Original article
DOI: https://doi.org/10.18721/JPM.19214

DOUBLE LONGITUDINAL SPIN ASYMMETRY OF J/ψ MESONS PRODUCED IN PROTON-PROTON COLLISIONS WITH LONGITUDINAL POLARIZATION

D. V. Kruashvili✉, *Ya. A. Berdnikov*

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

✉ kruashvili.dv@edu.spbstu.ru

Abstract. The paper puts forward an extension of the Pythia8 software package, which makes it possible to calculate collisions of longitudinally polarized protons with the production of J/ψ mesons. The transverse momentum spectra of J/ψ mesons and the double longitudinal spin asymmetry of them at an energy of 510 GeV have been obtained. The calculated results were compared with experimental data, and a satisfactory agreement between them was established. This success served as the basis for predicting the results of the SPD experiment at the NICA collider. The corresponding calculations of the transverse momentum spectrum and the double longitudinal spin asymmetry of the J/ψ meson at an energy of 27 GeV were presented. All conclusions were based on the collinear parton model.

Keywords: Pythia8, double longitudinal spin asymmetry, parton distribution function, parton cross section

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

Citation: Kruashvili D. V., Berdnikov Ya. A., Double longitudinal spin asymmetry of J/ψ mesons produced in proton-proton collisions with longitudinal polarization, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 19 (2) (2026) 171–177. DOI: https://doi.org/10.18721/JPM.19214

This is an open access article under the CC BY-NC 4.0 license (https://creativecommons.org/licenses/by-nc/4.0/)

Научная статья
УДК 532.517
DOI: https://doi.org/10.18721/JPM.19214

ДВОЙНАЯ ПРОДОЛЬНАЯ СПИНОВАЯ АСИММЕТРИЯ (J/ψ)-МЕЗОНОВ, РОЖДЕННЫХ В ПРОДОЛЬНО-ПОЛЯРИЗОВАННЫХ ПРОТОН-ПРОТОННЫХ СТОЛКНОВЕНИЯХ

Д. В. Круашвили✉, *Я. А. Бердников*

Санкт-Петербургский политехнический университет Петра Великого,
Санкт-Петербург, Россия

✉ kruashvili.dv@edu.spbstu.ru

Аннотация. В работе предложено расширение программного пакета Pythia8, благодаря которому появилась возможность рассчитывать столкновения продольно-поляризованных протонов с рождением (J/ψ)-мезонов. Получены спектры по поперечному импульсу и двойная продольная спиновая асимметрия (J/ψ)-мезонов при энергии 510 ГэВ. Проведено сравнение расчетных результатов с экспериментальными данными и установлено их вполне удовлетворительное согласие. Этот успех послужил

© Kruashvili D. V., Berdnikov Ya. A., 2026. Published by Peter the Great St. Petersburg Polytechnic University.

основанием для предсказания результатов эксперимента SPD на коллайдере NICA. Представлены соответствующие вычисления спектра по поперечному импульсу и двойная продольная спиновая асимметрия (J/ψ)-мезона при энергии 27 ГэВ. Все выводы сделаны в рамках коллинеарной партонной модели.

Ключевые слова: Pythia8, двойная продольная спиновая асимметрия, функция распределения партонов, партонное сечение рассеяния

Финансирование: Работа выполнена в рамках Государственного задания на проведение фундаментальных исследований (код темы FSEG-2025-0009).

Ссылка для цитирования: Круашвили Д. В., Бердников Я. А. Двойная продольная спиновая асимметрия (J/ψ)-мезонов, рожденных в продольно-поляризованных протон-протонных столкновениях // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2026. Т. 19. № 2. С. 171–177. DOI: https://doi.org/10.18721/JPM.19214

Статья открытого доступа, распространяемая по лицензии CC BY-NC 4.0 (https://creativecommons.org/licenses/by-nc/4.0/)

Introduction

Studies of J/ψ meson production in proton–proton (pp) collisions provide access to gluon distribution functions in the proton, which in turn makes it possible to estimate the gluon contribution to the proton spin [1].

The proton spin can be expressed using the Manohar–Jaffe sum rule [2]:

$$S_p = 1/2 = (1/2)\,\Delta\Sigma + \Delta G + L_q + L_g, \tag{1}$$

where $(1/2)\Delta\Sigma$ and ΔG are the contributions from quark and gluon helicities, respectively [3]; L_q and L_g are the contributions from the orbital angular momenta of quarks q and gluons g, respectively.

These contributions are given by [4]:

$$\Delta\Sigma = \sum_q \int \Delta f_q(x,Q^2)dx,\ \Delta G = \int \Delta g(x,Q^2)dx, \tag{2}$$

where

$$\Delta f_q(x,Q^2) = f_q^+(x,Q^2) - f_q^-(x,Q^2),\ \Delta g(x,Q^2) = g^+(x,Q^2) - g^-(x,Q^2) \tag{3}$$

(see [5]).

The quantities in (3) are defined as follows: $f_q^+(x,Q^2)$, $f_q^-(x,Q^2)$ are the quark distribution functions in protons with positive and negative helicities, with momentum fraction x at scale Q^2; $g^+(x,Q^2)$, $g^-(x,Q^2)$ are the gluon distribution functions in protons with positive and negative helicities, with momentum fraction x at scale Q^2.

In the literature, $\Delta f_q(x,Q^2)$ и $\Delta g(x,Q^2)$ are commonly referred to as the polarized quark and gluon distribution functions in the proton [5]. It should be noted, however, that according to [3], the $\Delta g(x,Q^2)$ functions are not as well studied as the $\Delta f_q(x,Q^2)$ functions.

This study was motivated by two factors: the limited knowledge of the polarized gluon distribution functions, and the fact that gluon-initiated processes are central to J/ψ meson production in proton–proton collisions [5].

Our goal was to investigate the conditions and features of J/ψ meson production in collisions of polarized and unpolarized protons.

© Круашвили Д. В., Бердников Я. А., 2026. Издатель: Санкт-Петербургский политехнический университет Петра Великого.

Computational procedure

The double longitudinal spin asymmetry (DLSA) [4] in collisions of longitudinally polarized protons is defined as:

$$A_{LL} = \frac{d\sigma^{(++)} - d\sigma^{(+-)}}{d\sigma^{(++)} + d\sigma^{(++)}} = \frac{d\Delta\sigma}{d\sigma}, \tag{4}$$

where $d\sigma^{(++)}$, $d\sigma^{(+-)}$ are the cross sections for collisions of protons with the same (++) and opposite (+−) helicities; $d\Delta\sigma^{(++)}$, $d\Delta\sigma^{(+-)}$ are the cross sections for J/ψ meson production in collisions of polarized and unpolarized protons (i.e., polarized and unpolarized cross sections, respectively) [4].

According to the factorization theorem [6], the unpolarized cross section

$$d\sigma(pp \to J/\psi + X)$$

for J/ψ meson production in semi-inclusive proton−proton collisions can be written as a convolution of the unpolarized parton distribution functions $f_a(x_a, Q^2)$ and $f_b(x_b, Q^2)$ [7, 8]:

$$d\sigma\left(pp \to J/\psi + X\right) = \sum_{a,b,d} \int dx_a f_a\left(x_a, Q^2\right) \int dx_b \cdot f_b\left(x_b, Q^2\right) \cdot d\sigma^{(ab\to(cc)d)} \hat{\sigma}\bar{c}. \tag{5}$$

The polarized cross section

$$d\Delta\sigma(pp \to J/\psi + X)$$

for $J//\psi$ meson production in semi-inclusive longitudinally polarized proton−proton collisions is written as a convolution of the longitudinally polarized parton distribution functions $\Delta f_a(x_a, Q^2)$ and $\Delta f_b(x_b, Q^2)$ [7−9]:

$$d\Delta\sigma\left(pp \to J/\psi + X\right) = \sum_{a,b,d} \int dx_a \Delta f_a\left(x_a, Q^2\right) \int dx_b \cdot \Delta f_b\left(x_b, Q^2\right) \cdot d\Delta\hat{\sigma}^{(ab\to(c\bar{c})d)}. \tag{6}$$

In expressions (5) and (6), a, b are the partons (quarks, gluons) of the colliding protons; the notation $(c\bar{c})d$ denotes the charm quark−antiquark pair $(c\bar{c})$ and the parton $d$produced in the process $ab \to (c\bar{c})d$; x_a, x_b are the momentum fractions carried by parton a from the first proton and by parton $b$from the second proton.

In the same expressions (5) and (6), $d\hat{\sigma}^{(ab\to(c\bar{c})d)}$, $d\Delta\hat{\sigma}^{(ab\to(c\bar{c})d)}$ are, respectively, the unpolarized and polarized parton scattering cross sections for $ab \to (c\bar{c})d$.

Within the color-octet model, the cross sections for J/ψ meson production take the following form [10]:

$$d\sigma\left(pp \to J/\psi + X\right) = \sum_{a,b,d} \int dx_a f_a\left(x_a, Q^2\right) \int dx_b \cdot f_b\left(x_b, Q^2\right) \sum_n \left\langle \mathcal{O}^{J/\psi}[n] \right\rangle \times \\ \times d\hat{\sigma}(ab \to c\bar{c}[n]d), \tag{7}$$

$$d\Delta\sigma\left(pp \to J/\psi + X\right) = \sum_{a,b,d} \int dx_a \Delta f_a\left(x_a, Q^2\right) \int dx_b \cdot \Delta f_b\left(x_b, Q^2\right) \sum_n \left\langle \mathcal{O}^{J/\psi}[n] \right\rangle \times \\ \times d\Delta\hat{\sigma}(ab \to c\bar{c}[n]d). \tag{8}$$

In expressions (7) and (8), the parton cross section is expressed as a sum over all possible $[n]$ states of the $c\bar{c}$ pair composed of the charm quark c and antiquark $\bar{c}$ [10]:

$$^3S_1^{(1)},\ ^3S_1^{(8)},\ ^3S_0^{(8)},\ ^3P_0^{(8)},\ ^3P_1^{(8)},\ ^3P_2^{(8)}. \tag{9}$$

The coefficients $\langle \mathcal{O}^{J/\psi}[n] \rangle$ are the probabilities for J/ψ meson production from a given state [10] (n is the index of the possible quark-antiquark state $c\bar{c}$ of the charm quark pair).

The following interaction processes of gluons g, quarks q, and antiquarks $\bar{q}$ that can produce J/ψ mesons were taken into account in this study:

$$gg \to (c\bar{c}) + g \to J/\psi + g,$$
$$qg \to (c\bar{c}) + q \to J/\psi + q,$$
$$q\bar{q} \to (c\bar{c}) + g \to J/\psi + g,$$

In the native version of the Pythia8 software package [11], unpolarized distribution functions are convolved with unpolarized parton cross sections to generate proton–proton collisions, which yields the unpolarized cross section (6). To obtain the polarized cross section (7), which is needed for calculating the DLSA, the unpolarized distribution functions and unpolarized parton cross sections should be replaced with polarized ones, which was done in this work. To generate J/ψ meson production, we modified the SigmaOnia.cc file in Pythia8. Polarized parton cross sections were used in this file instead of the original parton cross sections [10].

The distribution functions were replaced directly in the code using the command:

pythia.readString(«PDF: pSet = LHAPDF6:»+ name_pdf_set).

The original unpolarized distribution functions were replaced with the polarized ones [12].

This modification of Pythia8 allowed us to compute the polarized cross section $d\Delta\sigma$ for the J/ψ meson. This, in turn, made it possible to calculate the DLSA.

Computational results

To validate the algorithm proposed in this work and the modification of the program for calculating the DLSA of J/ψ mesons produced in longitudinally polarized proton–proton collisions, we obtained the following computational results at 510 GeV:

transverse momentum spectra of (J/ψ)- mesons produced in unpolarized proton–proton collisions (Fig. 1);

DLSA for the J/ψ meson (Fig. 2).

The choice of this energy was motivated by the results of the STAR and PHENIX experiments at the Brookhaven National Laboratory (USA) [3, 13]. The spectra shown in Fig. 1 are multiplied by the branching ratio (BR) for the J/ψ meson decay into muon and anti-muon. The BR is the relative fraction of a specific decay channel with respect to the total number of decays of the given particle: it shows how often a meson decays via this particular channel, and is defined as the ratio of the partial decay width Γ_i to the total decay width Γ_{tot}: Γ_i/Γ_{tot}.

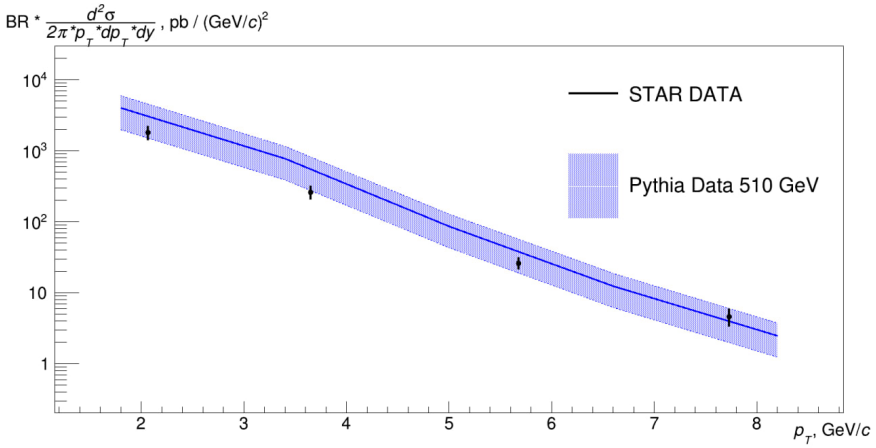


Fig. 1. Invariant p_T spectrum of J/ψ mesons produced in unpolarized proton–proton collisions at 510 GeV (the data are multiplied by the branching ratio BR for the $J/\psi \to \mu^+\mu^-$ decay)
Our simulation results are shown by the blue solid curve (the shaded band around it reflects the range of uncertainties due to PDF errors). The experimental data from the STAR Collaboration [13] are shown by points for comparison

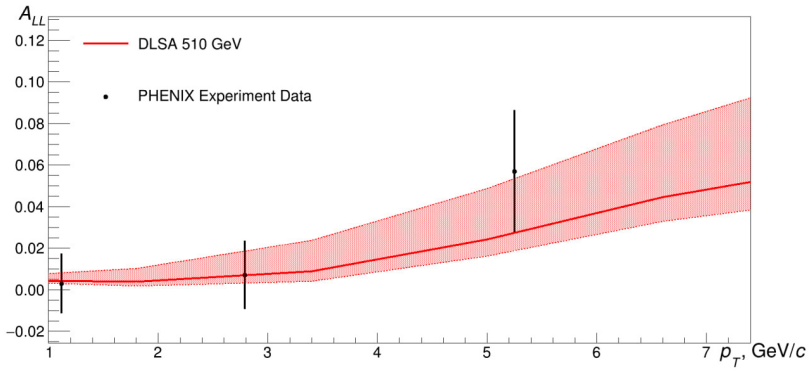


Fig. 2. Double longitudinal spin asymmetry of J/ψ mesons produced in longitudinally polarized proton–proton collisions at 510 GeV as a function of transverse momentum
Our simulation results are shown by the red solid curve (the shaded band around it reflects the range of uncertainties due to PDF errors [12]). The experimental data from the PHENIX Collaboration [3] are shown by points (the error bars represent the uncertainties) for comparison

Analyzing the data in Figs. 1 and 2, we reached the following conclusions:

the simulation data obtained with the modified Pythia8 program are in good agreement (within uncertainties) with the experimental p_T spectrum of J/ψ mesons produced in unpolarized proton–proton collisions at 510 GeV (Fig. 1);

our calculations with Pythia8 are also in good agreement (within uncertainties) with the experimental DLSA dependence of J/ψ mesons produced in longitudinally polarized proton–proton collisions at 510 GeV as a function of transverse momentum.

The satisfactory agreement between our calculations and the experimental data (see Figs. 1 and 2) makes it possible to predict the behavior of the DLSA dependences for J/ψ mesons in interactions of polarized protons. The results of such calculations were obtained in this work (Fig. 3) at 27 GeV, which is the energy characteristic of the planned SPD experiment at the NICA collider.

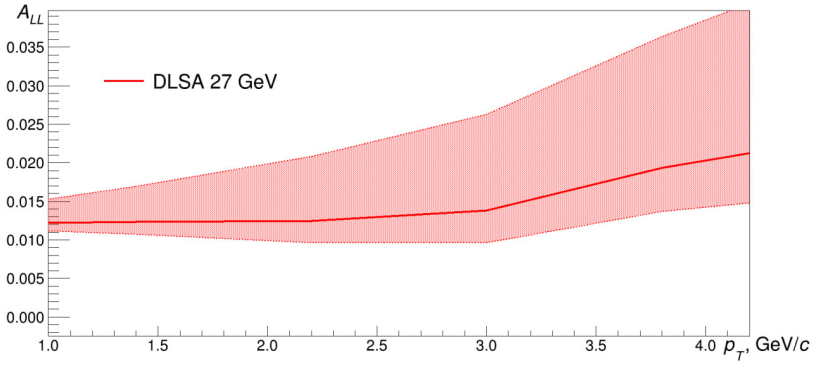


Fig. 3. Predicted DLSA dependence of J/ψ mesons produced in longitudinally polarized proton–proton collisions as a function of p_T. The calculated data are similar to those shown in Fig. 2, but for 27 GeV (instead of 510 GeV in Fig. 2)

Conclusion

In this work, we investigated the feasibility of calculating the double longitudinal spin asymmetry (DLSA) using the Pythia8 software package by modifying parts of the Pythia8 source code. This modification allows calculating the DLSA for J/ψ mesons in proton–proton collisions at various energies. We compared our calculated results with experimental data at 510 GeV and found them to be in satisfactory agreement. This agreement served as the basis for making predictions for the planned NICA experiment (see Fig. 3).

REFERENCES

1. **Ji X., Xiong X., Yuan F.,** Proton spin structure from measurable parton distributions, Phys. Rev. Lett. 109 (15) (2012) 152005.

2. **Jaffe R. L., Manohar A.,** The g_1 problem: Deep inelastic electron scattering and the spin of the proton, Nucl. Phys. B. 337 (3) (1990) 509–546.

3. **Adare A., Aidata C., Ajitanand N. N., et al.,** Measurements of double-helicity asymmetries in inclusive J/ψ production in longitudinally polarized $p + p$ collisions at $s = 510$ GeV, Phys. Rev. D. 94 (11) (2016) 112008.

4. **Saleev V. A., Shipilova A. V.,** Double longitudinal-spin asymmetries in direct photon production at NICA, Phys. Part. Nuclei. Lett. 20 (3) (2023) 400–403.

5. **Stratmann M.** Polarized parton densities and processes, New Trends in HERA Physics 1999: Proc. Ringberg Workshop Held at Tegernsee, Germany, 30 May–4 June 1999, Springer Berlin Heidelberg (2001) 83–97.

6. **Collins J. C., Soper D. E., Sterman G.** Factorization of hard processes in QCD, Adv. Ser. Dir. High Energy Phys. 5 (1988) 1–91.

7. **Sivers D. W.,** Single-spin production asymmetries from the hard scattering of pointlike constituents, Phys. Rev. D. 41 (1) (1990) 83–90.

8. **Collins J. C.,** Fragmentation of transversely polarized quarks probed in transverse momentum distributions, Nucl. Phys. B. 396 (1) (1993) 161–182.

9. **Bomhof C. J., Mulders P. J.,** Gluonic pole cross sections and single spin asymmetries in hadron-hadron scattering, J. High Energy Phys. 2007 (2) (2007) 029.

10. **Klasen M., Kniehl B. A., Mihaila L. N., Steinhauser M.,** Charmonium production in polarized high-energy collisions, Phys. Rev. D. 68 (3) (2003) 034017.

11. **Ciesielski R., Goulianos K.,** MBR Monte Carlo simulation in PYTHIA8, arXiv preprint arXiv:1205.1446 (2012).

12. **Gehrmann T., Stirling W. J.,** Spin-dependent parton distributions from polar-ized structure function data, Z. Phys. C. 65 (3) (1995) 461–470.

13. **Adam J., Adamczyk L., Adams J. R., et al.,** Measurements of the transverse-momentum-dependent cross sections of J/ψ production at mid-rapidity in proton + proton collisions at $s = 510$ and 500 GeV with the STAR detector, Phys. Rev. D. 100 (5) (2019) 052009.

СПИСОК ЛИТЕРАТУРЫ

1. **Ji X., Xiong X., Yuan F.** Proton spin structure from measurable parton distributions // Physical Review Letters. 2012. Vol. 109. No. 15. P. 152005.

2. **Jaffe R. L., Manohar A.** The g_1 problem: Deep inelastic electron scattering and the spin of the proton // Nuclear Physics. B. 1990. Vol. 337. No. 3. 509–546.

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

4. **Салеев В. А., Шипилова А. В.** Двойные продольные спиновые асимметрии в прямом рождении фотонов на коллайдере NICA // Письма в журнал «Физика элементарных частиц и атомного ядра». 2023. Т. 20. № 3(248). С. 417–421.

5. **Stratmann M.** Polarized parton densities and processes // New Trends in HERA Physics 1999: Proceedings of the Ringberg Workshop Held at Tegernsee, Germany, 30 May – 4 June 1999, Berlin, Heidelberg: Springer Berlin Heidelberg, 2001. С. 83–97.

6. **Collins J. C., Soper D. E., Sterman G.** Factorization of hard processes in QCD // Advanced Series on Directions in High Energy Physics. 1988. Vol. 5. Pp. 1–91.

7. **Sivers D. W.** Single spin production asymmetries from the hard scattering of pointlike constituents // Physical Review D. 1990. Vol. 41. No. 1. Pp. 83–90.

8. **Collins J. C.** Fragmentation of transversely polarized quarks probed in transverse momentum distributions // Nuclear Physics B. 1993. Vol. 396. No. 1. Pp. 161–182.

9. **Bomhof C. J., Mulders P. J.** Gluonic pole cross sections and single spin asymmetries in hadron-hadron scattering // Journal of High Energy Physics. 2007. Vol. 2007. No. 2. P. 029.

10. **Klasen M., Kniehl B. A., Mihaila L. N., Steinhauser M.** Charmonium production in polarized high-energy collisions // Physical Review D. 2003. Vol. 68. No. 3. P. 034017.
11. **Ciesielski R., Goulianos K.** MBR Monte Carlo simulation in PYTHIA8 // arXiv preprint arXiv:1205.1446. 2012.
12. **Gehrmann T., Stirling W. J.** Spin-dependent parton distributions from polarized structure function data // Zeitschrift für Physik C.: Particles and Fields. 1995. Vol. 65. No. 3. Pp. 461–470.
13. **Adam J., Adamczyk L., Adams J. R., et al.** Measurements of the transverse-momentum-dependent cross sections of J/ψ production at mid-rapidity in proton+ proton collisions at s = 510 and 500 GeV with the STAR detector // Physical Review D. 2019. Vol. 100. No. 5. P. 052009.

THE AUTHORS

KRUASHVILI Dmitry V.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
kruashvili.dv@edu.spbstu.ru

BERDNIKOV Yaroslav A.
Peter the Great St. Petersburg Polytechnic University
29 Politechnicheskaya St., St. Petersburg, 195251, Russia
berdnikov@spbstu.ru
ORCID: 0000-0003-0309-5917

СВЕДЕНИЯ ОБ АВТОРАХ

КРУАШВИЛИ Дмитрий Васильевич – *инженер Высшей школы фундаментальных физических исследований Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
kruashvili.dv@edu.spbstu.ru

БЕРДНИКОВ Ярослав Александрович – *доктор физико-математических наук, профессор Высшей школы фундаментальных физических исследований Санкт-Петербургского политехнического университета Петра Великого.*
195251, Россия, г. Санкт-Петербург, Политехническая ул., 29
berdnikov@spbstu.ru
ORCID: 0000-0003-0309-5917

Received 16.02.2026. Approved after reviewing 03.03.2026. Accepted 03.03.2026.
Статья поступила в редакцию 16.02.2026. Одобрена после рецензирования 03.03.2026. Принята 03.03.2026.

© Peter the Great St. Petersburg Polytechnic University, 2026