Ultraperipheral Collisions

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Ultraperipheral collisions at heavy ion colliders use the strong Coulomb fields surrounding the ions to study photon-photon and photon-hadron processes at high energy. A number of processes of interest are discussed here.

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1 Introduction

Ultraperipheral collisions (UPC) are the processes that occur at impact parameter \( b > 2R \), when the two ions do not interact hadronically. Instead one uses the strong Coulomb field surrounding the ions for elementary particle processes, see Fig. 1. The coherence of all the protons in the ion leads to an enhancement factor of \( Z^4 (\gamma\gamma) \) or \( Z^2 (\gamma A) \), respectively, compared to the one for \( pp \) or \( ee \). This offers the possibility to study a number of interesting \( \gamma\gamma \) and \( \gamma A \) processes at energies and masses, which were up to now not available. The flux of “equivalent photons” (quasireal photons) goes up to the region of 100 GeV for \( \gamma\gamma \) collisions (collider rest frame) and up to 500 TeV for \( \gamma A \) collisions (rest frame of the target ion).

Ultraperipheral collisions have been studied for some time now \cite{1, 2, 3, 4} and are part of the heavy ion program of ALICE \cite{5}, ATLAS \cite{6} and CMS \cite{7, 8}. Detailed studies have been made already for some specific processes for different LHC detectors, as will be discussed in the following.

Photon-photon physics has been studied in \( ee \) collisions at LEP at CERN, photon-proton, photon-photon and also photon-ion collisions were studied at HERA at DESY. UPC allow to extend these successful studies to higher energies and higher luminosities. The main theoretical tool is the “equivalent photons approximation” or “Fermi-Weizsäcker-Williams method”, first developed by Fermi \cite{9} and extended to relativistic energies by Weizsäcker and Williams \cite{10}. Its application was studied in detail in connection with lepton colliders in \cite{11}.

For the ion case there are some important differences compared to the lepton case, which need to be taken into account: The nucleus is not a point-like object,
Fig. 1. The Coulomb field surrounding the heavy ions in relativistic heavy ion collisions can be seen as a flux of quasireal equivalent photons. In ultra peripheral collisions (UPC) they are used for photon-photon and photon-nucleus processes.

but has a finite size, described by its elastic form factor $F(k^2)$. As $F(k^2) \approx 1$ only for $k^2 < \frac{1}{R^2}$, with $R$ the nuclear radius, this form factor leads to two restrictions; on the one hand the transverse momentum is limited to $k_{\perp} < 1/R \approx 30$ MeV. This means that in contrast to lepton beams, only “quasireal” photons can be studied. On the other hand it also limits the maximum energy which can be taken by the photon to $\omega < \gamma/R$. This maximum energy corresponds only to a tiny fraction of the total energy of the ion

$$x_{\max} = \frac{\omega_{\max}}{E_{\text{ion}}} \approx \frac{1}{RM_N A} = \frac{\lambda_C(A)}{R}$$

One finds $4 \times 10^{-3}$ for O, $1.4 \times 10^{-4}$ for Pb.

Furthermore the ions are interacting hadronically if their impact parameter is closer than $2R$. Whereas photon-photon and photon-nucleus processes will still take place at these collisions, they are completely covered by the hadronic processes. Therefore these collisions need to be removed to get the usable photon-photon luminosity.

Finally due to the strong fields there is also the possibility of additional photon exchanges and photon excitation processes. Whereas they were first seen as a nuisance [12], as most of them lead to breakup, e.g., neutron emission from the ions, and therefore the clean “no breakup” condition would be spoiled, they have now found some interesting applications, see below.

In order to describe the equivalent photons the semiclassical approach was found to be useful, as it allows to take into account all the “complication” discussed above. There exist already some reviews, where this approach is discussed [3, 2, 1].
2 Equivalent photon spectra and luminosities at the LHC

Integrating over all allowed impact parameter, one gets the effective photon-photon luminosity for the production of a final state with invariant mass $W$ and with rapidity $Y$ in the semiclassical picture as

$$\frac{dL_{\gamma\gamma}}{dWdY} = \frac{2}{W} \int_{R_{\text{min}}}^{\infty} d^2b_1 \int_{R_{\text{min}}}^{\infty} d^2b_2 \times N_1\left(\frac{W}{2}e^Y, b_1\right)N_2\left(\frac{W}{2}e^{-Y}, b_2\right)\Theta(|\vec{b}_1 + \vec{b}_2| - R_{\text{min}}).$$

(2)

Here $N_1$ and $N_2$ are the impact parameter dependent equivalent photon numbers. For further details, see [1]. With this the cross section for a $\gamma\gamma$ process factorizes into a luminosity and a (real) elementary $\gamma\gamma$ cross section

$$\sigma(A + A \rightarrow A + A + X) = \int dWdY \frac{dL_{\gamma\gamma}}{dWdY} \sigma(\gamma + \gamma \rightarrow X, W).$$

(3)

For photonuclear reactions the equivalent photon number is simply given by integrating over the allowed impact parameter between the two ions

$$n(\omega) = \int_{R_{\text{min}}}^{\infty} 2\pi bdbN(\omega, b).$$

(4)

and we get the cross section as

$$\sigma(AA \rightarrow A + X) = \int d\omega n(\omega)\sigma(\gamma A \rightarrow X, \omega)$$

(5)

Taking into account the expected different ion-ion luminosities for the LHC, see Table 1, one gets the effective photon-photon luminosity as shown in Fig. 2, taken from [1]. The available invariant masses for the $\gamma\gamma$ system are beyond what has been achieved at LEP. This figure also shows that $pp$ or ArAr collisions seem to be more favorable compared to PbPb. This is due to the fact, that the PbPb beam luminosity is five orders of magnitude smaller than the $pp$ luminosity, which compensates the $Z^4$ enhancement [13]. Also for $pp$ collisions the invariant mass of the $\gamma\gamma$ system goes beyond what is available for PbPb. The reason for this is the smaller size of the proton, giving rise to a harder photon spectrum. One might conclude from this that there is no real advantage in using heavy ion beams for $\gamma\gamma$ collisions, but one should keep in mind, that the most important background are diffractive processes (“Pomeron-Pomeron” processes) [14]. These events can have the same characteristic of leaving the two ions intact, which is an essential signal to distinguish ultraperipheral collisions from, e.g., grazing collisions. The coherence of the photon emission helps to reduce this background. In the case of $pp$ collisions diffractive processes clearly dominate the electromagnetic ones and additional care needs to be taken to distinguish the two. The electromagnetic cross section grows like $Z^4/Z^2$. The coherent diffractive processes is sensitive to the surface region of


|       | $L_{AA}$                     |
|-------|------------------------------|
| p p   | $1.4 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ |
| Ar Ar | $5.2 \times 10^{29}$ cm$^{-2}$ s$^{-1}$ |
| Pb Pb | $4.2 \times 10^{26}$ cm$^{-2}$ s$^{-1}$ |

Table 1. Beam Luminosities for different ions species at the LHC

Fig. 2. (a) Effective photon-photon luminosities for different ion species. (b) Equivalent Photon number for Pb Pb collisions at the LHC.

For the two ion, the cross section is therefore proportional to $A^\delta$ with $\delta \approx 1/3$ [14]. For lead ions the electromagnetic processes are expected to be dominant [15, 16].

For photonuclear reactions one takes the photon energy in the rest frame of the ion, using $\gamma_{ion} = 2\gamma_{coll}^{-2} - 1$ instead of $\gamma_{coll}$. This leads to photon energies of up to 500 TeV, way beyond the possibilities of HERA, see Fig. 2(b). In addition the use of heavy ions is an advantage here as well, photonuclear processes on ions can be measured at these high energies.

### 3 Potential for $\gamma \gamma$ Physics

#### 3.1 New physics searches

The production of the Higgs boson was studied by a number of people in the past, see [3] for a detailed review. It was found that electromagnetic production is favorable compared to hadronic production, as it allows for rather clean events [17, 18]. Unfortunately due to the lower effective luminosity and the higher mass limit from the LEP Higgs searches, rates for a SM or MSSM Higgs are rather
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small [19]. This will make UPC for a search or the study of the Higgs boson very unfavorable. Still models with a larger coupling of the Higgs to two photons, e.g., a “leptophobic” Higgs, or nonstandard models with a light Higgs might still be possible and could be investigated in this way [20, 21, 22].

Other particles have also been studied to be detected in photon-photon processes: With the increased mass limit, the production rates of SUSY particles were again found to be to small [23, 1]. Magnetic monopoles have been searched by looking for \( \gamma\gamma \rightarrow \gamma\gamma \) with a large transverse momentum at the TEVATRON [24, 25]. Due to the strong coupling of the magnetic monopole to the photon this cross section is strongly enhanced. Such a search could also be feasible at the LHC and could increase the mass limit. The process \( \gamma\gamma \rightarrow \gamma\gamma \) was also proposed to be used to study the \( \sigma \) meson [26].

3.2 Tagging of the final protons

At CMS/TOTEM one has the possibility to detect protons, which have lost more than about 1% of their energy [27, 28], corresponding to a photon energy of 70 GeV. This opens the possibility to study \( \gamma\gamma \) processes at high energies. It also allows to determine directly the energy of the emitted photon and therefore the mass of the \( \gamma\gamma \) system. Loosening the restriction of detecting both ions allows to increase the luminosity and also extend the invariant mass spectrum to lower energies. This allows to study electromagnetic processes in the electroweak sector. In \( pA \) collisions one can look also for \( \gamma\gamma, \gamma p \) or \( \gamma A \) processes. Due to the small \( x_{\text{max}} \) it will not be possible to detect the lead ions in this case.

Diffractive processes will again be a background. As the Pomeron also has a high probability to be emitted with the proton remaining intact, they cannot be distinguished from the event characteristics from UPC. On the other hand the photon has a very narrow transverse momentum distribution, whereas the Pomeron leads to a momentum distribution of the proton in the area of several 100 MeV. There is a theoretical limitation for using \( pp \) beams for UPC, coming from the occurrence of overlapping events [14]. E.g., at the high luminosity run of the LHC with \( L_{pp} \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) there will always be hadronic interaction in each bunch crossing, making the study of UPC rather difficult.

3.3 \( \gamma\gamma \) processes at lower energies

Even at lower invariant masses there are a number of processes of interest. One such possibility is double vector meson production, which was already studied in connection with FELIX [15, 16]. It allows for a test of the soft factorization hypothesis

\[
\frac{\sigma(\gamma p \rightarrow V_1 p)}{dt} \frac{\sigma(\gamma p \rightarrow V_2 p)}{dt} = \frac{\sigma(\gamma\gamma \rightarrow V_1 V_2)}{dt} \frac{\sigma(pp \rightarrow pp)}{dt}
\]

(6)

as well as

\[
\frac{\sigma(\gamma\gamma \rightarrow V_1 V_1)}{dt} \frac{\sigma(\gamma\gamma \rightarrow V_2 V_2)}{dt} = \left( \frac{\sigma(\gamma\gamma \rightarrow V_1 V_2)}{dt} \right)^2.
\]

(7)

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which allows to relate this process to other vector meson production processes. Deviations from this factorization are expected to be large.

Detailed studies taking into account the possibility to measure the muons from the decay in the ALICE Muon arm are under way. The muons can be used as L0 trigger at ALICE. The rapidity distribution, which centers around $Y = 3$, see Fig. 3 agrees quite well with the acceptance region of the Muon Arm of ALICE.

Another process of interest would be $\gamma \gamma \rightarrow$ hadrons, which has been studied at L3 at LEP [29, 30]. Deviation from the Regge universality was found at high energies and especially for final states containing heavy quarks. The total cross section measured by all the detectors at LEP has an overall uncertainty of about 40% coming from the uncertainty of different Monte Carlo generators in the forward region, which was not covered by LEP [31]. Here one might hope that the detectors at the LHC, some of which have extensive forward detection possibilities, could contribute to this process. Unfortunately it is not easy to measure such hadronic final states and to distinguish them from hadronic processes.

Finally meson spectroscopy of lighter mesons, containing $c$ and $b$ quarks can be studied. The $\gamma \gamma$ decay width of these mesons gives an insight into the question, whether they are predominantly build from quark or gluon degrees of freedom. QED processes can be studied in this way too. Lepton pair production is a process of interest due to its large cross section (about 200 kbar for PbPb collisions at the LHC), allowing for a luminosity measurement, but also as multiple pair production occurs in single collisions, an interesting higher order QED effect, see [32, 33] and also [1] were further references can be found. Bound-free pair production (also called “electron capture from pair production” ECPP) is the process, where the electron is not produced as a free particle, but into the bound state of one of the ions [1]. Even though this is only a tiny fraction of the free pair production process, it has a total cross section of 200 barn for PbPb collisions at the LHC and is (together with the electromagnetic excitations of the ions discussed below) the dominant loss
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\[
\begin{array}{|c|c|c|}
\hline
M [GeV] & \sigma_{\gamma\gamma} (barn) & \text{events/year} \\
\hline
10^{-6} & 10^0 & 10^8 \\
10^{-5} & 10^1 & 10^7 \\
10^{-4} & 10^2 & 10^6 \\
10^{-3} & 10^3 & 10^5 \\
10^{-2} & 10^4 & 10^4 \\
10^{-1} & 10^5 & 10^3 \\
\hline
\end{array}
\]

Fig. 4. Cross section and production rates for different mesons in $\gamma\gamma$ collisions for PbPb collisions at the LHC.

process of the lead beam. In addition the $\text{Pb}^{81+}$ ions hit the beam pipe at a very definite point and lead to the deposition of a large amount of energy [34, 35]. The quench limit of the superconducting magnets gives for PbPb beams the limit for the maximal beam luminosity. Finally positronium and muonium are produced in large numbers in both ortho- and para-states and could be studied as well [2, 1].

4 Photon hadron reactions

4.1 Photo-excitation of the nucleus

The photon spectrum available for photonuclear reactions ranges up to the TeV regime. A dominant feature at low energies is the excitation of the giant dipole resonance (GDR), followed by other nuclear and nucleon excitations at higher energies. In collisions close to $b \approx 2R$ the probability to excite one ion is about 75%, the excitation of the GDR contributes to this with about 40%. The total cross section for this excitation is about 200 barn [36, 37, 38]. As the GDR predominantly deexcites by neutron emission, this leads to a change in the $Z/A$ ratio of the ion and it is lost in the beam. Together with the bound free pair production cross section, mentioned above, it is the main loss process of the lead ions, limiting the total beam lifetime. Due to the strong fields, large probabilities exist for more than one process to occur in one collision. This can be either the excitation of higher states in the ions (double GDR, triple GDR) [39, 40] or of other processes in connection with a GDR excitation of one or both ions.

The mutual excitation and subsequent emission of the neutrons from both ions is used at RHIC as a luminosity measurement tool [38, 41], where the neutrons are detected in the ZDCs, see Fig. 5. The measured cross section for different processes (1,2,$x$ neutron emission) were compared with theoretical predictions from RELDIS [42] and good agreement was found.

These mutual excitations are also a useful trigger for UPCs. Single neutron
4.2 Coherent $\gamma A$ processes

At higher energies the diffractive production of vector mesons can be studied. After theoretical calculations \[44, 45, 46\] this was for the first time measured at STAR/RHIC \[47, 48\]. In their experiment the coherent production of $\rho$ mesons was measured with and without triggering for the additional mutual excitation of the ions, see Fig. 6. The coherent production was identified by an enhancement of their signal at small $p_\perp < 1/R$, see Fig. 6(a). The $\rho$-meson was identified by looking at the invariant mass spectrum, which could be very nicely fitted to Breit-Wigner amplitude for the $\rho$-production and a contribution from direct $\pi^+\pi^-$ production, see Fig. 6(b).

There is also an interesting interference phenomenon: As both ions can act as either the photon source or the target, the two processes need to be added coherently \[45\]. First hints of such an interference have been seen at STAR \[49, 48\].

At the LHC these studies can be extended to heavier mesons, especially to the $J/\Psi$ and even the $\Upsilon$. New phenomena are expected to occur for these heavier mesons \[50\]. Whereas the $\rho$ production is very well reproduced by (Gribov-) Glauber calculations \[51\], the cross section for $J/\Psi$ and $\Upsilon$ are smaller and are more sensitive to new phenomena like color transparencies and nuclear shadowing effects \[50\]. Different predictions have been made and it is of interest to determine between them at the LHC. Simulations have been made for ALICE, using the muons as L0 trigger.

The additional electromagnetic excitation of the ions can also be helpful here: As the additional excitation restricts the collisions to smaller impact parameter,
Fig. 6. The two measurements of $\rho$-production at STAR: a) without and b) with additional electromagnetic excitation of both ions.

Fig. 7. The transverse momentum (a) and invariant mass spectrum (b) for the coherent $\rho$-production at STAR is shown.

the photon spectra is harder than in the unrestricted case [52]. This allows to disentangle the contribution from both ions and to extend the measurement to rapidities $Y \neq 0$ without any model assumption.

4.3 Photon-gluon fusion processes and quark pdfs

Also semicoherent processes, where the photon emission occurs elastically, but there is an incoherent interaction with the target, are of interest. Inelastic vector meson production is one possible process of this type.

Most of the interest is focused on photon-gluon fusion as a possibility to measure the gluon distribution function inside the nuclei [5, 53, 54]. Different models, predicting nuclear modifications have been proposed, especially for small $x$. A precise measurement of these “initial state effects” would also be of importance to model the initial state of ion-ion collisions in central collisions.

A detailed study of the production of $b$ and $c$ quark pairs was made for the LHC [52, 55] taking into account not only the lowest order diagram, but also resolved...
Fig. 8. Feynman diagrams for the photon-gluon fusion process: (a) direct process, (b) resolved processes.

Fig. 9. Two possible options to measure the quark pdf of nuclei with UPCs: (a) Compton scattering on the quark with large transverse momenta, (b) inelastic pair production with one highly virtual photon.

contributions, see Fig. 8.

In connection with the change of the gluon distribution functions also a change of the quark distribution functions is expected. These distribution functions are accessible at a large $Q^2$ scale, e.g., through the Compton scattering process $\gamma q \rightarrow \gamma q$ at large transverse momenta \cite{55}. An alternative approach for smaller $Q^2$ scale is to use inelastic pair production \cite{56}, see Fig. 9(b). Whereas one photon is emitted elastically, the other is highly virtual. Therefore one can see this as lepton-ion deep inelastic scattering.

5 Summary and Conclusions

Ultraperipheral collisions at the LHC allow to study photon-photon and photon-nucleus processes at high energies and large luminosities. In photon-photon physics electroweak processes can be studied in tagged $pp$ collisions, meson production, double vector meson production are clearly possible. The total hadronic cross section $\gamma \gamma \rightarrow$ hadron would be an interesting study, but is probably difficult to do. The discovery potential for new physics seems unfortunately to be rather limited.

Photon-nucleus collisions can be used to study coherent vector meson production, especially of the $J/\Psi$ and probably also the $\Upsilon$. Photon-gluon fusion allows to study gluon-pdfs in nuclei. Quark distributions can be either studied by Compton
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scattering of photons or inelastic pair production.

UPC are also of practical importance for ion beams at the LHC: Bound-free pair production and electromagnetic excitation are the dominant loss processes at Pb beams and also limit the maximum achievable beam luminosity. Mutual electromagnetic excitation but also lepton pair production are interesting possibilities for luminosity measurements. The new measurements from RHIC help the LHC here.

At CERN a Yellow Report to document the physics potential for UPC collisions is currently being prepared. Details and also the talks of some workshops can be found at their webpage [57].

To summarize, let us just say that “The events are there, some of them are most interesting, just do not throw them away”.

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