We discuss production of $p\bar{p}$ pairs in two-photon interactions in heavy-ion collisions. We present predictions for the ultraperipheral, ultrarelativistic, heavy-ion collisions (UPC) $^{208}Pb^{208}Pb \rightarrow ^{208}Pb^{208}Pb p\bar{p}$. The parameters of vertex form factors are adjusted to the Belle data for the $\gamma\gamma \rightarrow p\bar{p}$ reaction. To described the Belle data we include the proton-exchange, the $f_2(1270)$ and $f_2(1950)$ s-channel exchanges, as well as the hand-bag mechanism. Then, the total cross section and several differential distributions for experimental cuts corresponding to the LHC experiments are presented. The distribution in $y_{diff}$, the rapidity distance between the proton and antiproton, is particularly interesting. We find the total cross sections: 100 $\mu$b for the ALICE cuts, 160 $\mu$b for the ATLAS cuts, 500 $\mu$b for the CMS cuts, and 104 $\mu$b taking into account the LHCb cuts. This opens a possibility to study the $\gamma\gamma \rightarrow p\bar{p}$ process in UPC at the LHC.

PACS numbers: 25.75.-q,25.75.Dw,13.60.Rj

1. Introduction

It was presented in Ref. [1] that the ultraperipheral collisions (UPC) of heavy ions may provide new information on $\gamma\gamma \rightarrow p\bar{p}$ interactions compared to the presently available data from $e^+e^-$ collisions. The baryon pair production via $\gamma\gamma$ fusion was measured at electron-positron colliders by various experimental groups: CLEO [2] at CESR, VENUS [3] at TRISTAN, OPAL [4] and L3 [5] at LEP, and Belle [6] at KEKB.

* Presented at the XIII Workshop on Particle Correlations and Femtoscopy, 22-26 May 2018, Kraków, Poland

(1)
The calculated cross sections from the leading-twist QCD terms [7, 8] turned out to be about one order of magnitude smaller than the experimental data on $\gamma\gamma \to p\bar{p}$ process. In order to explain these discrepancies, various phenomenological approaches were suggested, see e.g. [9] and references therein. In the hand-bag approach, see e.g. [10], the $\gamma\gamma \to p\bar{p}$ amplitude was factorized into a hard $\gamma\gamma \to q\bar{q}$ subprocess and form factors describing a soft $q\bar{q} \to p\bar{p}$ transition. The pQCD-inspired phenomenological models have more chances to describe the absolute size of the cross section for $W_{\gamma\gamma} > 2.5$ GeV, however, they contain a number of free parameters that are fitted to data. The low $W_{\gamma\gamma}$ region of $\gamma\gamma \to p\bar{p}$ may be dominated by $s$-channel resonance contributions. One of the effective approaches used for this region is the Veneziano model [11]. While a reasonable $\sigma(W_{\gamma\gamma})$ dependence was obtained without adjustable parameters in [11], the agreement of the model with the angular distributions was only qualitative.

In our approach, described in detail in [1], we consider all important theory ingredients in order to achieve a quantitative description of the Belle data [6] both the dependence of the total cross section on $W_{\gamma\gamma}$ as well as corresponding angular distributions. Then we presented predictions for the production of $p\bar{p}$ pairs in the ultraperipheral, ultrarelativistic, heavy-ion collisions at the LHC.

Central exclusive diffractive production of the $p\bar{p}$ pairs was also studied recently in proton-proton collisions [12].

2. Formalism

We focus on the process for ultraperipheral collisions of heavy ions

$$208Pb + 208Pb \to 208Pb + 208Pb + p + \bar{p},$$

see diagram (a) shown in Fig. 1. The nuclear cross section is calculated in the equivalent photon approximation in the impact parameter space $b = |b|$; for more details see [1]. The total (phase space integrated) cross section is expressed through the five-fold integral

$$\sigma_{AA \to AA p\bar{p}}(\sqrt{s_{AA}}) = \int \sigma_{\gamma\gamma \to pp}(W_{\gamma\gamma})N(\omega_1, b_1)N(\omega_2, b_2)S_{abs}^2(b)$$

$$\times \frac{W_{\gamma\gamma}}{2}dW_{\gamma\gamma}dY_{pp}d\vec{b}_x d\vec{b}_y 2\pi b db,$$

where the impact parameter $b$ means the distance between colliding nuclei in the plane perpendicular to their direction of motion, $W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}$ is the invariant mass of the $\gamma\gamma$ system, and $\omega_i$, $i = 1, 2$, is the energy of the photon which is emitted from the first or second nucleus, respectively. $Y_{pp} = \frac{1}{2}(y_p + y_{\bar{p}})$ is the rapidity of the $p\bar{p}$ system. The quantities $\vec{b}_x = \ldots$
Fig. 1. Diagram (a) represents \( p\bar{p} \) production in ultrarelativistic ultraperipheral collisions (UPC) of heavy ions and other diagrams describe the \( \gamma\gamma \to p\bar{p} \) subprocess; the \( t \)- and \( u \)-channel proton exchange (diagrams (b) and (c), respectively), the exchange of \( f_2 \) meson in the \( s \)-channel (diagram (d)) and the hand-bag mechanism (diagram (e) plus the one with the photon vertices interchanged).

\[
\frac{b_{ix} + b_{2x}}{2}, \quad \frac{b_{iy}}{2} = \frac{b_{1y} + b_{2y}}{2}
\]

are given in terms of \( b_{ix}, b_{iy} \) which are the components of the \( b_1 \) and \( b_2 \) vectors which mark a point (distance from first and second nucleus) where photons collide and particles are produced. In Ref. [13] the dependence of the photon flux \( N(\omega_i, b_i) \) on the charge form factors of the colliding nuclei was shown explicitly. In our calculations we use the so-called realistic form factor which is the Fourier transform of the charge distribution in the nucleus. The presence of the absorption factor \( S_{abs}^2(b) \) in Eq. (2) assures that we consider only peripheral collisions, when the nuclei do not undergo nuclear breakup.

3. Results for the \( \gamma\gamma \to p\bar{p} \) reaction

In Fig. 2 we show the energy dependence of the cross section for the \( \gamma\gamma \to p\bar{p} \) reaction together with the experimental data. In the Belle experiment [6] the \( \gamma\gamma \to p\bar{p} \) cross sections were extracted from the \( e^+e^- \to e^+e^- p\bar{p} \) reaction for the \( \gamma\gamma \) c.m. energy range of \( 2.025 < W_{\gamma\gamma} < 4 \) GeV and in the c.m. angular range of \( |\cos \theta| < 0.6 \). In Fig. 2 we show also our fit to the Belle angular distributions for the three selected intervals of \( W_{\gamma\gamma} \). We take
Fig. 2. Energy dependence of the total cross section for $\gamma \gamma \rightarrow p \bar{p}$ for $|\cos \theta| < 0.6$ and our fit to the Belle angular distributions. Here, the theoretical results for the parameter set B from Table II of [1] are shown. The experimental data are from the CLEO [2], VENUS [3], OPAL [4], L3 [5], and Belle [6] experiments.

into account the nonresonant proton exchange contribution, the $s$-channel tensor meson exchange contributions and the hand-bag mechanism, see the diagrams in Fig. 1 (b) - (e). Here, the results for the parameter set B from Table II of [1] are presented. One can observe the dominance of the $f_2(1950)$ resonance term at low energies. The proton exchange contribution plays an important role from the threshold to higher energy while the hand-bag contribution only at $W_{\gamma \gamma} > 3$ GeV. In our calculation of the nonresonant proton exchange we have included both Dirac- and Pauli-type couplings of the photon to the nucleon and form factors for the exchanged off-shell
protons. We have found that the Pauli-type coupling is very important, enhances the cross section considerably, and cannot therefore be neglected.

4. Predictions for the nuclear ultraperipheral collisions

\[ p \bar{p} \rightarrow p \bar{p} \]

\[ \sigma \]

\[ d \]

\[ t \]

\[ \eta \]

\[ W \]

\[ \gamma \gamma \]

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

In Fig. 3 we present distributions in \( W_{\gamma \gamma} \equiv M_{p \bar{p}} \) (the left panel) and \( y_{diff} = y_p - y_{\bar{p}} \) (the right panel) imposing cuts on rapidities and transverse momenta of outgoing baryons. From the left panel, we can observe that the dependence on invariant mass of the \( p \bar{p} \) pair is sensitive to the (pseudo)rapidity cut imposed. From Figs. 12 - 14 of [1] we clearly see that results for the nuclear reaction correspond to that for elementary \( \gamma \gamma \rightarrow p \bar{p} \) reaction. The \( f_2(1950) \) contribution dominates at smaller \( W_{\gamma \gamma} \) and at \( z \approx 0 \) and \( z \approx \pm 1 \) (\( z = \cos \theta \) in the \( \gamma \gamma \) c.m. system). This coincides with the result which was presented in Fig. 2, see Fig. 6 of [1]. In contrast to the resonant contribution, the proton-exchange one is concentrated mostly at larger invariant masses and around \( z = \pm 1 \). The cross section is concentrated along the diagonal \( y_p \simeq y_{\bar{p}} \). The distribution in the difference of proton and antiproton rapidities is interesting. The larger the range of phase space the broader is the \( y_{diff} \), i.e., the larger rapidity distance between \( p \) and \( \bar{p} \). There three maxima are visible. The broad peak at \( y_{diff} \approx 0 \) corresponds to the region \( |z| < 0.6 \) which for low-\( M_{p \bar{p}} \) is dominated by the \( f_2(1950) \) term. It seems that observation of the broader \( y_{diff} \) distribution, in particular identification of the outer maxima, could be a good test of model.
5. Conclusions

We have discussed the production of proton-antiproton pairs in photon-photon interactions. We have shown that the Belle data [6] for low photon-photon energies can be nicely described by including in addition to the proton exchange the \( s \)-channel exchange of the \( f_2(1950) \) resonance which was observed to decay into the \( \gamma \gamma \) and \( p\bar{p} \) channels. Adjusting the parameters of the vertex form factors for the proton exchange, of the tensor meson \( s \)-channel exchanges, and the parameters in the hand-bag contribution we have managed to describe both total cross section and differential angular distributions of the Belle Collaboration.

Having described the Belle data we have used the \( \gamma \gamma \to p\bar{p} \) cross section to calculate the predictions for the \( ^{208}Pb^{208}Pb \to ^{208}Pb^{208}Pb p\bar{p} \) reaction at \( \sqrt{s_{NN}} = 5.02 \) TeV with the LHC experimental cuts. Large cross sections of 0.1 - 0.5 mb have been obtained. We have presented distributions in the invariant mass of the \( p\bar{p} \) system as well as in the difference of rapidities for protons and antiprotons. The UPC of heavy ions may provide new information compared to the presently available data from \( e^+e^- \) collisions, in particular, when the structures of the \( y_{diff} \) distribution can be observed.

This work was supported by the National Science Centre, Poland (NCN) (grant number 2014/15/B/ST2/02528).

REFERENCES

[1] M. Khusek-Gawenda, P. Lebiedowicz, O. Nachtman, A. Szczurek, Phys. Rev. D 96, 094029 (2017).
[2] M. Artuso et al. [CLEO Collaboration], Phys. Rev. D 50, 5484 (1994).
[3] H. Hamasaki et al. [VENUS Collaboration], Phys. Lett. B 407, 185 (1997).
[4] G. Abbiendi et al. [OPAL Collaboration], Eur. Phys. J. C 28, 45 (2003).
[5] P. Achard et al. [L3 Collaboration], Phys. Lett. B 571, 11 (2003).
[6] C.C. Kuo et al. [Belle Collaboration], Phys. Lett. B 621, 41 (2005).
[7] V.L. Chernyak and I.R. Zhitnitsky, Nucl. Phys. B 246, 52 (1984).
[8] G.R. Farrar, H. Zhang, A.A. Ogloblin, I.R. Zhitnitsky, Nucl. Phys. B 311, 585 (1989).
[9] C.F. Berger and W. Schweiger, Eur. Phys. J. C 28, 249 (2003).
[10] M. Diehl, P. Kroll, C. Vogt, Eur. Phys. J. C 26, 567 (2003).
[11] K. Odagiri, Nucl. Phys. A 748, 168 (2005).
[12] P. Lebiedowicz, O. Nachtman, A. Szczurek, Phys. Rev. D 97, 094027 (2018).
[13] M. Khusek-Gawenda and A. Szczurek, Phys. Rev. C 82, 014904 (2010).