Single and Double Photonuclear Excitations in Pb+Pb Collisions at the LHC

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Abstract

Cross sections are calculated for single and double photon exchange in ultra-peripheral Pb+Pb collisions at the LHC. The particle production is simulated with the DPMJET event generator. Large cross sections are found for particle production around mid-rapidity making these processes an important background to hadronic nuclear interactions both at the trigger and analysis level.

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I. INTRODUCTION

The strong electromagnetic fields present in high-energy nuclear collisions with impact parameters larger than the sum of the nuclear radii lead to large cross sections for a variety of photonuclear processes. In these Ultra-Periphperal Collisions (UPC) there is no geometrical overlap between the colliding nuclei, so purely hadronic interactions are suppressed. Particle production in ultra-peripheral collisions has been studied in Au+Au collisions at RHIC and also in heavy-ion interactions at lower energies. See [1] for a review. These studies have so far been focused on the exclusive production of a single (vector) meson, e.g. $Au + Au \rightarrow Au + Au + V$ with $V = \rho^0$ or J/Ψ, or on two-photon production of dilepton pairs. The nuclei have remained intact or have only been excited to low energies by the exchange of an additional soft photon.

In this paper, we consider particle production in a general photonuclear interaction, $\gamma + A \rightarrow X$ in ultra-peripheral collisions between two lead nuclei at the CERN Large Hadron Collider (LHC). We do the calculations for the collision energy $\sqrt{s_{NN}} = 2.76$ TeV which will be available during the first two heavy-ion runs in 2010 and 2011/12. As will be discussed further below, the relevant photon energies for particle production around mid-rapidity are between ~ 10 GeV and ~ 100 TeV in the rest–frame of the target nucleus. We consider the cases when one or two photons are exchanged. In the former case, the photon-emitting nucleus remains intact, $A + A \rightarrow A + X$, while in the latter case both nuclei disintegrate.

The particle production in the photonuclear interactions is modeled using the DPMJET Monte Carlo Event Generator[2, 3].

We begin by discussing the photon flux associated with relativistic heavy-ions and derive the relevant spectrum for single and double photon exchange. We then discuss particle production in these collisions and how the produced particles a are distributed in phase space. We conclude by briefly discussing the experimental consequences of these processes in a typical high-energy collider experiment.

II. THE PHOTON SPECTRUM

The electromagnetic field of a relativistic particle can be treated as an equivalent flux of photons. This is the Weizsäcker-Williams method. For collisions between relativistic nuclei, the photon spectrum should be calculated in impact parameter space[4, 5]. In this way, interactions with nuclear overlap, where the strong interaction dominates, can easily be excluded.

The photon spectrum, dn/dk, of one ion in an ultra-peripheral collision is given by an integral over impact parameter, b,

$$\frac{dn}{dk} = 2\pi \int_0^\infty \frac{d^3n}{dkdb^2}(1 - P_{had}(b))bdb \tag{1}$$

The cut-off at small impact parameters $\sim 2R$ is implemented using a smooth function for the probability of not having any hadronic interaction $(1 - P_{had}(b))$; $P_{had}(b)$ is calculated from a Glauber model. Since the photonuclear interaction probabilities are highest in grazing collisions with impact parameters $b \approx 2R$, it is important to take the hadronic interaction probability into account properly and not rely on a simple cut-off at $b = 2R$ (cf. Fig. 1 below). The doubly differential photon spectrum $d^3n/dkdb^2$ is

$$\frac{d^3n}{dkdb^2} = \frac{Z^2\alpha}{\pi^2}\frac{1}{kb^2}x^2K_1^2(x) \tag{2}$$

where $x = bk/\gamma$ and $\gamma >> 1$ is the Lorentz factor.

The cross section for a photonuclear interaction with photons from a single beam is then given by

$$\sigma_{A+A\to A+X} = \int_{k_{min}}^\infty \frac{dn}{dk}\sigma_{\gamma A}(k)dk \tag{3}$$

The integral is cut-off by the rapid decrease of the photon spectrum for $k > \gamma/R \approx 120$ TeV in the rest-frame of the target nucleus.

By inserting the expression for dn/dk from Eq. 1 in Eq. 3 and changing the order of integration, the first order photonuclear interaction probability as function of impact parameter can be obtained through differentiation:

$$P_1(b) = \frac{d\sigma}{db^2} = \int_{k_{min}}^\infty \frac{d^3n}{dkdb^2}\sigma_{\gamma A}(k)dk \tag{4}$$

The photonuclear interaction probability as function of impact parameter is shown in Fig. 1 for three different values of k_{min} = 6 GeV, 1000 GeV, and 10 TeV. The minimum value 6 GeV is chosen as the lowest photon energy that can be handled by DPMJET. The effect of this minimum on the particle production in different rapidity intervals will be discussed futher below. The photonuclear cross section, $\sigma_{\gamma A}(k)$, is the cross section for particle production calculated by DPMJET; it depends weakly on the photon energy, k, and increases monotonically from 8.1 to 12.9 mb over the relevant energy range (6 GeV – 100 TeV).

The interaction probability has a maximum of ≈15% for $k_{min} = 6$ GeV in grazing collisions with impact parameter ≈16 fm. For $k_{min} = 1000$ GeV and 10 TeV, the corresponding maximum probabilities are 6% and 2%, respectively. These high probabilities make exchange of multiple photons in the same event likely. For cases where the collision time b/γ is much smaller than the excitation time, $1/k$, the sudden approximation applies, and the probability for multiple photon exchange factorizes[6]. This method has been used to calculate the total cross sections for correlated forward-backward Coulomb dissociation previously[7]. The cross section for exchanging one photon from each nucleus is thus given by

$$\sigma_{AA} = 2\pi \int_0^\infty [P_1(b)]^2 (1 - P_{had}(b)) b db \tag{5}$$

The photon energy spectrum for double excitation is obtained by differentiating Eq. 5 with respect to the photon energies k_1 and k_2. The result can be written

$$\frac{d\sigma}{dk_1 dk_2} = 2\pi \int_0^\infty \frac{d^3n}{dk_1 db^2} \sigma(k_1) \frac{d^3n}{dk_2 db^2} \sigma(k_2) (1 - P_{had}(b)) b db \tag{6}$$

It is worth noting that there is a positive correlation between the two photon energies. The photon spectrum from a single nucleus under the requirement that the other nucleus emits a photon is obtained by integrating over one of k_1 or k_2. The result is

$$\frac{d\sigma}{dk_1} = 2\pi \int_0^\infty \frac{d^3n}{dk_1 db^2} \sigma(k_1) P_1(b) (1 - P_{had}(b)) b db \tag{7}$$

The spectrum is thus weighted towards smaller impact parameter by the photonuclear interaction probability $P_1(b)$, resulting in a harder spectrum. This is in agreement with what was found for photonuclear vector meson production in coincidence with Coulomb break up[8].

Although the interactions probabilities for these photon energies are fairly high, they are sufficiently smaller than 1 for the first order probabilities to be used. Unitarity restoration[6] has been estimated to reduce the cross sections with at most a few percent.

III. PARTICLE PRODUCTION IN PHOTONUCLEAR INTERACTIONS

A high energy photon may interact with a nucleon or nucleus in two different ways: it can appear as a bare photon, which interacts with a parton in the target, or it can first fluctuate to a $q\overline{q}$–pair, which then interacts with the target via the strong interaction, see e.g. [9]. Since the quantum numbers of the photon are 1^{--}, it tends to fluctuate to a virtual vector meson (Vector Meson Dominance). The resolved processes, where the photon appears as a $q\overline{q}$–state, can be subdivided in to Vector Meson Dominance interactions resembling soft meson-nucleon interactions, and anomalous interactions, where a parton from the hadronic state interacts with a parton in the target[9]. The bulk of the photonuclear cross section and the soft particle production can be understood from resolved vector meson interactions.

The DPMJET[2, 3] Monte Carlo event generator is based on the two-component dual parton model. The resolved part of the photon-hadron interaction is handled by the dual parton model through its implementation in PHOJET. The scaling from photon-hadron to photon-nucleus interactions, including shadowing, is treated within the framework of the Gribov-Glauber approximation. The high-p_T partonic processes are calculated from lowest order perturbative QCD. The model has been tested against data from fixed target π-nucleus, p+nucleus, and μ+nucleus experiments. It has been shown to reproduce the bulk particle production well[3]. It can handle low or intermediate photon virtualities, which is fine in this case, since the photons from the Weizsacker-Williams fields have very low virtualities $Q^2 \leq (1/R)^2 \approx 10^{-3}$ GeV^2. The fragmetation of the target nucleus is not considered in the current version of DPMJET, but knock-out protons from the target remnant are included.

Samples of events have been generated with DPMJET with the photon spectrum described in the previous section and with different minimum photon energies. Six samples have been generated with 500,000 events per sample. Samples with single and double excitation have been generated with values of k_{min} = 6, 1000, 10,000 GeV. The cross section for these samples are listed in Table I. The Table also includes the corresponding cross sections when it is required that there should be at least one charged particle at central rapidities.

The normalized charged particle pseudorapidity ($\eta = -\ln(\tan(\theta/2))$) density distributions for the samples are shown in Figure 2 a) - f). As expected, the particle production becomes more centered around mid-rapidity with increasing photon energy. The corresponding multiplicity distributions of charged particles with $|\eta| < 1$ are shown in Figure 3 a) - f).

The cross sections in Table I are huge. The total photoproduction cross section for $k > 6$ GeV is about 3 times larger than the total hadronic cross section. If one requires at least one photoproduced charged particle within $|\eta| < 1$, the cross section is about 4 b or roughly 50% of the total hadronic cross section. As can be inferred from Fig. 3, the probability for having larger multiplicities around mid–rapidity is also very high.

The transverse momenta of the photoproduced particles are typical for soft hadron-nucleus interactions. The p_T distribution at mid-rapidity for single production with $k_{min} = 6$ GeV is shown in Figure 4 a). The distribution is essentially the same for all samples studied with a mean transverse momentum of $< p_T > \approx 450$ MeV/c.

The large cross sections and the characteristics of these interactions should make them an important background to hadronic nuclear interactions at colliders. Single excitations, which have the largest cross sections, are characterized by a strong asymmetry around mid–rapidity event–by–event. They can thus to some extent be rejected by requiring the presence of particles on either side of mid–rapidity. The cross sections for double excitations are lower, but these events have particles produced over a wider range of rapidities. They may therefore be harder to separate from hadronic interactions with low or intermediate multiplicities.

The photon spectrum of course extends to in principle arbitrarily low values of k. The lowest $k_{min} = 6$ GeV used here is therefore in that sense arbitrary. However, for particle production around mid-rapidity, photons with low energy do not contribute. This is illustrated in Figure 4 b) and c). Figure 4 b) shows the ratio of the number of events with at least one charged particle within $|\eta| < 1$ to all events as a function of photon energy. The distribution goes to zero around $k \approx 150$ GeV, and photons with energy lower than this do thus not contribute to the particle production within the two most central units of pseudorapidity. Figure 4 c) shows the same distribution for events with at least one charged particle within $|\eta| < 4.5$. The ratio goes to zero above the lowest $k_{min} = 6$ GeV used here. The photon energy range considered should thus give a complete description of photoproduction within the nine most central units of pseudorapidity, $|\eta| < 4.5$.

Unlike exclusive production of single mesons or dilepton pairs, inclusive photoproduction in ultra-peripheral collisions has so far attracted rather limited interest. Some early studies were done for the BNL Relativistic Heavy-Ion Collider[10], mainly to find the background rates for exclusive production. The cross sections are about an order of magnitude lower at RHIC energies ($\sqrt{s_{NN}} = 200$ GeV) than at the LHC. Inclusive photoproduction of mesons in high energy heavy-ion interactions were also studied in[11]. The results are not directly comparable to the present work, because of a lower minimum photon energy, k_{min}, and because only multiple photons hitting the *same* nucleus were considered.

IV. CONCLUSIONS

We have calculated the photon energy spectrum for single and double photonuclear excitations in Pb+Pb collisions at the LHC. Events have been generated with the DPMJET Monte Carlo according to these spectra. Large cross sections are found, also for particle production around mid-rapidity.

The large cross sections and the non-zero probability for having charged particles produced with intermediate or high p_T around mid-rapidity make these events an important background to peripheral and semi-central Pb+Pb collisions at the LHC. They have to be taken into account if one should be able to correctly determine what fraction of the total hadronic cross section a given event selection corresponds to.

If the photonuclear events can be clearly separated from the hadronic events, e.g. using the rapidity gap between the photon-emitting nucleus and the produced particles, much interesting physics could be extracted from them. The cross section to produce a $c\bar{c}$–pair through γ+gluon fusion is for example nearly 1 b at the full LHC energy[12]. If these events can be measured, they would provide valuable information on the nuclear parton distribution functions.

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TABLE I: Cross section for particle production for single and double photonuclear excitations with different minimum photon energies, k_{min}. The total cross sections and the cross sections for having at least one charged particle within $|\eta| < 1$ are shown. The cross section for single take into account that both nuclei can act as photon–emitter and target.

	single		double	
k_{min} [GeV]	σ [b]	σ [b]	σ [mb]	σ [mb]
	all	$n_{ch}(\lvert\eta\rvert < 1) \geq 1$	all	$n_{ch}(\lvert\eta\rvert < 1) \geq 1$
6	24.2	4.5	240	130
1000	4.9	3.5	42	40
10,000	0.90	0.81	4.8	4.8

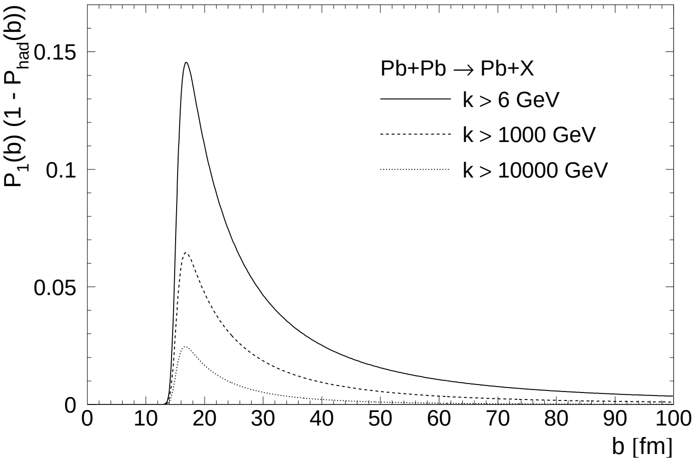

FIG. 1: The probability for having a photonuclear interaction and no hadronic interaction as a function of impact parameter for 3 different minimum photon energies, k_{min}.

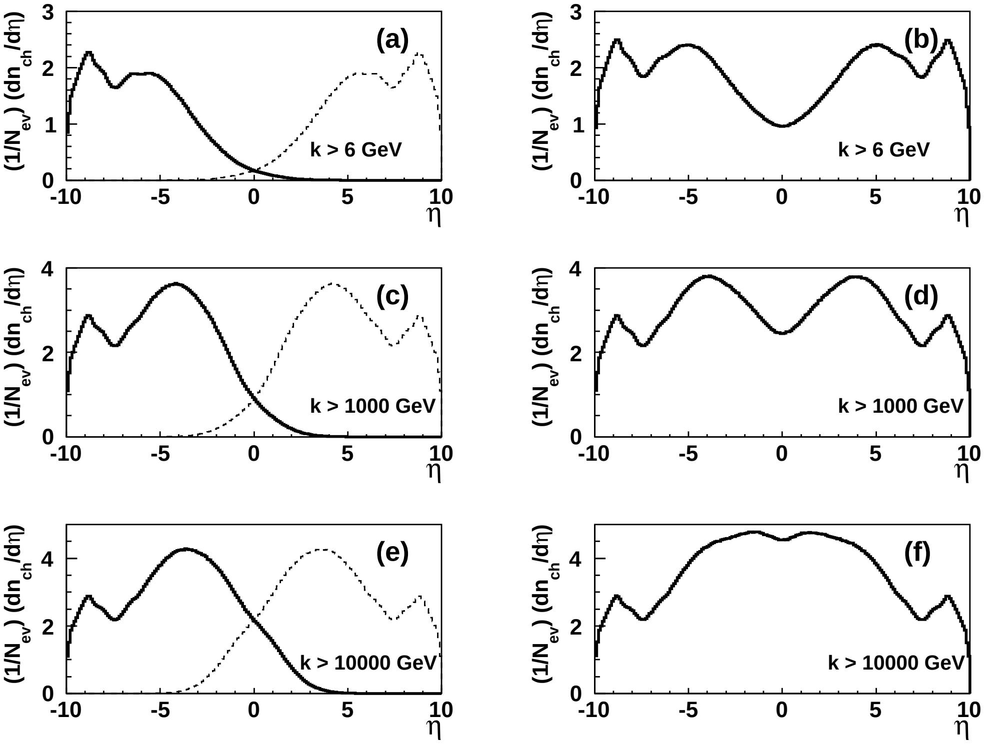

FIG. 2: Pseudorapidity distributions of charged particles for different minimum photon energies for single (left) and double (right) excitations with different cut-off energies, k_{min}. For single, the solid histograms are for photoproduction off the nucleus with negative rapidity and the dashed histogram corresponds production off the nucleus with positive rapidity. The peaks around $\eta = \pm\ 9$ are from knock-out protons from the target nucleus.

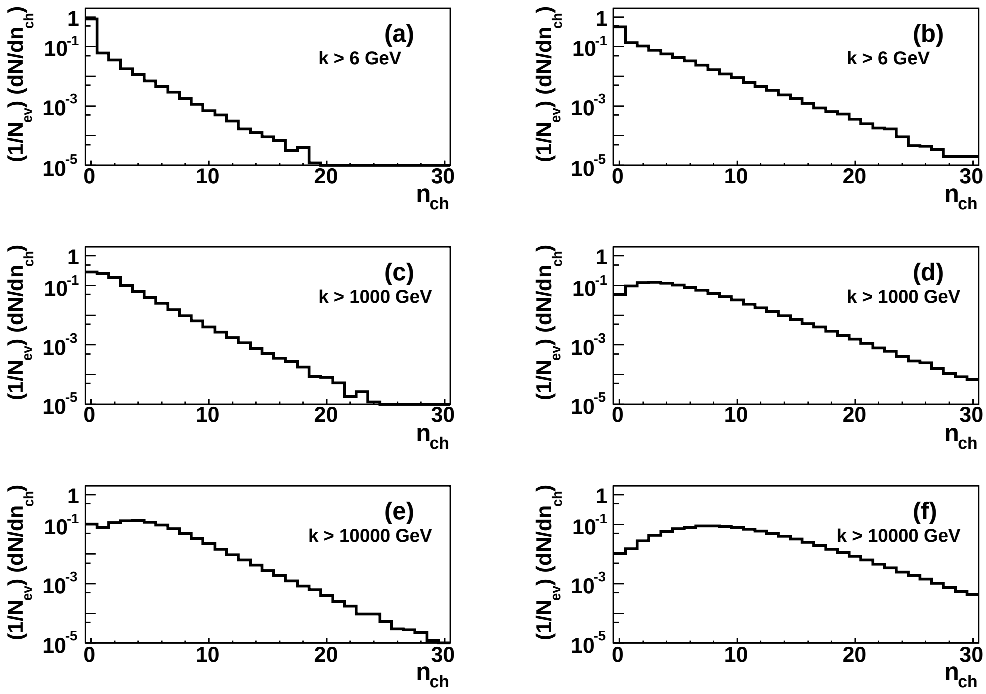

FIG. 3: Multiplicity distributions of charged particles at mid-rapity $|\eta| < 1$ for single (left) and double (right) excitations with different cut-off energies, k_{min}.

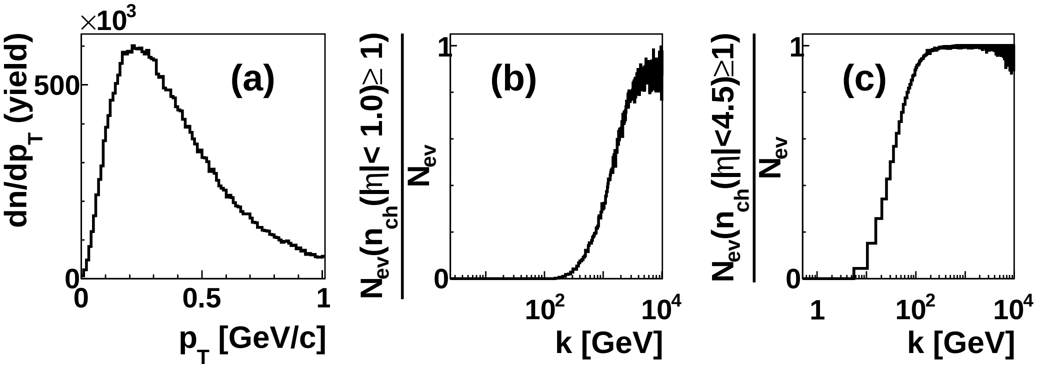

FIG. 4: (a) Transverse momentum distribution of charged particles within $|\eta| < 1$. (b) Fraction of events with at least one charged particle within $|\eta| < 1$ as function of photon energy. (c) Same as (b) but for $|\eta| < 4.5$.