Original article
DOI: https://doi.org/10.18721/JPM.18308

DIRECT PHOTON ASYMMETRIES IN THE LONGITUDINALLY POLARIZED PROTON-PROTON COLLISIONS AT ENERGIES FROM 9 TO 27 GEV

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Abstract. This paper presents the development of the Generative Adversarial Network (GAN) model to study the properties of direct photons produced in proton-proton collisions. The study aims to extend the capabilities of our model (developed previously) by introducing the initial collision energy parameter $\sqrt{s_{NN}}$ in the range from 9 to 27 GeV. The model has been trained on the data generated using PYTHIA8 and tested both at training energies and at intermediate energy values. Special attention was paid to the ability of the model to preserve kinematic dependencies and to reproduce the double longitudinal spin asymmetry A_{LL}. The results proved the possibility of using the GAN to interpolate the characteristics of direct photons in terms of collision energy.

Keywords: asymmetries, direct photons, neural network, generative-adversarial network

Funding: The reported study was carried out within the framework of the State Assignment for Fundamental Research (Subject Code FSEG-2025-0009).

Citation: Lobanov A. A., Berdnikov, Ya. A., Direct photon asymmetries in the longitudinally polarized proton-proton collisions at energies from 9 to 27 GeV, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3) (2025) 91–97. DOI: https://doi.org/10.18721/JPM.18308

Научная статья
УДК 539.12
DOI: https://doi.org/10.18721/JPM.18308

АСИММЕТРИИ ПРЯМЫХ ФОТОНОВ В ПРОДОЛЬНО-ПОЛЯРИЗОВАННЫХ ПРОТОН-ПРОТОННЫХ СТОЛКНОВЕНИЯХ ПРИ ЭНЕРГИЯХ 9 – 27 ГЭВ

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Аннотация. В работе представлено развитие модели генеративно-состязательной сети (ГСС) для изучения характеристик прямых фотонов, образующихся при столкновениях протонов. Исследование направлено на расширение возможностей ранее разработанной нами модели путем введения параметра начальной энергии столкновения $\sqrt{s_{NN}}$ в диапазоне 27 – 9 ГэВ. Модель обучена на данных, сгенерированных с помощью PYTHIA8, и протестирована как при энергиях обучения, так и при промежуточных значениях энергии. Особое внимание уделено способности модели сохранять кинематические зависимости и воспроизводить двойную продольную спиновую асимметрию A_{LL}. Результаты доказали возможность использования ГСС для интерполяции характеристик прямых фотонов по энергии столкновения.

Ключевые слова: асимметрия, прямые фотоны, нейронная сеть, генеративно-состязательная сеть

Финансирование: Государственное задание на проведение фундаментальных исследований (код темы FSEG-2025-0009).

Ссылка для цитирования: Лобанов А. А., Бердников Я. А. Асимметрии прямых фотонов в продольно-поляризованных протон-протонных столкновениях при энергиях 27 – 9 ГэВ // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3. С. 91–97. DOI: https://doi.org/10.18721/JPM.18308

Introduction

Study of the proton structure and the formation of its spin remains one of the key challenges in modern physics [1]. Various experimental facilities are constructed to solve this problem, among them, in particular, the SPD experiment at the NICA collider currently under construction at the Joint Institute for Nuclear Research (Dubna, Russia) [1].

Gluons play a major role to the total spin of the proton [1], described by gluon helicity functions $\Delta g(x)$, integrated to obtain the total contribution to proton spin. An effective approach to obtaining the values of $\Delta g(x)$ is to measure the double longitudinal spin asymmetry (DLSA) A_{LL} occurring in collisions of longitudinally polarized protons [1].

DLSA can be measured for various particles, including charged and neutral pions [2], as well as (J/ψ) mesons [3]. A particular interest lies in the direct photons produced in electromagnetic interactions of proton partons, in particular, in the Compton scattering reaction $gq(\bar{q}) \to \gamma q$ [4]. The advantage of direct photon measurement is in the simpler theoretical description that does not require hadronization models.

Despite this advantage, direct photon measurements are fraught with difficulties, including small sample size and problems with isolating direct photons against the background of photons from decay of secondary particles, for example, the decay of the π^0 mesons [4].

An approach using a generative adversarial network (GAN) was proposed in a previous paper to solve the problem of small samples [5]. It was proved that the GAN can faithfully reproduce the characteristics of direct photons produced in collisions of longitudinally polarized protons, allowing to calculate the asymmetries.

This paper develops the proposed approach to expand the capabilities of our GAN model [5].

For this purpose, we introduce the parameter of the initial collision energy $\sqrt{s_{NN}}$, which should provide results for arbitrary energies in a given range. Such an interpolation should provide improved accuracy in determining the values of $\Delta g(x)$, consequently yielding better estimates for the contribution of gluons to the proton spin.

Computational procedure

To verify that the GAN could be expanded to predict direct photon production at different energies $\sqrt{s_{NN}}$ and in the absence of experimental data, the model was trained on pre-generated simulation data. The PYTHIA8 program was used as a Monte Carlo generator [5, 6].

The main parameters of the Pythia8 program used in this study were as follows [5]:

PromptPhoton: qg2qgamma = on,

PromptPhoton: qqbar2ggamma = on,

MultipartonInteractions: pT0Ref = 2.2,

NNPDF31_nlo_as_0118 [7] (for unpolarized events),

NNPDFpol11_100 [8] (for polarized events).

The energy range of 9–27 GeV was considered for the initial collision energy $\sqrt{s_{NN}}$. The choice of the range was dictated by the experimental conditions of the SPD at the NICA facility [4]. To train the model, samples were generated at $\sqrt{s_{NN}}$ = 9, 15, 21, and 27 GeV for collisions of both unpolarized and polarized protons (the term 'events' is used throughout the paper). The size of each sample was 500,000 events (collisions).

Similar to the procedure adopted in the previous paper [5], the z-components of the momentum $p_{z\,q1}$ of the first and $p_{z\,q2}$ of the second partons, as well as the p_x-, p_y- and p_z-components of the momentum of the produced direct photon were extracted from the generated samples. Instead of the components $p_{z\,q1}$ and $p_{z\,q2}$, we used their transformed versions $T(p_{z\,q1})$ and $T(p_{z\,q2})$ to train the GAN, in accordance with the results from [5].

The GAN loss function remained unchanged and was a least square function [5]. The number of epochs for training was increased to 2,000. The batch size was also increased to 2,000. The gradient descent optimizer was replaced by Adam with the following parameter values:

The training step of $2\cdot10^{-4}$ was taken for the generator and discriminator, the forgetting factors β_1 = 0.9 and β_2 = 0.5 for the gradients and the second moments of the gradients, respectively [9].

The architecture of the generator is based on the results of our previous work [5]. A 128-dimensional vector whose elements are normally distributed is fed to the input of the generator. The initial energy $\sqrt{s_{NN}}$ and the polarization type of the event are used as conditional variables. Conditional variables are combined with a 128-dimensional vector so that the generator can adapt its output to different generation scenarios. The number of hidden layers was increased to 8. Each hidden layer has 512 neurons and a Leaky ReLU activation function with a dropout of 0.2 [10]. Next, the ResidualAdd procedure was applied to each hidden layer [11] to make the training process with a large number of hidden layers more stable. The ResidualAdd procedure is that the output of each layer after the activation function is summed with the output of the previous layer. This approach allows to mitigate the gradient vanishing problem in deep neural networks [11]. The output of the generator contains 5 generated values:

$$T(p_{z\,q1}),\ T(p_{z\,q2}),\ p_x,\ p_y,\ p_z.$$

The discriminator has almost the same architecture as the generator. The input of the discriminator is fed 6 values generated by the generator, along with conditional variables. The parameters of the hidden layers of the discriminator repeat the parameters of the hidden layers of the generator with one exception: Spectral Normalization is applied to each hidden layer [12]. The output from the discriminator contains one neuron reflecting the degree of confidence of the discriminator that the input is real data as opposed to those obtained using the generator.

Simulation results

To illustrate the performance of the GAN at different initial $\sqrt{s_{NN}}$, only a part of the complete set of parameters is shown below; these are p_{zq1} and $p_T = \sqrt{p_x^2 + p_y^2}$, as well as the DLSA values. The remaining values are not shown because their distributions are similar.

Fig. 1,*a* shows the distributions of the parton momentum $p_{z\,q1}$ in collisions of unpolarized protons. The simulation results obtained by PYTHIA8 and the GAN predictions were compared for $\sqrt{s_{NN}}$ of 9, 15, 21 and 27 GeV, at which the model was trained, as well as for intermediate energies of 12, 18, 24 and 30 GeV. Each subsequent distribution in the graphs in Fig. 1 was shifted by 10 GeV for clarity (to separate the distributions). Analyzing the graphs, we can see that the GAN model provides good predictive accuracy for both the energies at which the training was performed and the interpolated values.

A similar picture is observed in Fig. 1,*b*, showing the distributions of the transverse momentum p_T for photons in collisions of polarized protons. Notably, the model preserves the prediction accuracy in this case.

Fig. 2 shows the dependences of asymmetries A_{LL} on the momentum fraction $x_T = \frac{2p_T}{\sqrt{s_{NN}}}$ of direct photons, calculated from GAN predictions and PYTHIA8 simulations. It follows from this figure that GAN predictions yield A_{LL} values coinciding with the PYTHIA8 values (with an accuracy up to the uncertainty) over the entire range of initial energies $\sqrt{s_{NN}}$.

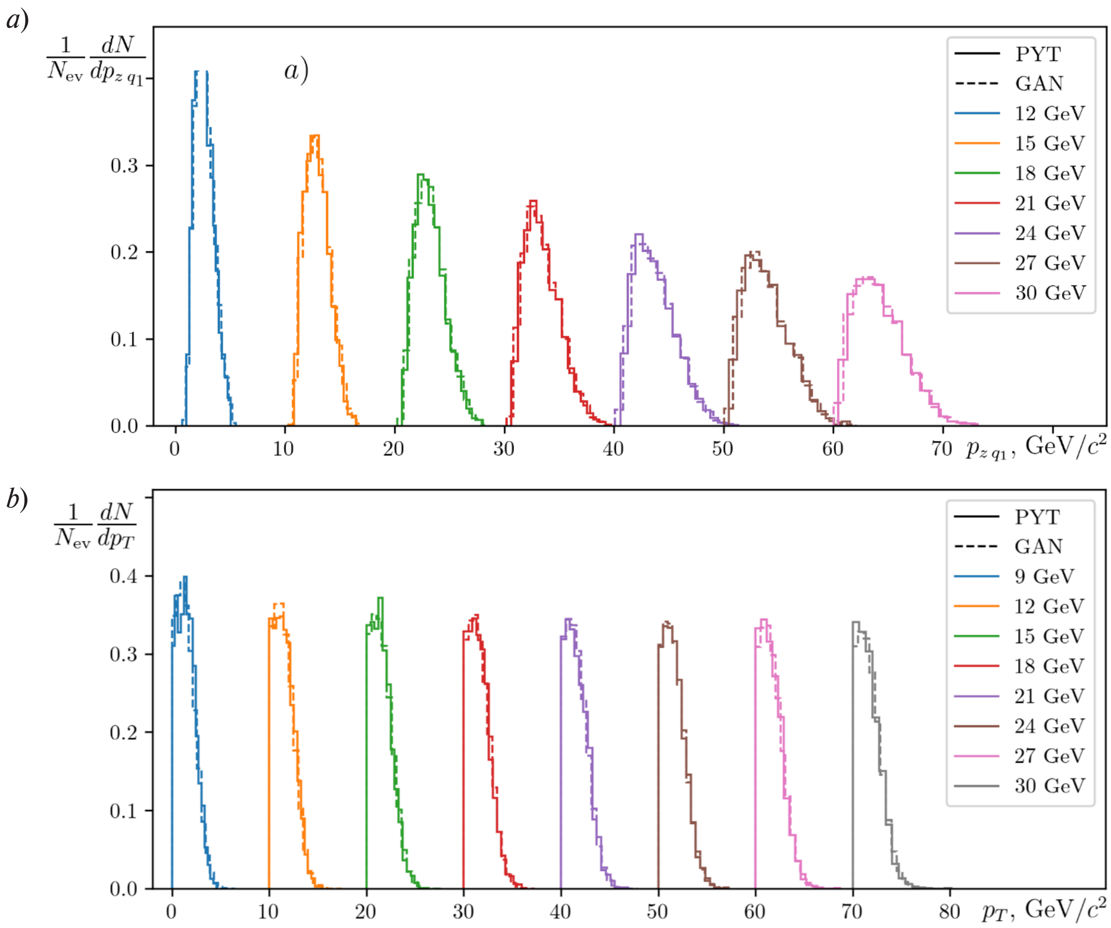

Fig. 1. Comparison of GAN predictions (solid lines) and simulations (dashed lines) for momentum distributions of partons $p_{z\,q1}$ (*a*) and direct photons p_T (*b*) in collisions of unpolarized (*a*) and polarized (*b*) protons at different initial $\sqrt{s_{NN}}$ (see the legends: the energies are given in GeV; odd values were obtained during training and even values were interpolated). Number of events N_{ev} = 500,000; the PYTHIA8 program was used for simulation

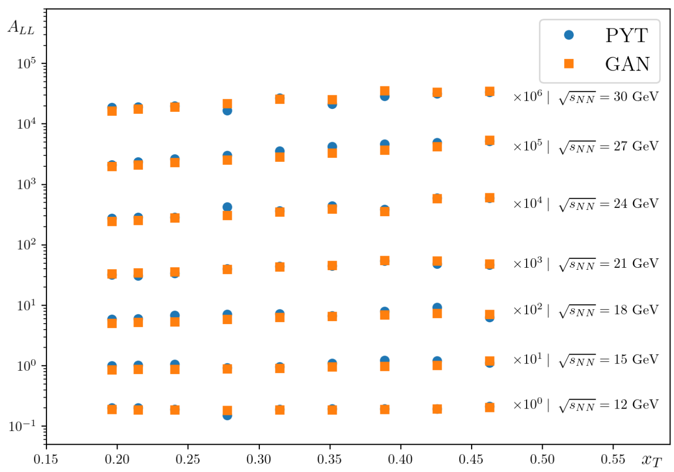

Fig. 2. Asymmetry A_{LL} as function of momentum fraciton x_T of direct photons in collisions of longitudinally polarized protons, at different initial energies of $\sqrt{s_{NN}}$ in the range of 12–30 GeV. The data were obtained using GAN and PYTHIA8 (orange squares and blue circles, respectively) The error bars are comparable in size to the data points

Conclusion

This paper continues to developed the generative adversarial network (GAN) developed earlier for predicting the characteristics of direct photon production in proton collisions. The model's predictive capabilities were expanded to extracting the characteristics of direct photon at various initial energies $\sqrt{s_{NN}}$ in the range of 9–27 GeV.

We confirmed that the model predicts the results of proton collisions with high accuracy both for the energies at which the training was performed and at intermediate values. From this, we can conclude that the model is capable of interpolating the given parameters based on the initial energies $\sqrt{s_{NN}}$. The accuracy of the predictions is preserved collisions of both unpolarized and longitudinally polarized protons ($\vec{p}\vec{p}^{(\leftarrow)}$).

In addition, we established that the GAN model preserves the kinematic dependences between the generated parameters, allowing to calculate the values of double longitudinal spin asymmetry A_{LL}. The A_{LL} values can also be obtained at any energies $\sqrt{s_{NN}}$ in the considered range of 9–30 GeV.

REFERENCES

1. **Arbuzov A., Bacchetta A., Butenschoen M., et al.,** On the physics potential to study the gluon content of proton and deuteron at NICA SPD, Prog. Part. Nucl. Phys. 119 (July) (2021) 103858.
2. **Acharya U., Adare A., Aidala C., et al.** (PHENIX Collaboration), Measurement of charged pion double spin asymmetries at midrapidity in longitudinally polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV, Phys. Rev. D. 102 (3) (2020) 032001.
3. **Adare A., Aidala C., Ajitanand N. N., et al.** (PHENIX Collaboration), Measurements of double-helicity asymmetries in inclusive J/ψ production in longitudinally polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV, Phys. Rev. D. 94 (11) (2016) 112008.
4. **Guskov A. and on behalf of the SPD working group,** Physics with prompt photons at SPD, J. Phys.: Conf. Ser. 1435 (2020) 012035.
5. **Lobanov A. A., Berdnikov Ya. A.,** Direct photon asymmetries in the longitudinally polarized proton-proton collisions at an energy of 27 GeV, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (1) (2025) 142–148 (in Russian).
6. **Sjöstrand T., Mrenna S., Skands P.** A brief introduction to PYTHIA 8.1 Comput. Phys. Commun. 178 (11) (2008) 852–867.
7. **Ball R. D., Bertone V., Carrazza S., et al.,** Parton distributions from high-precision collider data, Eur. Phys. J. C. 77 (04 Oct.) (2017) 663.
8. **Nocera E. R., Ball R. D., Forte S., et al.,** A first unbiased global determination of polarized PDFs and their uncertainties, Nucl. Phys. B. 887 (Oct) (2014) 276–308.
9. **Imran Khan M. J., Ismail R. A., Syed Qamrun N. A.,** Optimization algorithm for wide and deep neural network, Knowl. Eng. Data Sci. 2 (1) (2019) 41–46.
10. **Sharma O.,** A new activation function for deep neural network, Proc. Int. Conf. on Machine Learning, Big Data, Cloud and Parallel Computing (COMITCon); IEEE, Faridabad, India, Febr. 14–16 (2019) 84–86.
11. **Fengxiang H., Liu T., Tao D.,** Why ResNet works? Residuals Generalize. arXiv: 1904.01367, 2019. https://doi.org/10.48550/arXiv.1904.01367.
12. **Miyato T., Kataoka T., Koyama M., Yoshida Y.,** Spectral normalization for Generative Adversarial Networks, arXiv: 1802.05 957/v1, 2018. https://doi.org/10.48550/arXiv.1802.05957.

СПИСОК ЛИТЕРАТУРЫ

1. **Arbuzov A., Bacchetta A., Butenschoen M., et al.** On the physics potential to study the gluon content of proton and deuteron at NICA SPD // Progress in Particle and Nuclear Physics. 2021. Vol. 119. July. P. 103858.

2. **Acharya U., Adare A., Aidala C., et al.** (PHENIX Collaboration). Measurement of charged pion double spin asymmetries at midrapidity in longitudinally polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV // Physical Review D. 2020. Vol. 102. No. 3. P. 032001.

3. **Adare A., Aidala C., Ajitanand N. N., et al.** (PHENIX Collaboration), Measurements of double-helicity asymmetries in inclusive J/ψ production in longitudinally polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV // Physical Review D. 2016. Vol. 94. No. 11. P. 112008.

4. **Guskov A. and on behalf of the SPD working group.** Physics with prompt photons at SPD // Journal of Physics: Conference Series. 2020. Vol. 1435. P. 012035.

5. **Лобанов А. А., Бердников Я. А.** Асимметрии прямых фотонов в продольно-поляризованных протон-протонных столкновениях при энергии 27 ГэВ // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 1. С. 142–148.

6. **Sjöstrand T., Mrenna S., Skands P.** A brief introduction to PYTHIA 8.1 // Computer Physics Communications. 2008. Vol. 178. No. 11. Pp. 852–867.

7. **Ball R. D., Bertone V., Carrazza S., et al.** Parton distributions from high-precision collider data // The European Physical Journal C. 2017. Vol. 77. 04 October. P. 663.

8. **Nocera E. R., Ball R. D., Forte S., Ridolfi G., Rojo J.** A first unbiased global determination of polarized PDFs and their uncertainties // Nuclear Physics B. 2014. Vol. 887. October. Pp. 276–308.

9. **Imran Khan M. J., Ismail R. A., Syed Qamrun N. A.** Optimization algorithm for wide and deep neural network // Knowledge Engineering and Data Science. 2019. Vol. 2. No. 1. Pp. 41–46.

10. **Sharma O.** A new activation function for deep neural network // Proceedings of the International Conference on Machine Learning, Big Data, Cloud and Parallel Computing (COMITCon); IEEE, Faridabad, India, February 14–16, 2019. Pp. 84–86.

11. **Fengxiang H., Liu T., Tao D.** Why ResNet works? Residuals Generalize. arXiv: 1904.01367, 2019. https://doi.org/10.48550/arXiv.1904.01367.

12. **Miyato T., Kataoka T., Koyama M., Yoshida Y.** Spectral normalization for Generative Adversarial Networks. arXiv: 1802.05 957/v1, 2018. https://doi.org/10.48550/arXiv.1802.05957.

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Received 18.03.2025. Approved after reviewing 24.03.2025. Accepted 24.03.2025.
Статья поступила в редакцию 18.03.2025. Одобрена после рецензирования 24.03.2025. Принята 24.03.2025.