PRODUCTION OF $p\bar{p}$ PAIRS IN UPC AT THE LHC*

Piotr Lebiedowicz, Mariola Kłusek-Gawenda, Antoni Szczurek

Institute of Nuclear Physics Polish Academy of Sciences
Radzikowskiego 152, 31-342 Kraków, Poland

Otto Nachtmann

Institut für Theoretische Physik, Universität Heidelberg
Philosophenweg 16, 69120 Heidelberg, Germany

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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) $^{208}\mathrm{Pb}^{208}\mathrm{Pb} \to ^{208}\mathrm{Pb}^{208}\mathrm{Pb}\, p\bar{p}$. The parameters of vertex form factors are adjusted to the Belle data for the $\gamma\gamma \to p\bar{p}$ reaction. To the described 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 μb for the ALICE cuts, 160 μb for the ATLAS cuts, 500 μb for the CMS cuts, and 104 μb taking into account the LHCb cuts. This opens a possibility to study the $\gamma\gamma \to p\bar{p}$ process in UPC at the LHC.

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1. Introduction

It was presented in Ref. [1] that the ultraperipheral collisions (UPC) of heavy ions may provide new information on $\gamma\gamma \to p\bar{p}$ 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.

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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 considered 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

$$^{208}\mathrm{Pb} + {}^{208}\mathrm{Pb} \to {}^{208}\mathrm{Pb} + {}^{208}\mathrm{Pb} + p + \bar{p}\,, \tag{1}$$

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

$$\sigma_{AA\to AAp\bar{p}}\left(\sqrt{s_{AA}}\right) = \int \sigma_{\gamma\gamma\to p\bar{p}}(W_{\gamma\gamma}) N(\omega_1, \boldsymbol{b_1}) N(\omega_2, \boldsymbol{b_2}) S^2_{\mathrm{abs}}(\boldsymbol{b}) \times \frac{W_{\gamma\gamma}}{2} \mathrm{d}W_{\gamma\gamma}\, \mathrm{d}Y_{p\bar{p}}\, \mathrm{d}\bar{b}_x\, \mathrm{d}\bar{b}_y\, 2\pi\, b\, \mathrm{d}b\,, \tag{2}$$

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 ω_i, $i = 1, 2$, is the energy of the photon which is emitted from the first or second nucleus, respectively.

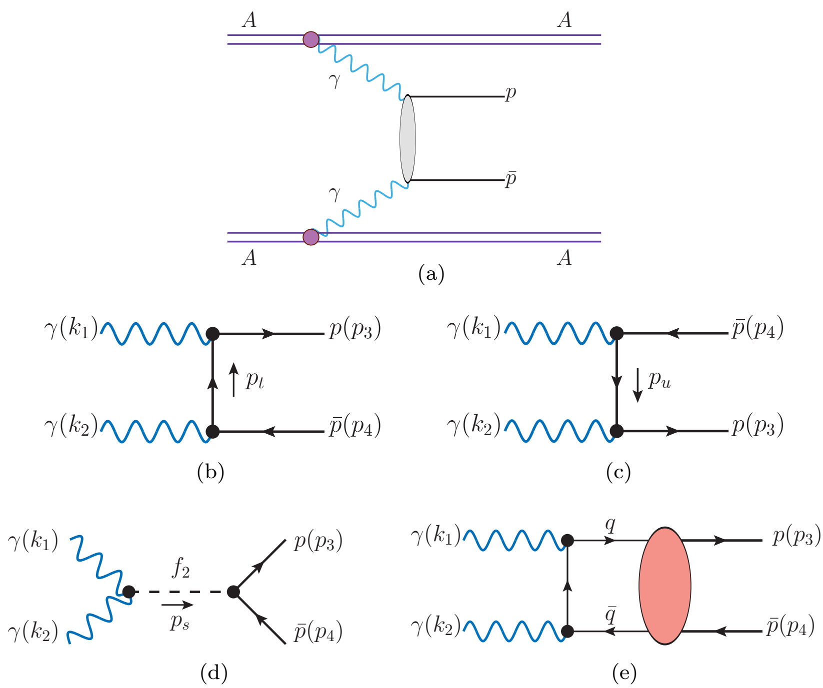

Fig. 1. Diagram (a) represents $p\bar{p}$ production in ultrarelativistic ultraperipheral collisions (UPC) of heavy ions and other diagrams describe the $\gamma\gamma \to p\bar{p}$ subprocess; the t- and u-channel proton exchange (diagrams (b) and (c), respectively), the exchange of f_2 meson in the s-channel (diagram (d)) and the hand-bag mechanism (diagram (e) plus the one with the photon vertices interchanged).

$Y_{p\bar{p}} = \frac{1}{2}(y_p + y_{\bar{p}})$ is the rapidity of the $p\bar{p}$ system. The quantities $\bar{b}_x = (b_{1x} + b_{2x})/2$, $\bar{b}_y = (b_{1y} + b_{2y})/2$ are given in terms of b_{ix}, b_{iy} which are the components of the $\boldsymbol{b_1}$ and $\boldsymbol{b_2}$ 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 $N(\omega_i, \boldsymbol{b_i})$ 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 $S^2_{\rm abs}(\boldsymbol{b})$ 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 $e^+e^- \to e^+e^- p\bar{p}$

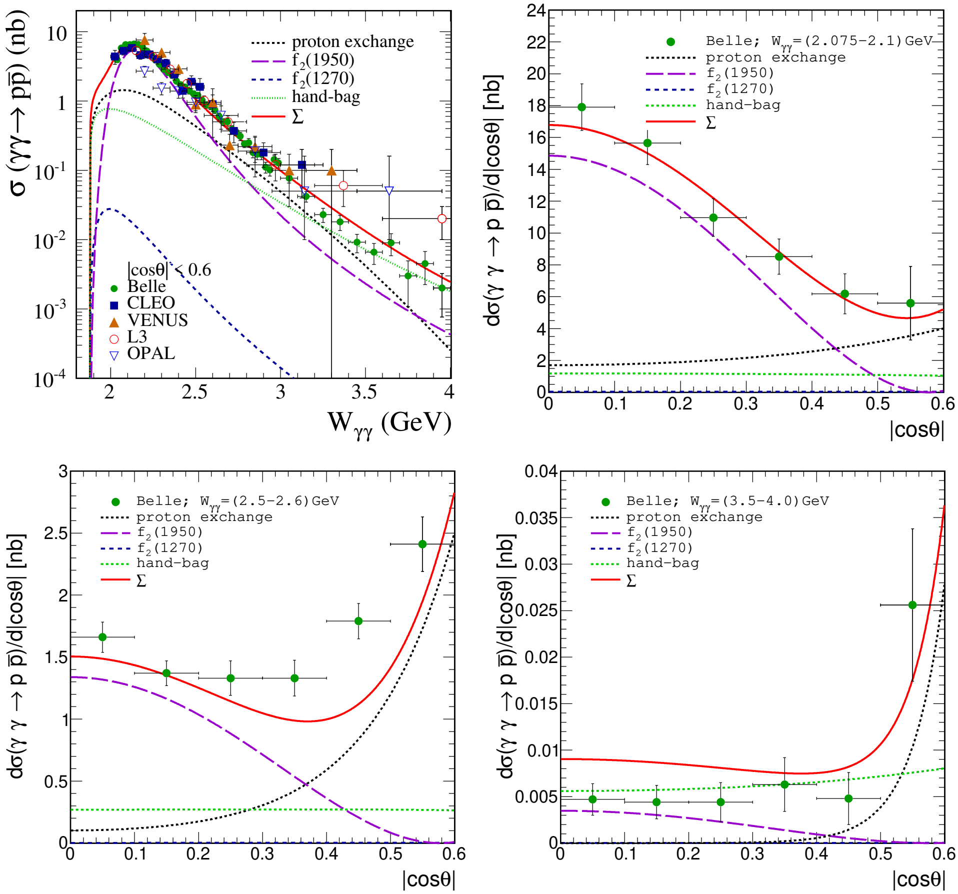

Fig. 2. Energy dependence of the total cross section for $\gamma\gamma \to p\bar{p}$ for $|\cos\theta| < 0.6$ and our fit to the Belle angular distributions. Here, the theoretical results for the parameter set B from Table II of [1] are shown. The experimental data are from the CLEO [2], VENUS [3], OPAL [4], L3 [5], and Belle [6] experiments.

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 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

In Fig. 3, we present distributions in $W_{\gamma\gamma} \equiv M_{p\bar{p}}$ (the left panel) and $y_{\rm diff} = y_p - y_{\bar{p}}$ (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 $\gamma\gamma \to p\bar{p}$ 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 $y_{\rm diff}$, *i.e.*, the larger rapidity distance between p and $\bar{p}$. There three maxima are visible. The broad peak at $y_{\rm diff} \approx 0$ 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 $y_{\rm diff}$ distribution, in particular identification of the outer maxima, could be a good test of model.

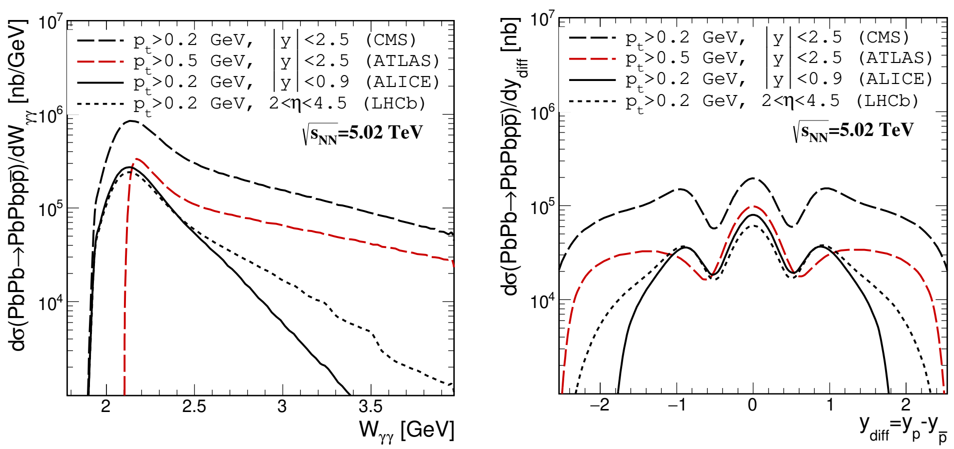

Fig. 3. The differential nuclear cross sections as a function of $p\bar{p}$ invariant mass (the left panel) and $y_{\rm diff} = y_p - y_{\bar{p}}$ (the right panel) for the Pb Pb $\to$ Pb Pb $p\bar{p}$ reaction at $\sqrt{s_{NN}} = 5.02$ TeV. The results for different experimental cuts are presented.

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 $^{208}\mathrm{Pb}^{208}\mathrm{Pb} \to {}^{208}\mathrm{Pb}^{208}\mathrm{Pb}\, p\bar{p}$ 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.

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