Two Photon Physics in pp and AA Collisions

Gerhard Baur

Institut für Kernphysik,
Forschungszentrum Jülich, Jülich, Germany
E-mail: G.Baur@fz-juelich.de

Kai Hencken

Institut für Physik,
Universität Basel, Basel, Switzerland
E-mail: hencken@quasar.physik.unibas.ch

Dirk Trautmann

Institut für Physik,
Universität Basel, Basel, Switzerland
E-mail: trautmann@ubaclu.unibas.ch

Abstract

In central collisions at relativistic heavy ion colliders like the Relativistic Heavy Ion Collider RHIC/Brookhaven and the Large Hadron Collider LHC (in its heavy ion mode) at CERN/Geneva, one aims at detecting a new form of hadronic matter — the Quark Gluon Plasma. We discuss here a complementary aspect of these collisions, the very peripheral ones. Due to coherence, there are strong electromagnetic fields of short duration in such collisions. They give rise to photon-photon and photon-nucleus collisions with high flux up to an invariant mass region hitherto unexplored experimentally. After a general survey photon-photon luminosities in relativistic heavy ion collisions are discussed. Special care is taken to include the effects of strong interactions and nuclear size. Then photon-photon physics at various $\gamma\gamma$-invariant mass scales is discussed. The region of several GeV, relevant for RHIC is dominated by QCD phenomena (meson and vector meson pair production). Invariant masses of up to about 100 GeV can be reached at LHC, and the potential for new physics is discussed. Photonuclear reactions and other important background effects, especially diffractive processes are also discussed. Lepton-pair production, especially electron-positron pair production is copious. Due to the strong fields there will be new phenomena, especially multiple $e^+e^-$ pair production.
\section{Introduction}

The parton model is very useful to study scattering processes at very high energies. The scattering is described as an incoherent superposition of the scattering of the various constituents. For example, nuclei consist of nucleons which in turn consist of quarks and gluons, photons consist of lepton pairs, electrons consist of photons, etc. We note that relativistic nuclei have photons as an important constituent, especially for low enough virtuality \( Q^2 = -q^2 > 0 \) of the photon. This is due to the coherent action of all the charges in the nucleus. The virtuality of the photon is related to the size \( R \) of the nucleus by

\[ Q^2 \lesssim 1/R^2, \]

the condition for coherence. The radius of a nucleus is given approximately by \( R = 1.2 \text{ fm} \ A^{1/3} \), where \( A \) is the nucleon number. From the kinematics of the process one has

\[ Q^2 = \frac{\omega^2}{\gamma^2} + q_{\perp}^2. \]

Due to the coherence condition the maximum energy of the quasireal photon is therefore given by

\[ \omega_{\text{max}} \approx \frac{\gamma}{R}, \]

and the maximum value of the perpendicular component is given by

\[ q_{\perp} \lesssim \frac{1}{R}. \]

We define the ratio \( x = \omega/E \), where \( E \) denotes the energy of the nucleus \( E = M_N \gamma A \) and \( M_N \) is the nucleon mass. It is therefore smaller than

\[ x_{\text{max}} = \frac{1}{RM_N A} = \frac{\lambda_C(A)}{R}, \]

where \( \lambda_C(A) \) is the Compton wave length of the ion. Here and also throughout the rest of the paper we use natural units, setting \( \hbar = c = 1 \).

The collisions of \( e^+ \) and \( e^- \) has been the traditional way to study \( \gamma\gamma \)-collisions. Similarly photon-photon collisions can also be observed in hadron-hadron collisions. Since the photon number scales with \( Z^2 \) (\( Z \) being the charge number of the nucleus) such effects can be particularly large. Of course, the strong interaction of the two nuclei has to be taken into consideration.

The equivalent photon flux present in medium and high energy nuclear collisions is very high, and has found many useful applications in nuclear physics \([\text{1}]\), nuclear astrophysics \([\text{2, 3}]\), particle physics \([\text{4}]\) (sometimes called the “Primakoff effect”), as well as, atomic physics \([\text{5}]\). It is the main purpose of this review to discuss the physics of photon-photon and photon-hadron (nucleus) collisions in high energy heavy ion collisions. With the construction of the “Relativistic Heavy Ion Collider” (RHIC) and the “Large Hadron Collider” (LHC) scheduled for 1999 and for 2004/2008, respectively, one will be able to investigate such collisions experimentally. The main purpose of these heavy ion colliders is the formation and detection of the quark-gluon-plasma, a new form of highly excited dense hadronic matter. Such a state of matter will be created in central collisions. The present interest is in the “very peripheral (distant) collisions”, where the nuclei do not
Figure 1: A fast moving nucleus with charge Ze is surrounded by a strong electromagnetic field. This can be viewed as a cloud of virtual photons. These photons can often be considered as real. They are called equivalent or quasireal photons. The ratio of the photon energy ω and the incident beam energy E is denoted by $x = \omega/E$. Its maximal value is restricted by the coherence condition to $x < \lambda_C(A)/R \approx 0.175/A^{1/3}$, that is, $x < 10^{-3}$ for Ca ions and $x < 10^{-4}$ for Pb ions.

Figure 2: Two fast moving electrically charged objects are an abundant source of (quasireal) photons. They can collide with each other and with the other nucleus. For peripheral collisions with impact parameters $b > 2R$, this is useful for photon-photon as well as photon-nucleus collisions.

interact strongly with each other. From this point of view, grazing collisions and central collisions are considered as a background. It is needless to say that this “background” can also be interesting physics of its own.

The equivalent photon spectrum extends up to several GeV at RHIC energies ($\gamma \approx 100$) and up to about 100 GeV at LHC energies ($\gamma \approx 3000$), see Eq. (3). Therefore the range of invariant masses $M_{\gamma\gamma}$ at RHIC will be up to about the mass of the $\eta_c$, at LHC it will extend into an invariant mass range hitherto unexplored.

Relativistic heavy ion collisions have been suggested as a general tool for two photon physics about a decade ago. Yet the study of a special case, the production of $e^+e^-$ pairs in nucleus-nucleus collisions, goes back to the work of Landau and Lifschitz in 1934 [9] (In those days, of course, one thought more about high energy cosmic ray nuclei than relativistic heavy ion colliders). The general possibilities and characteristic features of two-photon physics in relativistic heavy ion collisions have been discussed in [10]. The possibility to produce a Higgs boson via $\gamma\gamma$-fusion was suggested in [11, 12]. In these papers the effect of strong absorption in heavy ion collisions was not taken into account. This
absorption is a feature, which is quite different from the two-photon physics at $e^+e^-$ colliders. The problem of taking strong interactions into account was solved by using impact parameter space methods in \[10, 11, 12\]. Thus the calculation of $\gamma\gamma$-luminosities in heavy ion collisions is put on a firm basis and rather definite conclusions were reached by many groups working in the field \[13\]; for recent reviews see \[14\] and \[15\]. This opens the way for many interesting applications. Up to now hadron-hadron collisions have not been used for two-photon physics. An exception can be found in \[16\]. There the production of $\mu^+\mu^-$ pairs at the ISR was observed. The special class of events was selected, where no hadrons are seen associated with the muon pair in a large solid angle vertex detector. In this way one makes sure that the hadrons do not interact strongly with each other, i.e., one is dealing with peripheral collisions (with impact parameters $b > 2R$); the photon-photon collisions manifest themselves as “silent events”. Dimuons with a very low sum of transverse momenta are also considered as a luminosity monitor for the ATLAS detector at LHC \[17\].

Experiments are planned at RHIC \[18, 19, 20, 21, 22\] and discussed at LHC \[23, 24, 25\]. We quote J. D. Bjorken \[26\]:

It is an important portion (of the FELIX program at LHC) to tag on Weizsaecker Williams photons (via the nonobservation of completely undissociated forward ions) in ion-ion running, creating a high luminosity $\gamma - \gamma$ collider.

2 From impact-parameter dependent equivalent photon spectra to $\gamma\gamma$-luminosities

Photon-photon collisions have been studied extensively at $e^+e^-$ colliders. The theoretical framework is reviewed, e.g., in \[27\]. The basic graph for the two-photon process in ion-ion collisions is shown in Fig. 3. Two virtual (space-like) photons collide to form a final state $f$. In the equivalent photon approximation it is assumed that the square of the 4-momentum of the virtual photons is small, i.e., $q_1^2 \approx q_2^2 \approx 0$ and the photons can be treated as quasireal. In this case the $\gamma\gamma$-production is factorized into an elementary cross section for the process $\gamma + \gamma \rightarrow f$ (with real photons, i.e., $q^2 = 0$) and a $\gamma\gamma$-luminosity function. In contrast to the pointlike elementary electrons (positrons), nuclei are extended, strongly interacting objects with internal structure. This gives rise to modifications in the theoretical treatment of two photon processes. The emission of a photon depends on the (elastic) form factor. Often a Gaussian form factor or one of a homogeneous charged sphere is used. The typical behavior of a form factor is

\[
f(q^2) \approx \begin{cases} 
Z & \text{for } |q^2| < \frac{1}{R^2} \\
0 & \text{for } |q^2| \gg \frac{1}{R^2}
\end{cases}.
\]

For low $|q^2|$ all the protons inside the nucleus act coherently, whereas for $|q^2| \gg 1/R^2$ the form factor is very small, close to 0. For a medium size nucleus with, say, $R = 5$ fm, the limiting $Q^2 = -q^2 = 1/R^2$ is given by $Q^2 = (40\text{MeV})^2 = 1.6 \times 10^{-3}$ GeV$^2$. Apart from $e^+e^-$ (and to a certain extent also $\mu^+\mu^-$) pair production, this scale is much smaller than typical scales in the two-photon processes. Therefore the virtual photons in relativistic heavy ion collisions can be treated as quasireal. This is a limitation as compared to $e^+e^-$ collisions, where the two-photon processes can also be studied as a function of the corresponding masses $q_1^2$ and $q_2^2$ of the exchanged photon (“tagged mode”).

As was discussed already in the previous section, relativistic heavy ions interact strongly when the impact parameter is smaller than the sum of the radii of the two
nuclei. In such cases $\gamma\gamma$-processes are still present and are a background that has to be considered in central collisions. In order to study “clean” photon-photon events however, they have to be eliminated in the calculation of photon-photon luminosities as the particle production due to the strong interaction dominates. In the usual treatment of photon-photon processes in $e^+e^-$ collisions plane waves are used and there is no direct information on the impact parameter. For heavy ion collisions on the other hand it is very appropriate to introduce impact parameter dependent equivalent photon numbers. They have been widely discussed in the literature, see, e.g., [1, 28, 29].

The equivalent photon spectrum corresponding to a point charge $Ze$, moving with a velocity $v$ at impact parameter $b$ is given by

$$N(\omega, b) = \frac{Z^2 \alpha}{\pi^2} \frac{1}{b^2} \left( \frac{c}{v} \right)^2 x^2 \left[ K_1^2(x) + \frac{1}{\gamma^2} K_0^2(x) \right],$$

(7)

where $K_n(x)$ are the modified Bessel Functions (MacDonald Functions) and $x = \frac{\omega b}{\gamma v}$. Then one obtains the probability for a certain electromagnetic process to occur in terms of the same process generated by an equivalent pulse of light as

$$P(b) = \int \frac{d\omega}{\omega} N(\omega, b) \sigma_\gamma(\omega).$$

(8)

Possible modifications of $N(\omega, b)$ due to an extended spherically symmetric charge distribution are given in [30]. It should be noted that Eq. (7) also describes the equivalent photon spectrum of an extended charge distribution, such as a nucleus, as long as $b$ is larger than the extension of the object. This is due to the fact that the electric field of a spherically symmetric system depends only on the total charge, which is inside it. As one often wants to avoid also final state interaction between the produced system and the nuclei, one has to restrict oneself to $b_i > R_i$ and therefore the form factor is not very important.

As the term $x^2 [K_1^2(x) + 1/\gamma^2 K_0^2(x)]$ in Eq. (7) can be roughly approximated as 1 for $x < 1$ and 0 for $x > 1$, so that the equivalent photon number $N(\omega, b)$ is almost a constant up to a maximum $\omega_{max} = \gamma/b$ ($x = 1$). By integrating the photon spectrum (Eq. (7)) over $b$ from a minimum value of $R_{min}$ up to infinity (where essentially only impact parameter up to $b_{max} \approx \gamma/\omega$ contribute, compare with Eq. (3)), one can define an equivalent photon
number \( n(\omega) \). This integral can be carried out analytically and is given by \([1,28]\)

\[
n(\omega) = \int d^2 b N(\omega, b) = \frac{2}{\pi} Z_1^2 \alpha \left( \frac{\xi}{\gamma v} \right)^2 \left[ \xi K_0 K_1 - \frac{\nu^2 \xi^2}{2c^2} \left( K_1^2 - K_0^2 \right) \right],
\]

(9)

where the argument of the modified Bessel functions is \( \xi = \frac{\omega R_{\min}}{\gamma v} \). The cross section for a certain electromagnetic process is then

\[
\sigma = \int \frac{d\omega}{\omega} n(\omega) \sigma_\gamma(\omega).
\]

(10)

Using the approximation above for the MacDonald functions, we get an approximated form, which is quite reasonable and is useful for estimates:

\[
n(\omega) \approx \frac{2Z^2\alpha}{\pi} \ln \frac{\gamma}{\omega R_{\min}}.
\]

(11)

The photon-photon production cross-section is obtained in a similar factorized form, by folding the corresponding equivalent photon spectra of the two colliding heavy ions \([11,12]\) (for polarization effects see \([11]\), they are neglected here)

\[
\sigma_c = \int d\omega_1 \int \frac{d\omega_2}{\omega_2} F(\omega_1, \omega_2) \sigma_{\gamma\gamma}(W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}),
\]

(12)

with

\[
F(\omega_1, \omega_2) = 2\pi \int_{R_1}^\infty b_1 \int_{R_2}^\infty b_2 db_1 \int_0^{2\pi} d\phi \times N(\omega_1, b_1) N(\omega_2, b_2) \Theta \left( b_1^2 + b_2^2 - 2b_1 b_2 \cos \phi - R_{\text{cutoff}}^2 \right),
\]

(13)

\((R_{\text{cutoff}} = R_1 + R_2)\). This can also be rewritten in terms of the invariant mass \(W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}\) and the rapidity \(Y = 1/2 \ln [(\not{P}_0 + \not{P}_z)/(\not{P}_0 - \not{P}_z)] = 1/2 \ln (\omega_1/\omega_2)\) as:

\[
\sigma_c = \int dW_{\gamma\gamma} dY \frac{d^2 L}{dW_{\gamma\gamma} dY} \sigma_{\gamma\gamma}(W_{\gamma\gamma}),
\]

(14)

with

\[
\frac{d^2 L_{\gamma\gamma}}{dW_{\gamma\gamma} dY} = \frac{2}{W_{\gamma\gamma}} F\left( \frac{W_{\gamma\gamma}}{2} e^Y, \frac{W_{\gamma\gamma}}{2} e^{-Y} \right).
\]

(15)

Here energy and momentum in the beam direction are denoted by \(P_0\) and \(P_z\). The transverse momentum is of the order of \(P_\perp \leq 1/R\) and is neglected here. The transverse momentum distribution is calculated in \([31]\).

In \([31]\) and \([32]\) this intuitively plausible formula is derived ab initio, starting from the assumption that the two ions move on a straight line with impact parameter \(b\). Eqs. \((12)\) and \((14)\) are the basic formulae for \(\gamma\gamma\)-physics in relativistic heavy-ion collisions. The advantage of heavy nuclei is seen in the coherence factor \(Z_1^2 Z_2^2\) contained in Eqs. \((12)-(15)\).

As a function of \(Y\), the luminosity \(d^2 L/dW_{\gamma\gamma} dY\) has a Gaussian shape with the maximum at \(Y = 0\). The width is approximately given by \(\Delta Y = 2 \ln [(2\gamma)/(RW_{\gamma\gamma})]\). Depending on the experimental situation additional cuts in the allowed \(Y\) range are needed.

Additional effects due to the nuclear structure have been also studied. For inelastic vertices a photon number \(N(\omega, b)\) can also be defined, see, e.g., \([13]\). Its effect was found
to be small. The dominant correction comes from the electromagnetic excitation of one of the ion in addition to the photon emission. We refer to [15] for further details.

In Fig. 4 we give a comparison of effective $\gamma\gamma$ luminosities for various collider scenarios. We use the following collider parameters: LEP200: $E_{el} = 100\text{GeV}$, $L = 10^{32}\text{cm}^{-2}\text{s}^{-1}$, NLC/PLC: $E_{el} = 500\text{GeV}$, $L = 2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$, Pb-Pb heavy-ion mode at LHC: $\gamma = 2950$, $L = 10^{26}\text{cm}^{-2}\text{s}^{-1}$, Ca-Ca: $\gamma = 3750$, $L = 4 \times 10^{30}\text{cm}^{-2}\text{s}^{-1}$, p-p: $\gamma = 7450$, $L = 10^{30}\text{cm}^{-2}\text{s}^{-1}$. In the Ca-Ca heavy ion mode, higher effective luminosities (defined as collider luminosity times $\gamma\gamma$-luminosity) can be achieved as, e.g., in the Pb-Pb mode, since higher AA luminosities can be reached there. For further details see [33].

Figure 4: Comparison of the effective $\gamma\gamma$-luminosities ($L_{AA} \times L_{\gamma\gamma}$) for different ion species. For comparison the same quantity is shown for LEP200 and a future NLC/PLC (next linear collider/photon linear collider, photons are obtained by LASER backscattering, two different polarizations are shown).

3 $\gamma$-A interactions

There are many interesting phenomena ranging from the excitation of discrete nuclear states, giant multipole resonances (especially the giant dipole resonance), quasi-deuteron absorption, nucleon resonance excitation to the nucleon continuum. Photo-induced processes lead in general to a change of the charge-to-mass ratio of the nuclei, and with their large cross section they are therefore a serious source of beam loss. Especially the cross section for the excitation of the giant dipole resonance, a collective mode of the nucleus, is rather large for the heavy systems (of the order of 100b). The cross section scales approximately with $Z^{10/3}$. Another serious source of beam loss is the $e^+e^-$ bound-free pair creation. The contribution of the nucleon resonances (especially the $\Delta$ resonance) has also been confirmed experimentally in fixed target experiments with 60 and 200 GeV/A (heavy ions at CERN, “electromagnetic spallation”) [34, 35, 36]. For details of these aspects, we refer the reader to [14, 37, 38, 39], where scaling laws, as well as detailed calculations for individual cases are given.
The interaction of quasi-real photons with protons has been studied extensively at the electron-proton collider HERA (DESY, Hamburg), with $\sqrt{s} = 300$ GeV ($E_e = 27.5$ GeV and $E_p = 820$ GeV in the laboratory system). This is made possible by the large flux of quasi-real photons from the electron (positron) beam. The obtained $\gamma p$ center-of-mass energies (up to $W_{\gamma p} \approx 200$ GeV) are an order of magnitude larger than those reached by fixed target experiments. Similar and more detailed studies will be possible at the relativistic heavy ion colliders RHIC and LHC, due to the larger flux of quasi-real photons from one of the colliding nuclei. In the photon-nucleon subsystem, one can reach invariant masses $W_{\gamma N}$ up to $W_{\gamma N,\max} = \sqrt{4W_{\max}E_N} \approx 0.8\gamma A^{-1/6}$ GeV. In the case of RHIC ($^{197}$Au, $\gamma = 106$) this is about 30 GeV, for LHC ($^{208}$Pb, $\gamma = 2950$) one obtains 950 GeV. Thus one can study physics quite similar to the one at HERA, with nuclei instead of protons. Photon-nucleon physics includes many aspects, like the energy dependence of total cross-sections, diffractive and non-diffractive processes.

An important subject is the elastic vector meson production $\gamma p \rightarrow V p$ (with $V = \rho, \omega, \phi, J/\Psi, \ldots$). A review of exclusive neutral vector meson production is given in [40]. The diffractive production of vector mesons allows one to get insight into the interface between perturbative QCD and hadronic physics. Elastic processes (i.e., the proton remains in the ground state) have to be described within nonperturbative (and therefore phenomenological) models. It was shown in [41] that diffractive (“elastic”) $J/\Psi$ photoproduction is a probe of the gluon density at $x \approx M_{\Psi}^2 W_{\gamma N}$ (for quasi-real photons). Inelastic $J/\Psi$ photoproduction was also studied recently at HERA [12].

Going to the hard exclusive photoproduction of heavy mesons on the other hand, perturbative QCD is applicable. Recent data from HERA on the photoproduction of $J/\Psi$ mesons have shown a rapid increase of the total cross section with $W_{\gamma N}$, as predicted by perturbative QCD. Such studies could be extended to photon-nucleus interactions at RHIC, thus complementing the HERA studies. Equivalent photon flux factors are large for the heavy ions due to coherence. On the other hand, the A-A luminosities are quite low, as compared to HERA. Of special interest is the coupling of the photon of one nucleus to the Pomeron-field of the other nucleus. Such studies are envisaged for RHIC, see [18, 19, 20, 21] where also experimental feasibility studies were performed.

Estimates of the order of magnitude of vector meson production in photon-nucleon processes at RHIC and LHC are given in [15]. In $AA$ collisions there is incoherent photoproduction on the individual $A$ nucleons. Shadowing effects will occur in the nuclear environment and it will be interesting to study these. There is also the coherent contribution where the nucleus remains in the ground state. Due to the large momentum transfer, the total (angle integrated) coherent scattering shows an undramatic $A^{1/3}$ dependence. (It will be interesting to study shadow effects in this case also). This is in contrast to, e.g., low energy $\nu A$ elastic scattering, where the coherence effect leads to an $A^2$ dependence. For a general pedagogical discussion of the coherence effects see, e.g., [13]. In addition there are inelastic contributions, where the proton (nucleon) is transformed into some final state $X$ during the interaction (see [12]).

At the LHC one can extend these processes to much higher invariant masses $W$, therefore much smaller values of $x$ will be probed. Whereas the $J/\Psi$ production at HERA was measured up to invariant masses of $W \approx 160$ GeV, the energies at the LHC allow for studies up to $\approx 1$ TeV.

At the LHC [24] hard diffractive vector meson photoproduction can be investigated especially well in $AA$ collisions. In comparison to previous experiments, the very large
photon luminosity should allow observation of processes with quite small $\gamma p$ cross sections, such as $\Upsilon$-production. For more details see [24].

4 Photon-Photon Physics at various invariant mass scales

Up to now photon-photon scattering has been mainly studied at $e^+e^-$ colliders. Many reviews [27, 44, 45] as well as conference reports [16, 19] [18, 19] exist. The traditional range of invariant masses has been the region of mesons, ranging from $\pi^0$ ($m_{\pi^0} = 135$ MeV) up to about $\eta_c$ ($m_{\eta_c} = 2980$ MeV). Recently the total $\gamma\gamma \rightarrow$ hadron cross-section has been studied at LEP2 up to an invariant mass range of about 70 GeV [50]. We are concerned here mainly with the invariant mass region relevant for RHIC and LHC (see the $\gamma\gamma$-luminosity figures below). Apart from the production of $e^+e^-$ (and $\mu^+\mu^-$) pairs, the photons can always be considered as quasi-real. The cross section section for virtual photons deviates from the one for real photons only for $Q^2$, which are much larger then the coherence limit $Q^2 \lesssim 1/R^2$ (see also the discussion in [27]). For real photons general symmetry requirements restrict the possible final states, as is well known from the Landau-Yang theorem. Especially it is impossible to produce spin 1 final states. In $e^+e^-$ annihilation only states with $J^{PC} = 1^{--}$ can be produced directly. Two photon collisions give access to most of the $C = +1$ mesons.

$C = -1$ vector mesons can be produced in principle by the fusion of three (or, less important, five, seven, ...) equivalent photons. The cross section scales with $Z^6$. It is smaller than the contributions discussed above from $\gamma A$ collisions, even for nuclei with large $Z$ (see [13]).

The cross section for $\gamma\gamma$-production in a heavy ion collision factorizes into a $\gamma\gamma$-luminosity function and a cross-section $\sigma_{\gamma\gamma}(W_{\gamma\gamma})$ for the reaction of the (quasi)real photons $\gamma\gamma \rightarrow f$, where $f$ is any final state of interest (see Eq. (12)). When the final state is a narrow resonance, the cross-section for its production in two-photon collisions is given by

$$\sigma_{\gamma\gamma \rightarrow R}(M^2) = 8\pi^2(2J_R + 1)\Gamma_{\gamma\gamma}(R)\delta(M^2 - M_R^2)/M_R,$$

where $J_R$, $M_R$ and $\Gamma_{\gamma\gamma}(R)$ are the spin, mass and two-photon width of the resonance $R$. This makes it easy to calculate the production cross-section $\sigma_{AA \rightarrow AA + R}$ of a particle in terms of its basic properties. We will now give a general discussion of possible photon-photon physics at relativistic heavy ion colliders. Invariant masses up to several GeV can be reached at RHIC and up to about 100 GeV at LHC.

We can divide our discussion into the following two main subsections: Basic QCD phenomena in $\gamma\gamma$-collisions (covering the range of meson, meson-pair production, etc.) and $\gamma\gamma$-collisions as a tool for new physics, especially at very high invariant masses. An interesting topic in itself is the $e^+e^-$ pair production. The fields are strong enough to produce multiple pairs in a single collisions. A discussion of this subject together with calculations within the semiclassical approximation can be found in [51, 52, 53, 54].

4.1 Basic QCD phenomena in $\gamma\gamma$-collisions
4.1.1 Hadron spectroscopy: Light quark spectroscopy

One may say that photon-photon collisions provide an independent view of the meson and baryon spectroscopy. They provide powerful information on both the flavor and spin/angular momentum internal structure of the mesons. Much has already been done at $e^+e^-$ colliders. Light quark spectroscopy is very well possible at RHIC, benefiting from the high $\gamma\gamma$-luminosities. Detailed feasibility studies exist [18, 19, 20, 21]. In these studies, $\gamma\gamma$ signals and backgrounds from grazing nuclear and beam gas collisions were simulated with both the FRITIOF and VENUS Monte Carlo codes. The narrow $p_\perp$-spectra of the $\gamma\gamma$-signals provide a good discrimination against the background. The possibilities of the LHC are given in the FELIX LoI [24].

The absence of meson production via $\gamma\gamma$-fusion is also of great interest for glueball search. The two-photon width of a resonance is a probe of the charge of its constituents, so the magnitude of the two-photon coupling can serve to distinguish quark dominated resonances from glue-dominated resonances ("glueballs"). In $\gamma\gamma$-collisions, a glueball can only be produced via the annihilation of a $q\bar{q}$ pair into a pair of gluons, whereas a normal $q\bar{q}$-meson can be produced directly. The "stickiness" of a mesonic state $X$ is defined as

$$S_X = \frac{\Gamma(J/\Psi \to \gamma X)}{\Gamma(X \to \gamma\gamma)}. \quad (17)$$

We expect the stickiness of all mesons to be comparable, while for glueballs it should be enhanced by a factor of about $1/\alpha_s^4 \sim 20$. In a recent reference [55] results of the search for $f_J(2220)$ production in two-photon interactions were presented. There a very small upper limit for the product of $\Gamma_{\gamma\gamma}B_{K_sK_s}$ was given, where $B_{K_sK_s}$ denotes the branching fraction of its decay into $K_sK_s$. From this it was concluded that this is a strong evidence that the $f_J(2220)$ is a glueball.

4.1.2 Heavy Quark Spectroscopy

For charmonium production, the two-photon width $\Gamma_{\gamma\gamma}$ of $\eta_c$ (2960 MeV, $J^{PC} = 0^{-+}$) is known from experiment. But the two-photon widths of $P$-wave charmonium states have been measured with only modest accuracy. For RHIC the study of $\eta_c$ is a real challenge [19]; the luminosities are falling and the branching ratios to experimental interesting channels are small.

In Table 1 (adapted from table 2.6 of [24]) the two-photon production cross-sections for $c\bar{c}$ and $b\bar{b}$ mesons in the rapidity range $|Y| < 7$ are given. Also given are the number of events in a $10^6$ sec run with the ion luminosities of $4 \times 10^{30}$ cm$^{-2}$ s$^{-1}$ for Ca-Ca and $10^{36}$ cm$^{-2}$ s$^{-1}$ for Pb-Pb. Millions of $C$-even charmonium states will be produced in coherent two-photon processes during a standard $10^6$ sec heavy ion run at the LHC. The detection efficiency of charmonium events has been estimated as 5% for the forward-backward FELIX geometry [24], i.e., one can expect detection of about $5 \times 10^3$ charmonium events in Pb-Pb and about $10^6$ events in Ca-Ca collisions. This is two to three orders of magnitude higher than what is expected during five years of LEP200 operation. Further details, also on experimental cuts, backgrounds and the possibilities for the study of $C$-even bottomium states are given in [24].
| State | Mass, MeV | $\Gamma_{\gamma\gamma}$, keV | $\sigma(AA \rightarrow AA + X)$, Pb-Pb | $\sigma(AA \rightarrow AA + X)$, Ca-Ca | Events for $10^6$ sec, Pb-Pb | Events for $10^6$ sec, Ca-Ca |
|-------|-----------|------------------|----------------------------|----------------------------|-----------------|-----------------|
| $\eta'$ | 958 | 4.2 | 22 nb | 125 $\mu$b | $2.2 \times 10^7$ | $5.0 \times 10^8$ |
| $\eta_c$ | 2981 | 7.5 | 590 $\mu$b | 3.8 $\mu$b | $5.9 \times 10^5$ | $1.5 \times 10^7$ |
| $\chi_0c$ | 3415 | 3.3 | 160 $\mu$b | 1.0 $\mu$b | $1.6 \times 10^5$ | $4.0 \times 10^6$ |
| $\chi_2c$ | 3556 | 0.8 | 160 $\mu$b | 1.0 $\mu$b | $1.6 \times 10^5$ | $4.0 \times 10^6$ |
| $\eta_b$ | 9366 | 0.43 | 370 nb | 3.0 nb | 370 | 12000 |
| $\eta_{b0}$ | 9860 | $2.5 \times 10^{-2}$ | 18 nb | 0.14 nb | 18 | 640 |
| $\eta_{b2}$ | 9913 | $6.7 \times 10^{-3}$ | 23 nb | 0.19 nb | 23 | 76 |

Table 1: Production cross sections and event numbers for heavy quarkonia produced in a $10^6$ sec run in Pb-Pb and Ca-Ca collisions at the LHC with luminosities $10^{27}$ and $4 \times 10^{30}$ cm$^{-2}$sec$^{-1}$. Adapted from [24].

4.1.3 Vector-meson pair production. Total hadronic cross-section

There are various mechanisms to produce hadrons in photon-photon collisions. Photons can interact as point particles which produce quark-antiquark pairs (jets), which subsequently hadronize. Often a quantum fluctuation transforms the photon into a vector meson ($\rho, \omega, \phi, \ldots$) (VMD component) opening up all the possibilities of hadronic interactions. In hard scattering, the structure of the photon can be resolved into quarks and gluons. Leaving a spectator jet, the quarks and gluon contained in the photon will take part in the interaction. It is of great interest to study the relative amounts of these components and their properties.

The L3 collaboration recently made a measurement of the total hadron cross-section for photon-photon collisions in the interval $5\text{GeV} < W_{\gamma\gamma} < 75\text{GeV}$ [50]. It was found that the $\gamma\gamma \rightarrow \text{hadrons}$ cross-section is consistent with the universal Regge behavior of total hadronic cross-sections. The production of vector meson pairs can well be studied at RHIC with high statistics in the GeV region [18]. For the possibilities at LHC, we refer the reader to [24] and [25], where also experimental details and simulations are described.

4.2 $\gamma\gamma$-collisions as a tool for new physics

The high flux of photons at relativistic heavy ion colliders offers possibilities for the search of new physics. This includes the discovery of the Higgs-boson in the $\gamma\gamma$-production channel or new physics beyond the standard model, like supersymmetry or compositeness.

Let us mention here the plans to build an $e^+e^-$ linear collider. Such future linear colliders will be used for $e^+e^-$, $e\gamma$ and $\gamma\gamma$-collisions (PLC, photon linear collider). The photons will be obtained by scattering of laser photons (of eV energy) on high energy electrons ($\approx$ TeV region) (see [56]). Such photons in the TeV energy range will be monochromatic and polarized. The physics program at such future machines is discussed in [57], it includes Higgs boson and gauge boson physics and the discovery of new particles.

While the $\gamma\gamma$ invariant masses which will be reached at RHIC will mainly be useful to explore QCD at lower energies, the $\gamma\gamma$ invariant mass range at LHC will open up new possibilities.

A number of calculations have been made for a medium heavy standard model Higgs [58, 59, 60, 61]. For masses $m_H < 2m_{W^\pm}$ the Higgs bosons decays dominantly into $b\bar{b}$. 
Chances of finding the standard model Higgs in this case are marginal \cite{25}.

An alternative scenario with a light Higgs boson was, e.g., given in \cite{32} in the framework of the “general two Higgs doublet model”. Such a model allows for a very light particle in the few GeV region. With a mass of 10 GeV, the $\gamma\gamma$-width is about 0.1 keV. The authors of \cite{32} proposed to look for such a light neutral Higgs boson at the proposed low energy $\gamma\gamma$-collider. We want to point out that the LHC Ca-Ca heavy ion mode would also be very suitable for such a search.

One can also speculate about new particles with strong coupling to the $\gamma\gamma$-channel. Large $\Gamma_{\gamma\gamma}$-widths will directly lead to large $\gamma\gamma$ production cross-sections. We quote the papers \cite{63, 64}. Since the $\gamma\gamma$-width of a resonance is mainly proportional to the wave function at the origin, huge values can be obtained for very tightly bound systems. Composite scalar bosons at $W_{\gamma\gamma} \approx 50$ GeV are expected to have $\gamma\gamma$-widths of several MeV \cite{63, 64}. The search for such kind of resonances in the $\gamma\gamma$-production channel will be possible at LHC.

In Refs. \cite{65, 66} $\gamma\gamma$-processes at $pp$ colliders (LHC) are studied. It is observed there that non-strongly interacting supersymmetric particles (sleptons, charginos, neutralinos, and charged Higgs bosons) are difficult to detect in hadronic collisions at the LHC. The Drell-Yan and gg-fusion mechanisms yield low production rates for such particles. Therefore the possibility of producing such particles in $\gamma\gamma$ interactions at hadron colliders is examined. Since photons can be emitted from protons which do not break up in the radiation process, clean events can be generated which should compensate for the small number. In \cite{65} it was pointed out that at the high luminosity of $L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$ at the LHC($pp$), one expects about 16 minimum bias events per bunch crossing. Even the elastic $\gamma\gamma$ events will therefore not be free of hadronic debris. Clean elastic events will be detectable at luminosities below $10^{33}\text{cm}^{-2}\text{s}^{-1}$. This danger of “overlapping events” has also to be checked for the heavy ion runs, but it will be much reduced due to the lower luminosities.

5 Conclusion

In this article the basic properties of electromagnetic processes in very peripheral hadron-hadron collisions are described. The method of equivalent photons is a well established tool to describe these kinds of reactions. Reliable results of quasireal photon fluxes and $\gamma\gamma$-luminosities are available. Unlike electrons and positrons heavy ions and protons are particles with an internal structure. Effects arising from this structure are well under control. A problem, which is difficult to judge quantitatively at the moment, is the influence of strong interactions in grazing collisions, i.e., effects arising from the nuclear stratosphere and Pomeron interactions.

The high photon fluxes open up possibilities for photon-photon as well as photon-nucleus interaction studies up to energies hitherto unexplored at the forthcoming colliders RHIC and LHC. Interesting physics can be explored at the high invariant $\gamma\gamma$-masses, where detecting new particles could be within range. Also very interesting studies within the standard model, i.e., mainly QCD studies will be possible. This ranges from the study of the total $\gamma\gamma$-cross section into hadronic final states up to invariant masses of about 100 GeV to the spectroscopy of light and heavy mesons.
6 Acknowledgement

One of the authors (G.B.) wishes to thank the organizers for inviting him to this stimulating conference in a pleasant atmosphere.

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