photon (direct interactions).

Two-photon and elastic photomagnetic interactions are characterized by two rapidity gaps void of particles on both side of the produced system. If the fields couple coherently to the entire nucleus, the total transverse momentum will be determined by the nuclear form factors and will typically be small compared with that for competing processes. The inelastic photomagnetic interactions have a single rapidity gap between the photon-emitting nucleus and the produced system.

The cross section for inelastic photomagnetic interactions is dominated by resolved processes, but the cross sections for direct photon-parton interactions are large. For example, the cross section to produce a $c\bar{c}$ pair through $\gamma$-gluon fusion in Pb+Pb collisions is about 1 barn at the LHC[5]. The cross section for photon-induced
di-jet production is also appreciable with, e.g., a cross section larger than 1 \(\mu\)b for jets with \(p_T > 50\) GeV/c and rapidity \(|y| < 1\) in Pb+Pb collisions\[6\].

The elastic photonuclear reactions are dominated by exclusive vector meson production\[7\]. For comparable final states, the cross sections for two-photon production are typically two or three orders of magnitude smaller than for photonuclear production.

The characteristics of ultra-peripheral collisions form the basis for defining the trigger and separating the ultra-peripheral events from the hadronic interactions and various types of background processes.

ALICE is designed to handle multiplicities of several thousand particles in a single event. The multiplicities in ultra-peripheral collisions are normally much lower and reconstructing the events should not pose a problem. The key challenge is instead to implement an efficient trigger.

In central collisions, it is possible to trigger on charged particles emitted outside the acceptance of the central barrel, since the produced particles are distributed more or less evenly over the entire rapidity interval. The default trigger for hadronic interactions is therefore based on a coincident signal in the V0 and T0 detectors on both sides of the interaction point. For ultra-peripheral collisions, the idea is instead to let the V0 and T0 detectors define rapidity gaps by requiring an absence of a signal in those detectors in coincidence with a low multiplicity trigger around mid-rapidity. The low multiplicity trigger can be implemented through the Si-pixel and TOF detectors in the central barrel or through the muon trigger chambers. For two-photon and elastic photonuclear interactions, the T0 and V0 detectors on both sides should be empty, whereas for inelastic photonuclear interactions one should require a signal in the V0 and T0 on one side while the other side should be empty.

ALICE should have the capability to study many different types of ultra-peripheral collisions, with and without breakup of the nuclei. The focus so far has, however, been on exclusive production where both nuclei remain intact, in particular exclusive vector meson production. This will be discussed in more detail for heavy-ion and proton-proton interactions in the following two sections.

3. Exclusive Vector Meson Production in Heavy-Ion Collisions

At high photon energies and low virtualities, a photon may fluctuate into a vector meson and remain in that state for times that are long compared with the time it takes for it to pass nuclear distances. While in the vector meson state, the photon may scatter diffractively off the target nucleus and emerge as a real vector meson. The cross sections for exclusive photoproduction of vector mesons are large in heavy-ion interactions at the LHC\[7\]. Table 1 shows the the cross sections and expected detection rates for \(\rho^0\), \(J/\Psi\), and \(\Upsilon\) in ALICE in a one month \((10^6\) s\) Pb+Pb run. The detection rates were calculated from the geometrical acceptance of the central barrel \((|\eta| < 0.9, p_T > 0.2\) GeV/c\). In this section, the possibilities to reconstruct
Figure 3. Generated (a) and reconstructed (b) transverse momentum distributions of vector mesons and \( e^+e^- \)-pairs from two-photon interactions in Pb+Pb collisions.

exclusively produced \( J/\Psi \) and \( \Psi' \) mesons in the ALICE central barrel will be discussed. The \( J/\Psi \) and \( \Psi' \) are assumed to decay via their \( e^+e^- \) decay channel. The dominating background process is expected to be continuum production of \( e^+e^- \)-pairs in two-photon interactions\[8\].

Other backgrounds include hadronic interactions in peripheral nucleus–nucleus collisions, beam-gas interactions, cosmic rays (mainly at the trigger level), and incoherent photonuclear interactions. These backgrounds have been studied through simulations\[4\]. The results show that the coherent and exclusive events can be identified with good signal to background ratios when the entire event is reconstructed and a cut is applied on the summed \( p_T \) of the event. This is confirmed by the measurements of exclusive production of \( \rho^0 \) and \( J/\Psi \) mesons at RHIC, where similar techniques were used\[9,10\].

A simulation has been performed based on 1.5 hours of running at a Pb+Pb luminosity of \( 5 \cdot 10^{26} \) cm\(^{-2}\)s\(^{-1}\). Three samples of events were generated: 375,000 \( \gamma\gamma \rightarrow e^+e^- \) events with an invariant mass of the \( e^+e^- \)-pairs greater than 1.5 GeV/c\(^2 \) (\( \sigma = 140 \) mb); 5,141 \( J/\Psi \) events (\( \sigma \cdot Br.(e^+e^-) = 1.9 \) mb); and 122 \( \Psi' \) events (\( \sigma \cdot Br.(e^+e^-) = 45 \) mb).

The events were processed through AliRoot, the framework for the ALICE detector response simulation and off-line event reconstruction. The simulation gave about 3,500 reconstructed \( \gamma\gamma \rightarrow e^+e^- \) continuum pairs, 500 reconstructed \( J/\Psi \)s and 10 reconstructed \( \Psi' \)s. The vector meson decay products and the continuum \( e^+e^- \)-pairs have very different angular distributions and thus different acceptances. The simulation did not include the vertex reconstruction efficiency (\( \approx 85 \% \) for two-track events) and the electron/positron identification efficiency.

The invariant mass spectrum of the reconstructed \( e^+e^- \)-pairs is shown in Fig. 2. A clear \( J/\Psi \) peak is visible above the continuum background. The 10 reconstructed \( \Psi' \) cannot be distinguished from the background with the current statistics.

As was mentioned above, the identification of the coherently produced vector mesons and two-photon events will rely on the low \( p_T \) of the final state. The generated distribution is shown in Fig. 3 a). It is the result of a convolution of the photon \( p_T \) spectrum with the form factor of the target nucleus. The corresponding distribution for the reconstructed events is shown in Fig. 3 b). Because of the finite momentum resolution,
Table 1

Vector meson cross sections\cite{7}, production and detection rates, and geometrical acceptances in ALICE. The calculations are for a nominal heavy-ion month of $10^6$ seconds at the luminosity $5 \cdot 10^{26} \text{ cm}^{-2} \text{s}^{-1}$.

| Meson     | $\sigma(\text{PbPb} \rightarrow \text{PbPb} + V)$ | Prod. rate | Decay | Br. ratio | Geo. Acc. | Det. rate |
|-----------|---------------------------------|------------|-------|-----------|-----------|-----------|
| $\rho^0$  | 5.2 b                           | 2.6 $\cdot 10^9$ | $\pi^+\pi^-$ | 100 %     | 0.079     | 2.0 $\cdot 10^8$ |
| $J/\Psi$  | 32 mb                           | 1.6 $\cdot 10^7$ | $e^+e^-$ | 5.93 %    | 0.101     | 1.0 $\cdot 10^5$ |
| $\Upsilon(1S)$ | 280 $\mu$b                     | 1.5 $\cdot 10^5$ | $e^+e^-$ | 2.38 %    | 0.141     | $\approx 400$    |

The geometrical acceptances for $J/\Psi$ and $\Upsilon$ are different compared with those in \cite{4}. The earlier values were incorrect because of incorrect angular distributions of the decay products in the event generator.

the reconstructed distribution is wider than the generated one, but it is still clearly peaked below $p_T < 100 \text{ MeV}/c$. This shows that the momentum resolution is good enough for the summed $p_T$ to be used to identify the events.

It should be noted that the $p_T$ in Fig. 3 is the $p_T$ of the final state (the vector meson or the two-photon system). The electrons/positrons have transverse momenta of about 1.5 GeV/c.

4. Exclusive Vector Meson Production in proton-proton Collisions

Exclusive vector meson production can be studied also in proton-proton (pp) collisions. This reaction channel is interesting for several reasons. In pp collisions, Odderon-Pomeron fusion is a competing process by which vector mesons can be produced\cite{11}. This could also occur in nucleus-nucleus collisions, but one expects photoproduction to dominate there. If the cross section for photoproduction can be accurately determined, for example by using data from HERA, any excess can be attributed to the Odderon. One furthermore expects the Odderon and photon to have different $p_T$ spectra. If the Odderon contribution can be separated, measuring exclusive production of $\Upsilon$ in pp collisions at the LHC could improve the statistics and the energy range of the measurements of exclusive photoproduction of $\Upsilon$ at HERA. Finally, it has been proposed to use two-photon production of di-lepton pairs for luminosity calibration in pp collisions. Photoproduction of vector mesons will then be an important background that must be understood.

A simulation similar to that for Pb+Pb collisions has been performed based on about 18 days of running at the ALICE $p+p$ luminosity $5 \cdot 10^{30} \text{ cm}^{-2} \text{s}^{-1}$. This luminosity is a factor $2 \cdot 10^3$ lower than the LHC design luminosity because of the long dead time of the TPC. Three samples of events were generated for pp collisions: 150,000 $\gamma\gamma \rightarrow e^+e^-$ events with an invariant mass of the $e^+e^-$-pairs greater than 1.5 GeV/c\(^2\) ($\sigma = 19 \text{ nb}$); 35,796 $J/\Psi$ events ($\sigma \cdot Br.(e^+e^-) = 4.5 \text{ nb}$); and 729 $\Psi'$ events ($\sigma \cdot Br.(e^+e^-) = 91 \text{ pb}$).

As for Pb+Pb, the pp events were processed...
through the ALICE detector response simulation and off-line event reconstruction. The simulation gave about 700 reconstructed $\gamma\gamma \rightarrow e^+e^-$ continuum pairs, 1,400 reconstructed $J/\Psi$s and 30 reconstructed $\Psi'$s. The invariant mass spectrum of the reconstructed $e^+e^-$ pairs is shown in Fig. 4. One notes that the continuum background from two-photon interactions is much smaller in pp compared with Pb+Pb collisions. The background is small enough for the peak from the 30 reconstructed $\Psi'$s to be visible.

The reconstructed transverse momentum and rapidity distributions are shown in Fig. 5 a) and b), respectively. The $p_T$ spectrum is considerably wider than in heavy-ion collisions, and not very different from that of background processes, because of the different form factors. The identification of the exclusive production must therefore rely more on the presence of rapidity gaps in pp collisions.

5. Summary and Conclusions

The rates for many interesting ultra-peripheral reaction channels are high within the acceptance of the ALICE detector. This study shows that with a suitable trigger these events can be reconstructed with high efficiency in ALICE. The momentum resolution is good enough for the summed $p_T$ to be used to identify coherent events in nucleus-nucleus collisions.

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