New theoretical results
in ultrarelativistic ultraperipheral lead-lead collisions

Mariola Kłusek-Gawenda, Antoni Szczurek[1]

Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 Krakow, Poland

We study dilepton, proton-antiproton and diphoton production in ultraperipheral lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ and 5.5 TeV. The nuclear calculations are based on equivalent photon approximation in the impact parameter space. For correct description of the $\gamma\gamma \to p\overline{p}$ Belle data we include the proton-exchange, the $f_2(1270)$ and $f_2(1950)$ s-channel exchanges, as well as the handbag mechanism. For four muon production, we take into account electromagnetic (two-photon) double-scattering production and direct $\gamma\gamma$ production of four muons in one scattering. The cross sections for elementary $\gamma\gamma \to \gamma\gamma$ subprocess are calculated including three different mechanisms: box diagrams with leptons and quarks in the loops, a VDM-Regge contribution with virtual intermediate hadronic excitations of the photons and the two-gluon exchange contribution. We find that the cross section for elastic $\gamma\gamma$ scattering could be measured in the lead-lead collisions for the diphoton invariant mass up to $W_{\gamma\gamma} \approx 15$ - 20 GeV. Our Standard Model predictions are compared with a recent ATLAS experimental result.

We discuss results for PbPb→PbPb$\mu^+\mu^-\mu^+\mu^-$, PbPb→PbPb$e^+e^-e^+e^-$, PbPb→PbPb$p\overline{p}$ and PbPb→PbPb$\gamma\gamma$ reactions at LHC energy.

PRESENTED AT

EDS Blois 2017, Prague,
Czech Republic, June 26-30, 2017

---

[1]Faculty of Mathematics and Natural Sciences, University of Rzeszów, ul. Pigonia 1, 35-310 Rzeszów

1 Introduction

Ultraperipheral heavy ion scattering is a special category of nuclear collisions [1, 2]. This field got a new impulse with the start of the Large Hadron Collider. Several final states are possible in ultraperipheral collisions (UPC) of heavy ion. The present experiments on UPC concentrated on one- [3, 4, 5, 6] and two-body final states [5, 7]. Recently we have studied theoretically production in nuclear collisions of one pair of electrons and double scattering production of two positron-electron pairs [8] as well as single scattering and double scattering production of two $\mu^+\mu^-$ pairs [9], proton-antiproton production [10] and elastic $\gamma\gamma$ scattering [11, 12].
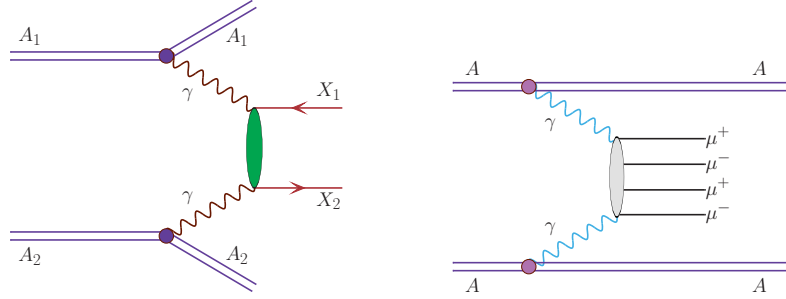
2 Theory background

Figure 1: Single-scattering production of a pair of particles (left panel) and two pairs of charged leptons (right panel) in ultrarelativistic UPC of heavy ions.
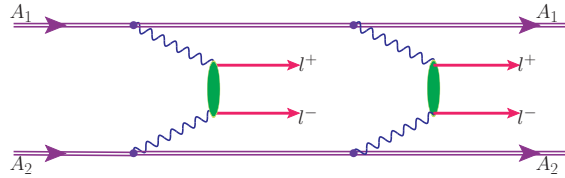

Figure 2: Double-scattering production of two pairs of leptons in ultraperipheral collisions of heavy ions.

A nuclear cross section is calculated in the equivalent photon approximation in the impact parameter space. The total cross section for the single-scattering production (see Fig. 1) is expressed through the five-fold integral (for more details see e.g. [13])

$$\sigma_{A_1 A_2 \to A_1 A_2 X_1 X_2}\left(\sqrt{s_{A_1 A_2}}\right) = \int \sigma_{\gamma\gamma \to X_1 X_2}\left(W_{\gamma\gamma}\right) N\left(\omega_1, \mathbf{b_1}\right) N\left(\omega_2, \mathbf{b_2}\right) S_{abs}^2\left(\mathbf{b}\right)$$

$$\times \quad \mathrm{d}^2 b \, \mathrm{d}\bar{b}_x \, \mathrm{d}\bar{b}_y \frac{W_{\gamma\gamma}}{2}\mathrm{d}W_{\gamma\gamma}\,\mathrm{d}Y_{X_1 X_2}\,, \tag{1}$$

where $X_1 X_2$ is a pair of produced particles (we considered $p\bar{p}$, $\gamma\gamma$, $e^+ e^-$ or $\mu^+ \mu^-$; see left panel of Fig. 1), $W_{\gamma\gamma}$ and $Y_{X_1 X_2}$ is invariant mass and rapidity of the outgoing $X_1 X_2$ system. Energy of photons is expressed through $\omega_{1/2} = W_{\gamma\gamma}/2 \exp(\pm Y_{X_1 X_2})$. $\mathbf{b_1}$ and $\mathbf{b_2}$ are impact parameters of the photon-photon collision point with respect to parent nuclei 1 and 2, respectively, and $\mathbf{b} = \mathbf{b_1} - \mathbf{b_2}$ is the standard impact parameter for the $A_1 A_2$ collision. Absorption factor $S_{abs}^2(\mathbf{b})$ assures that we consider only ultraperipheral collisions, when the nuclei do not undergo nuclear breakup. The photon flux $(N(\omega, b))$ is expressed through a nuclear charge form factor of the nucleus. In our calculations we use a realistic form factor which is a Fourier transform of the charge distribution in the nucleus. More details can be found e.g. in [13]. In our study we calculate also distributions in kinematical variables of each of the produced particles. Then one can impose easily experimental cuts on (pseudo)rapidities and transverse momenta of the particles.

The elementary cross section for $\gamma\gamma \to \mu^+ \mu^- \mu^+ \mu^-$ was calculated with the help of KaTie [14]. It is an event generator that is designed to deal with initial states that have an explicit transverse momentum dependence, but can also deal with on-shell initial states, like for this subprocess. KaTie is a parton-level generator for hadron scattering. A detailed consideration of this process was studied in Ref. [9].

The cross section for double-scattering production of four leptons (see Fig. 2) is expressed through a probability density to produce a first and second pair of leptons. The expression for probability density takes almost the same form as Eq. (1). More details one can find in [8] and [9].

3   Results

Before calculating cross section for $l^+ l^- l^+ l^-$ production $(l = e, \mu)$ we have checked whether our approach describes the production of a single $l^+ l^-$ pair. In the case of electron-positron production, we get a good agreement with the ALICE invariant mass distribution [5]. Even imposing experimental cuts relevant for different experiments we have obtained cross sections that could be measured at the LHC even with relatively low luminosity required for UPC of heavy ions of the order of 1 nb^{-1}. For $L_{int} = 1$ nb^{-1} and for the main ATLAS detector angular coverage and transverse momentum cut on each electron/positron $p_t > 0.5$ GeV we predict 235 events.

Similarly as for the $e^+ e^-$ production, we get very good description of data for one muon pair production. We have compared our result with ATLAS preliminary data [15]. For a first time, we have shown explicitly that the cross section for the single-scattering mechanism is considerably smaller than the cross section for the double-scattering mechanism. This shows that the double-scattering mechanism is sufficient for detailed studies and planning experiments. The cross sections for four-muon production strongly depend on the cuts on muon transverse momenta.

We have discussed in detail also the production of proton-antiproton pairs in photon-photon collisions [10]. We have shown that the Belle data [16] for low photon-photon energies can be nicely described by including in addition to the proton exchange also the s-channel exchange of the $f_2(1950)$ resonance, which was observed to decay into the $\gamma\gamma$ and $p\overline{p}$ channels. Having described the Belle data we have used the elementary $\gamma\gamma \to p\overline{p}$ cross section to calculate a cross section for $p\overline{p}$ pairs production in heavy ion UPC. The integrated (no cuts) cross section for the full phase space is by a factor 5 larger than the one corresponding to the Belle angular coverage. The larger the range of phase space the broader is the distribution in $y_{diff} = y_p - y_{\overline{p}}$. In Ref. [10] we have shown predictions for experimental cuts corresponding to the ATLAS, CMS and ALICE experiments. We find cross sections of 35 μb for the ALICE cuts ($|y| <$ 0.9, $p_t > 1$ GeV) and 155 μb taking into account ATLAS or CMS cuts ($|y| < 2.5$, $p_t > 0.5$ GeV).

In addition we have studied how to measure elastic photon-photon scattering in lead-lead UPC [11, 12]. The cross section for photon-photon scattering was calculated taking into account well known box diagrams with elementary standard model particles (leptons and quarks), a VDM-Regge component as well as a two-gluon exchange mechanism, including massive quarks, all helicity configurations of photons and massive and massless gluons. For the PbPb→PbPb$\gamma\gamma$ reaction we identified regions of the phase space where the two-gluon contribution could be enhanced relatively to the box contribution. The region of large rapidity difference between the two emitted photons and intermediate transverse momenta 1 GeV $< p_t <$ 2 - 5 GeV seems optimal in this respect.

This year the ATLAS Collaboration published a new result [7] for light-by-light scattering in quasi-real photon interactions in ultraperipheral lead-lead collisions at $\sqrt{s_{NN}}=$ 5.02 TeV. The measured fiducial cross section which includes limitation on photon transverse momentum, photon pseudorapidity, diphoton invariant mass, diphoton transverse momentum and diphoton accoplanarity, were measured to be 70 $\pm$ 20 (stat.) $\pm$ 17 (syst.) nb. This result is compatible with the value of 49 $\pm$ 10 nb predicted by us for the ATLAS cuts and experimental luminosity.

Over the past few years, many exciting UPC results have been presented. We hope that our new theoretical predictions will be a source of inspiration for future experiments.

ACKNOWLEDGEMENTS

References

[1] V. M. Budnev, I. F. Ginzburg, G. V. Meledin and V. G. Serbo, *The Two pho-ton particle production mechanism. Physical problems. Applications. Equivalent photon approximation*, Phys. Rept. **15** (1975) 181.

[2] C. A. Bertulani and G. Baur, *Electromagnetic Processes in Relativistic Heavy Ion Collisions*, Phys. Rept. **163** (1988) 299.

[3] K. Skjerdal et al. (ALICE Collaboration), *Photoproduction of ρ^0 in ultra–peripheral nuclear collisions at ALICE*, J. Phys. Conf. Ser. **455** (2013) 012010.

[4] B. Abelev et al. (ALICE Collaboration), *Coherent J/ψ photoproduction in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV*, Phys. Lett. **B718** (2013) 1273.

[5] E. Abbas et al. (ALICE Collaboration), *Charmonium and e^+e^- pair photopro-duction at mid-rapidity in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}=2.76$ TeV*, Eur.Phys.J. C73 (2013) 2617.

[6] CMS Collaboration, *Photoproduction of the coherent J/ψ accompanied by the forward neutron emission in ultra-peripheral PbPb collisions at 2.76 TeV*, CMS-PAS-HIN-12-009 (2014) 11 pp.

[7] M. Aaboud, Morad et al. (ATLAS Collaboration), *Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC*, Nature Phys. **13** (2017) 852.

[8] M. Kłusek-Gawenda and A. Szczurek, *Double scattering production of two positronelectron pairs in ultraperipheral heavy-ion collisions*, Phys. Lett. **B763** (2016) 416.

[9] A. van Hameren, M. Kłusek-Gawenda and A. Szczurek, *Single- and double-scattering production of four muons in ultraperipheral PbPb collisions at the Large Hadron Collider*, arXiv:1708.07742 [hep-ph].

[10] M. Kłusek-Gawenda, P. Lebiedowicz, O. Nachtmann and A. Szczurek, *From the $\gamma\gamma \to p\overline{p}$ reaction to the production of $p\overline{p}$ pairs in ultraperipheral ultrarelativistic heavy-ion collisions at the LHC*, arXiv:1708.09836 [hep-ph].

[11] M. Kłusek-Gawenda, P. Lebiedowicz and A. Szczurek, *Light-by-light scattering in ultraperipheral Pb-Pb collisions at energies available at the CERN Large Hadron Collider*, Phys. Rev. **C93** (2016) 044907.

[12] M. Kłusek-Gawenda, W. Schäfer and A. Szczurek, *Two-gluon exchange contribution to elastic $\gamma\gamma \rightarrow \gamma\gamma$ scattering and production of two-photons in ultraperipheral ultrarelativistic heavy ion and proton-proton collisions*, Phys. Lett. **B761** (2016) 399.

[13] M. Kłusek-Gawenda and A. Szczurek, *Exclusive muon-pair productions in ultra-relativistic heavy-ion collisions – realistic nucleus charge form factor and differential distributions*, Phys. Rev. **C82** (2010) 014904.

[14] A. van Hameren, *KaTie: for parton-level event generation with k_T-dependent initial states*, arXiv:1611.00680 [hep-ph].

[15] ATLAS Collaboration, *Measurement of high-mass dimuon pairs from ultraperipheral lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with the ATLAS detector at the LHC*, ATLAS-CONF-2016-025.

[16] C. C. Kuo et al. (Belle Collaboration), *Measurement of $\gamma\gamma \rightarrow p\bar{p}$ production at Belle*, Phys. Lett. **B621** (2005) 41.