TWO-PHOTON FUSION PRODUCTION OF e^+e^- IN PROTON–LEAD COLLISION*

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We present our results concerning elastic and semi-elastic photon-initiated e^+e^- pair production processes in proton–nucleus collisions at the LHC energy. In the calculations, the k_{T}-factorization approach was used, and the research area was divided into low-mass region (LMR) and intermediate-mass region (IMR) according to the ALICE Collaboration definition. The one- and two-dimensional distributions of various kinematic variables obtained on the basis of various parameterizations of the proton structure function tested here in the non-perturbative region of small Q^2 and small W are discussed further on. The values of the gap survival factor for this type of processes are also presented.

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1. Introduction

Photon fusion processes in nucleus–nucleus collisions are usually considered in two areas: real hadronic collisions ($b < R_1 + R_2$) and ultraperipheral collisions ($b > R_1 + R_2$), in which their contribution dominates [1]. It has been shown that photon fusion processes also survive in semi-central collisions, where they actually dominate at a very small transverse momentum of the lepton pairs. The only considerations concerning these processes in proton–nucleus collisions can be found in [2], however they focus on the ATLAS experimental apparatus. The aim of [4], which we review here, is

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therefore to thoroughly investigate the contribution of photon-initiated processes to the production of e^+e^- pairs in proton–nucleus collisions, which may enable appropriate measurements to be made in the future.

Photons as partons of a proton can make a significant contribution to the precise determination of inclusive observables, see *e.g.* [3]. The production of dileptons in pA collisions with a rapidity gap between the nucleus and the high-$p_{\rm T}$ lepton has been suggested as the photon content of the proton [2].

As the nucleus is only the source of elastic photons in proton–nucleus collisions of energy 5.02 TeV, we will distinguish only doubly elastic collisions and single dissociation of protons.

2. Formalism

The results presented here are based on our recent paper [4]. The transverse momentum factorization approach assumes that the dilepton production cross section is calculated as [5, 6]

$$\begin{aligned}\sigma \;=\; & S^2 \int \mathrm{d}x_p\, \mathrm{d}x_{\rm Pb} \frac{\mathrm{d}^2\vec{q}_{\rm T}}{\pi} \left[\frac{\mathrm{d}\gamma^p_{\rm el}\left(x_p, Q^2\right)}{\mathrm{d}Q^2} + \frac{\mathrm{d}\gamma^p_{\rm inel}\left(x_p, Q^2\right)}{\mathrm{d}Q^2} \right] \\ & \times \gamma^{\rm Pb}_{\rm el}\left(x_{\rm Pb}, Q^2\right) \sigma_{\gamma^*\gamma\to l^+l^-}\left(x_p, x_{\rm Pb}, \vec{q}_{\rm T}\right) \,. \end{aligned} \tag{1}$$

To obtain distributions of elastic photon in the proton, it is necessary to express the equivalent photon flux using electric $G_{\rm E}(Q^2)$ and magnetic $G_{\rm M}(Q^2)$ form factors

$$\frac{\mathrm{d}\gamma^p_{\rm el}\left(x_p, Q^2\right)}{\mathrm{d}Q^2} = \frac{\alpha_{\rm em}}{\pi} \left[\left(1 - \frac{x}{2}\right)^2 \frac{4m_p^2 G_{\rm E}^2\left(Q^2\right) + Q^2 G_{\rm M}^2\left(Q^2\right)}{4m_P^2 + Q^2} + \frac{x^2}{4} G_{\rm M}^2\left(Q^2\right) \right], \tag{2}$$

where x is the fraction of the proton's momentum carried by the photon, while m_p is the proton mass. In order to relate Eq. (2) to nuclear flux, the following [5] amendment is necessary

$$\frac{4m_p^2 G_{\rm E}^2\left(Q^2\right) + Q^2 G_{\rm M}^2\left(Q^2\right)}{4m_p^2 + Q^2} \to Z^2 F_{\rm em}^2\left(Q^2\right) \,, \tag{3}$$

where Z is the nucleus charge and $F_{\rm em}(Q^2)$ is its charge form factor. The last one in Eq. (1) is an inelastic photon whose flux is described by the structure functions F_2 and $F_{\rm L}$. In deep inelastic scattering limit it can be calculated from the following equation [6, 7]:

$$\frac{\mathrm{d}\gamma^p_{\rm inel}\left(x_p, Q^2\right)}{\mathrm{d}Q^2} = \frac{1}{x} \int\limits_{M^2_{\rm thr}} \mathrm{d}M_x^2 \mathcal{F}_{\gamma^*\leftarrow p}\left(x, \vec{q}_{\rm T}^{\,2}, M_x^2\right) \,. \tag{4}$$

3. Results

The study area was divided into two mass regions corresponding to the ALICE-defined low-mass region (LMR) and intermediate-mass region (IMR) [8], which allowed for a direct reference to the inclusive data. The contribution of two-photon processes was included in these for the first time, and turned out to be significantly smaller than other dilepton production mechanisms and experimental data, as shown in Fig. 1. However, imposing an additional condition on the rapidity gap allows for selecting this mechanism, for which the dominance of the elastic case for small transverse momentum and the dominance of larger transverse momentum for inelastic cases is visible. Differences between individual parameterizations are also visible, but greater discrepancies between them correspond to small values of the cross section.

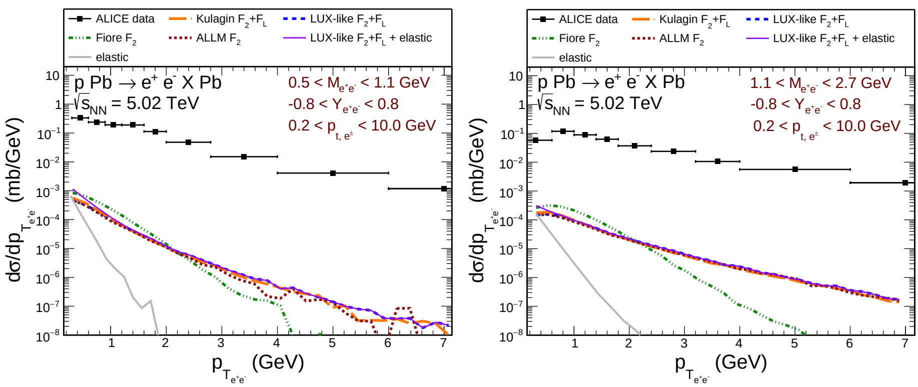

Fig. 1. Distributions of the pair transverse momentum $p_{\mathrm{T}_{e^+e^-}}$ for the LMR (left) and IMR (right).

Figure 2 presents the entire energy range in one graph. It can be seen here that the Fiore *et al.* parameterization gives a quite different distribution than the others, differing in the low W_1 region, where the proton resonances occur. While Fig. 3 shows that this process covers a rather wide Bjorken-x range, and a large contribution to the cross section comes from $Q^2 < 1$ GeV, which is clearly a non-perturbative region.

The rapidity gap corrections were calculated similarly to nuclear collisions. The SuperChic program [9] was used for the calculations, and the results are summarized in Table 1. The cross-section attenuation is visible, but for small masses $M \in$ (0–5 GeV), the rapidity gap survival factor is 0.95, so the modification is rather small.

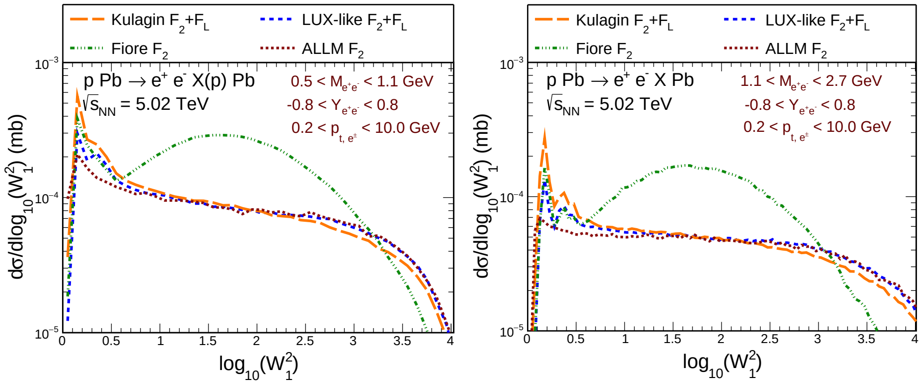

Fig. 2. Distribution of the hadronic final-state invariant mass $\log(W^2)$ for the LMR (left) and IMR (right).

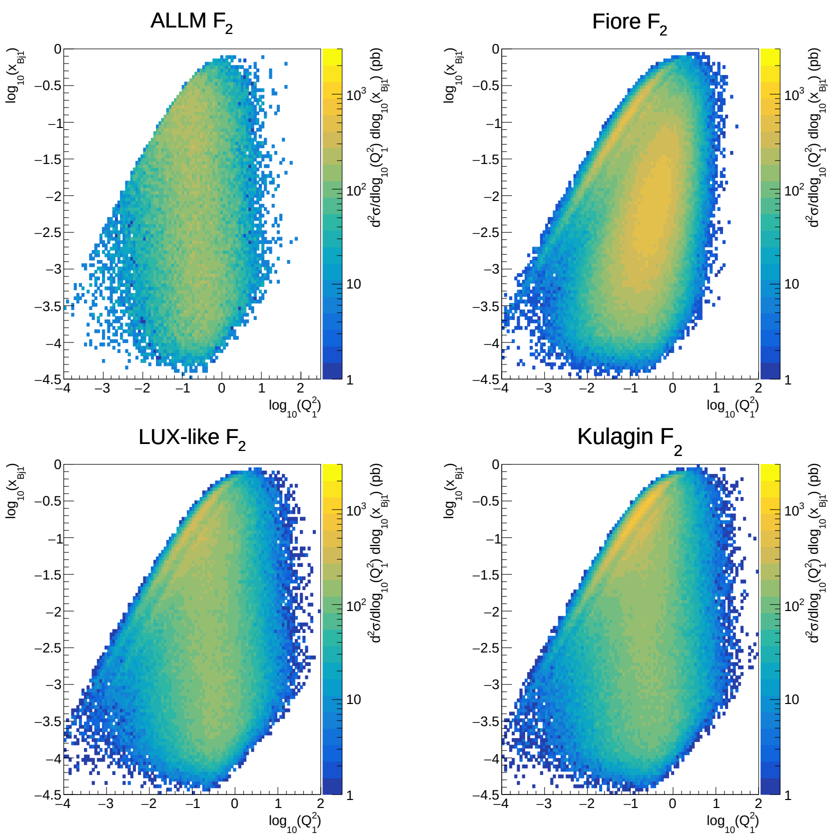

Fig. 3. Distribution of $\log_{10} x_{\mathrm{Bj}}$ and $\log_{10} Q^2$ for four approaches to structure function: ALLM, Fiore, LUX-like, and Kulagin for the LMR.

Table 1. The total cross section as predicted by the SuperChic program [9] for different bins of masses from 0 to 20 GeV with corresponding gap survival factor S_G.

Mass region	0.5–5 [GeV]	5–10 [GeV]	10–15 [GeV]	15–20 [GeV]
No soft S_G	755.91 [nb]	687.74 [nb]	98.68 [nb]	28.23 [nb]
With soft S_G	718.84 [nb]	623.27 [nb]	87.01 [nb]	24.33 [nb]
$\langle S_\mathrm{G} \rangle$	0.95	0.91	0.88	0.86

4. Conclusions

In this article, the contribution of two-photon fusion to the inclusive production of e^+e^- pairs in p–Pb collisions was analyzed using the k_T factorization approach, taking into account the survival of the proton and its dissociation. The results for various structure function parameterizations were compared with the existing data measured by the ALICE Collaboration for two dielectron invariant mass windows, reaching the conclusion that the contribution to these types of processes is negligible. However, two-photon processes are interesting in themselves, so it is worth exploring them in the future, *e.g.* by imposing the rapidity gap veto. Analyzing these processes in more detail, distributions of the cross section as a function of the transverse momentum of the lepton pair were calculated for various modern parameterizations of proton structure functions.

It was also revealed that the region containing the small masses of dielectrons is sensitive to the non-perturbative regions (low-Q^2) and the wide Bjorken-x range, while the distributions in $\log(W^2)$ showed that the ALICE kinematics can also test the region of nucleon resonances, where the large contribution to the cross-section distributions actually comes from.

The used parameterizations — Fiore *et al.*, ALLM, LUX-like, Kulagin *et al.*— treat this domain of the structure functions slightly differently. The Fiore *et al.* parameterization gives a quite different result than the other parametrizations. However, this parameterization was derived from a fit performed in a narrow range of Q^2 and W suitable only for JLAB kinematics, so using this fit beyond the JLAB region may be unjustified.

We estimated also the gap survival factor by calculating it in the impact parameter space. The found gap survival factor depends on the invariant dielectron mass, but reduces the cross section by only 5–10%.

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