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SPIN PHYSICS PROGRAM OF NEW GENERATION sPHENIX DETECTOR AT RHIC[1]

The sPHENIX experiment is a new experiment and its new detector of Relativistic Heavy Ion Collider (RHIC) in the Brookhaven National Laboratory. It is an upgrade of the PHENIX experiment. The sPHENIX is to complete the scientific mission of RHIC in the study of QGP and the spin structure of the proton. The sPHENIX detector provides precision vertexing, tracking and electromagnetic and hadronic calorimetry in the central pseudorapidity region $|\eta| \leq 1.1$*, with full azimuth coverage, at the full RHIC collision rate, delivering unprecedented data sets for hard probe tomography measurement at RHIC. The sPHENIX was commissioned using* $Au + Au$ *collision in 2023, and took physics data with transversely polarized proton + proton collisions at the center-of-mass energy of* $\sqrt{s} = 200$ *GeV in 2024. The status of detector commissioning and achieved physics targets of the proton spin program using the sPHENIX detector will be discussed.*

Keywords: RHIC, sPHENIX, cold-QCD, proton spin, transverse single spin asymmetry, orbital angular momentum.

1. Introduction

The sPHENIX[1][2] is a second generation experiment and its detector at Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory (BNL). It is an upgrade of the PHENIX experiment [3] which was decommissioned in 2016. The sPHENIX is to complete the scientific mission of RHIC in study of QGP and the spin structure of the proton. The physics goals of sPHENIX are illustrated in Fig. 1[2]. They are:

1. Measurement of hadron jets, direct photons, and heavy quarks and the study of parton energy loss in the QGP.

2. Measurement of the Upsilon particles and temperature of the QGP.

3 Measurement of jet substructure and the study of parton QGP interaction.

4. Study of the spin structure of the proton.

The primary focus of this document is the spin structure study of proton at sPHENIX. The RHIC is the only polarized proton collider in the world, providing unique testing ground for the proton spin. By colliding polarized protons against each other at high energies, one can study how the spin of a proton is carried by its constituent quarks and gluons. Prior to the RHIC, it was known that only 1/3 of the proton spin is carried by quark spin. Previous works at the RHIC have revealed that gluon spin also contributes to proton spin. However, the quark and gluon spins together do not appear to be sufficient to explain 100% of the proton spin. If there is any remainder, it is the orbital angular momentum of the partons within the proton.

There are numerous attempts have been made in the last decades in order to reveal the origin of the exexpectedly large transverse single spin asymmetry A_N observed in inclusive hadron productions at forward rapidity regions in transversely polarized proton + proton collisions in wide range of center-of-mass energies $\sqrt{s}$. The theoretical frameworks that

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[1] This work is based on the results presented at the 2024 "New Trends in High-Energy and Low-x Physics" Conference.

[2] The scientific illustration by Misaki Ouchida (Hokkaido University).

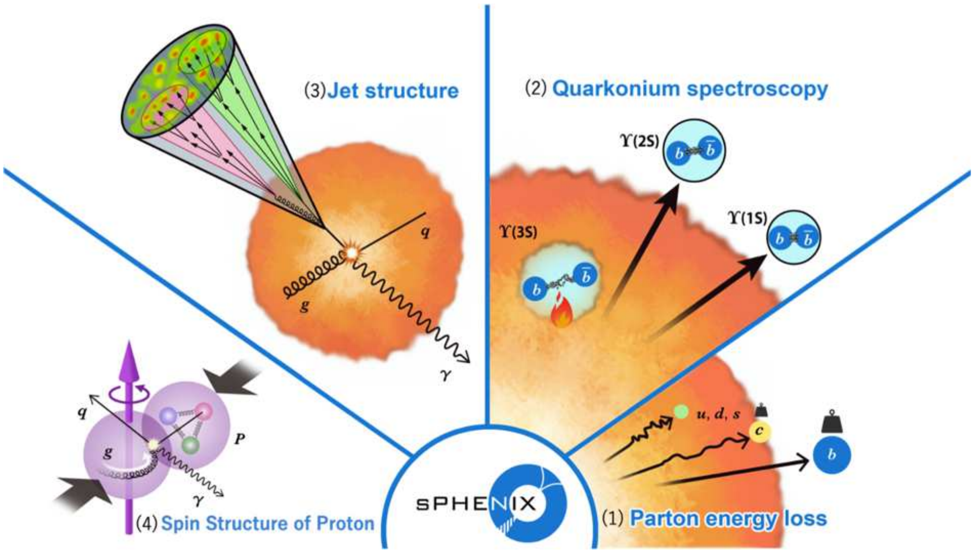


Fig. 1. Illustration of physics goals of the sPHENIX

explain this puzzle include the twist-3 contributions in collinear factorization framework, the transverse-momentum-dependent contributions from the initial-state quark and gluon Sivers functions, and/or final state final-state Collins fragmentation functions. Hereby Sivers functions are considered to be associated with the orbital motion of partons in the proton.

The sPHENIX will investigate the contribution of the orbital mortion of partons in the proton spin, as illustrated in the bottom left image of Fig. 1 using transversely polarized proton + proton collisions at $\sqrt{s} = 200$ GeV.

2. sPHENIX Detector

The sPHENIX[2] is a new state-of-art jet detector at the RHIC. The construction of the detector complex was completed by the end of April 2023 as shown in Fig. 2 [3]. The concept of sPHENIX follows the geometry of typical collider detectors, depicted in Fig. 3, covering the full azimuth and pseudo rapidity range of $-1.1 \leq \eta \leq 1.1$, with a tracking system consisting of a pixel detector (MVTX) based on monolithic active pixel sensor technology, a silicon strip intermediate tracker (INTT), and a time projection chamber (TPC). The calorimeter stack includes a tungsten/scintillating fiber electromagnetic calorimeter (EMCAL) and a steel/scintillator tile hadronic calorimeter (HCAL), divided into inner and outer parts. The inner HCAL sits inside a 1.4 T superconducting solenoid, which was refurbished from the decommissioned BaBar detector [4].

The tracking system consisting of the MVTX, the INTT, and the TPC is the well-established detector formation of modern particle collider detectors such as STAR [5, 6] and ALICE [7]. Each detector is excellent in position, timing, and momentum resolution, respectively and, thus, an essential component of a desirable high-energy collider detector.

The data acquisition (DAQ) of the sPHENIX is designed to handle a trigger rate of 15 kHz. The Felix server system developed in ATLAS [8] was employed as a part of the DAQ system for tracking detectors, which enables the processing of data in a stream readout mode as well.

A minimum bias trigger is provided by the pair of minimum bias detectors (MBDs) implemented 2.5 m downstream of the collision point along a beam pipe in both directions. They are constructed from the reuse of the PHENIX beam beam counter (BBC), consisting of Čerenkov detectors made of a 3-cm-thick quartz radiator readout with mesh dynode photomultipliers. The collision vertex position along the beam axis is determined from the observed hit-timing difference between the MBD pair. The MBD has timing resolution of 50–60 ps for a single hit, which is translated to the reconstruction position resolution

[3] Courtesy of Brookhaven National Laboratory

of <2 cm for proton + proton collisions and of few mm for Au + Au collisions.

A pair of event plane detectors (EPD) is implemented further downstream of the MBD exploits 1.2-cm-thick scintillators with wavelength shifting fibers. Each EPD consists of two wheels of 12 sectors with 31 optically-isolated tiles. The EPD provides significant improvement in the event plane resolution of the Au + Au collision.

The Zero Degree Calorimeter is a Cherenkov light sampling calorimeter. The ZDCs are located in series at ±18 m away from the collision point, each side of the beam direction. Mechanically, each arm of the ZDC is subdivided into 3 identical modules with 2 interaction length each. The active medium is made from clear PMMA fibers interleaved with Tungsten absorber plates. This sandwich structure is tilted at 45 degree to the beam to align the optical fibers with the Cherenkov angle of forward particles in the shower. The energy resolution of the ZDC for 100 GeV neutrons is 21%.

The SMD is an X-Y scintillator strip detector inserted between 1st and 2nd ZDC modules. This location corresponds (approximately) to hadronic shower maximum position. The horizontal x coordinate is sampled by 7 scintillator strips of 15 mm width each, while the vertical y coordinate is sampled by 8 strips of 20 mm width each, tilted by 45 degrees. The active area covered by SMD is 105 mm × 110 mm. The SMD position resolution depends on energy deposited in the scintillator and varies from around 10 mm at a small number of charged particles crossing the SMD to values smaller than 3 mm, when the number of particles exceeds 100. For comparison, the spread of neutrons due to of nucleon Fermi motion is about 2.2 cm at 100 GeV. A pair of scintillator paddles with matching acceptance with ZDC was implemented upstream and down- stream of ZDC, respectively. It is called charge veto counters.

Fig. 2. Photograph of the sPHENIX detector

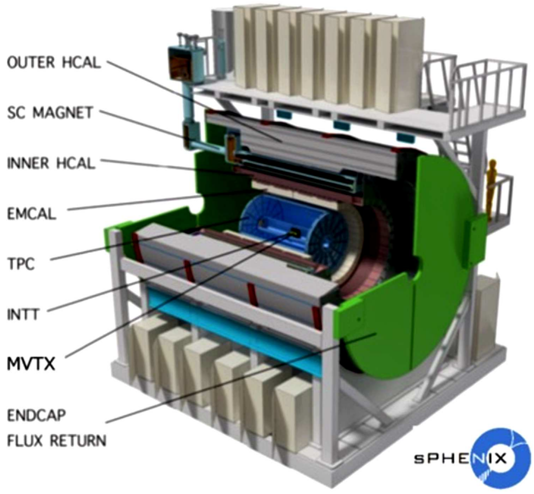


Fig. 3. The engineering drawing of the sPHENIX detector

3. Projected Errors

Photons, jets and heavy-quark flavors have been considered as the "golden probes" for the decomposition of proton spin components. However there are short of existing measurements of these observables due to their small cross section and technical difficulty in their measurements. The sPHENIX detector is thus designed to measure heavy flavor mesons, hadron jets, high transverse momentum (p_T) hadrons, high-energy photons over a wide energy range. The broad kinematic range of p_T covered by the sPHENIX is depicted in Fig. 4.

The TSSAs in direct photon and heavy-flavor production probe the gluon dynamics within a transversely polarized nucleon, described by the tri-gluon correlation function in the collinear twist-3 framework, which is connected with the gluon Sivers TMD parton distribution function (PDF). This is yet well known. The Sivers function correlates the nucleon

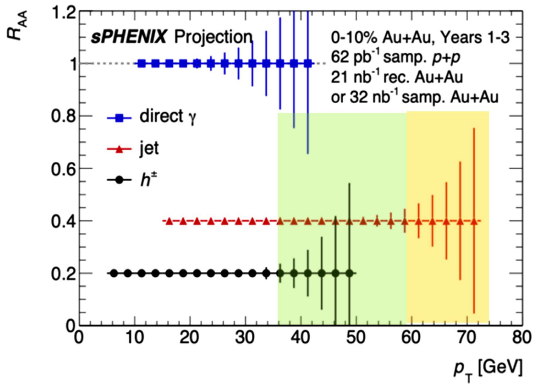


Fig. 4. Kinematic coverage in tranverse momentum p_{T} of sPHENIX detector [1]

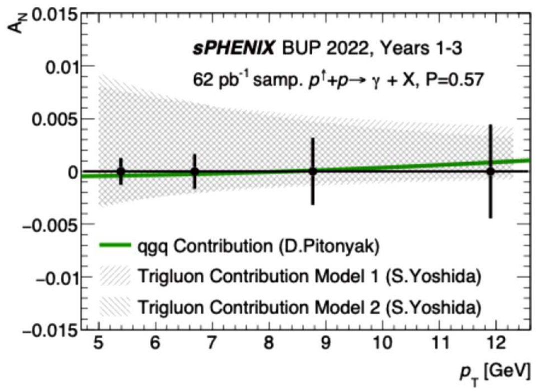


Fig. 5. Projected errors of the transverse single spin asymmetry for direct photon A_N at sPHENIX compared with theoretical model predictions

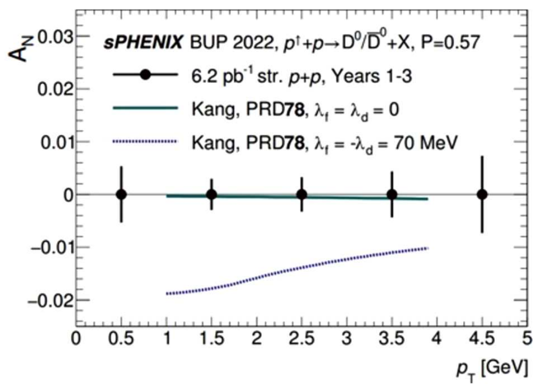


Fig. 6. Projected errors of the transverse single spin asymmetry A_N of D^0 meson production

transverse spin with the parton transverse momentum. Therefore it is an important step forward to understand the orbital angular momentum components

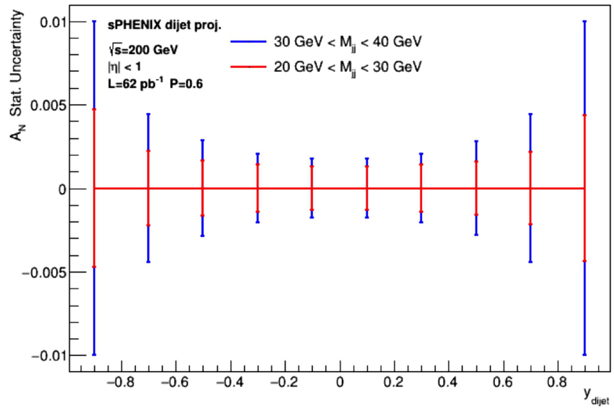


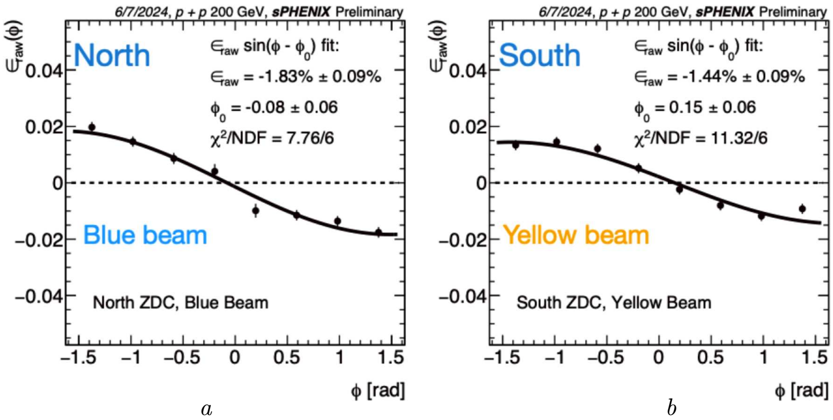
Fig. 7. Projected errors of the transverse single spin asymmetry A_N of dijects production

of proton spin. Shown in Fig. 5 and Fig. 6 are the projected errors of the transverse single spin asymmetry for direct photon and D^0 mesons A_N compared with theoretical model predictions [10].

The EMCal-based high-energy cluster trigger enables us to collect high statistical samples of direct photon in mid-rapidity region. The new capability of the streaming readout of sPHENIX tracking system also enables a high precision measurement of D_0 meson TSSA.

The sPHENIX is the first jet detector with fully implemented hadron calorimeters in the mid-rapidity at RHIC. Therefore it allows the inclusive jet TSSA measurement in high precision to the level of a few times 10^{-4}. The opposite sign contribution of up and down quarks to Sivers asymmetry is expected from existing semi-inclusive deep inelastic scattering experiments. By tagging the leading hadron charge in sPHENIX will allow Sivers asymmetry measurements in flavor separated manner, since they preferably enhance the contribution from fragmenting up or down quarks. Without the tagging, the asymmetries of the overall jet can be canceled out due to the hadron asymmetries in opposite signs.

As a trade off of the statistics with respect to the inclusive jet measurement, dijet measurements certainly provides the advantage in the direct access to parton intrinsic transverse momentum k_{T}. Recent STAR measurement showed nonzero effect for charged tagged jets. As a dedicated detector for jet and photon measurements, sPHENIX is expected to contribute to dijets measurements as shown projected errors of dijet A_{N} in Figure 7 [10].



a *b*

Fig. 8. Observed transverse single spin asymmetries of neutron production in zero degree at $\sqrt{s} = 200$ GeV with respect to North (*a*) and South (*b*) going polarized proton beams, respectively

Full jet measurement with hadron calorimeters also allows detailed measurement of the Collins mechanism, which correlates the transverse polarization of a fragmented quark to the angular distribution of hadrons within a jet. This gives access to the transversity distribution in the proton which can be interpreted as the net transverse polarization of quarks within a transversely polarized proton. Along with the unpolarized PDF and helicity PDF, tranversity is one of three leading-twist PDFs. The integral in x over the valence quark transversity distribution defines the tensor charge, a fundamental value calculable in lattice QCD, therefore enabling the crucial comparison of experimental measurements with *ab initio* theoretical calculations. Unlike semi-inclusive DIS measurements, $p + p$ collisions are more sensitive to the d-quark transversity and its tensor charge.

4. Run24 Performance

In this section, some selected detector performance plots observed in polarized proton + proton collision in Run24 are presented. Plots are results of first semi-online analyses and the resolution will be improved in later careful calibrations.

The polarization of proton beams are measured by the proton-carbon and hydrogen jet polarimeters implemented at 12 o'clock region of the RHIC ring. In order to pursue the spin program at sPHENIX, it is important to monitor the spin vector of the polarized beam locally at sPHENIX throughout the proton + proton run. Since the asymmetry analysis will be pursued assuming the spin vector to be perfectly

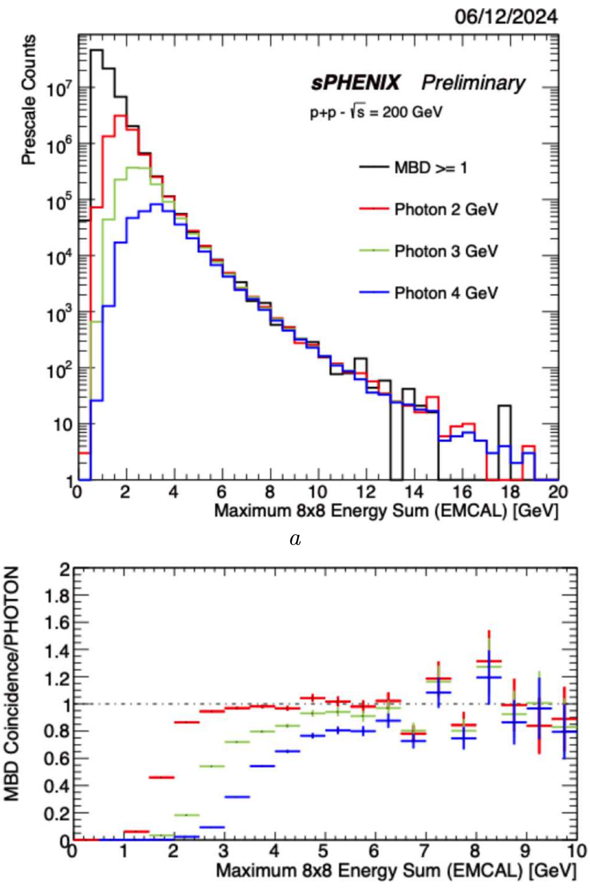


Fig. 9. Turn on curves of the minimum bias *1* (black) and photon triggers for threshold of *2* (red), *3* (green), *4* (blue) (*a*). Ratio of photon triggers with respect to the minimum bias trigger (*b*)

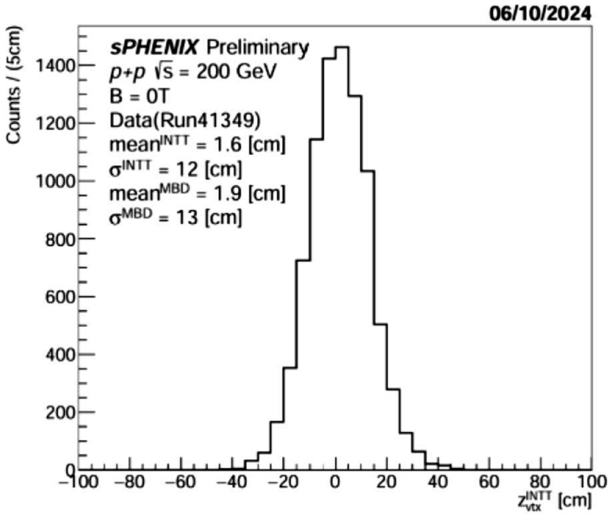


Fig. 10. The reconstructed collision vertex distribution along the beam axis using observed tracklets in INTT detector in $\mathrm{p+p}$ collision at $\sqrt{s} = 200$ GeV

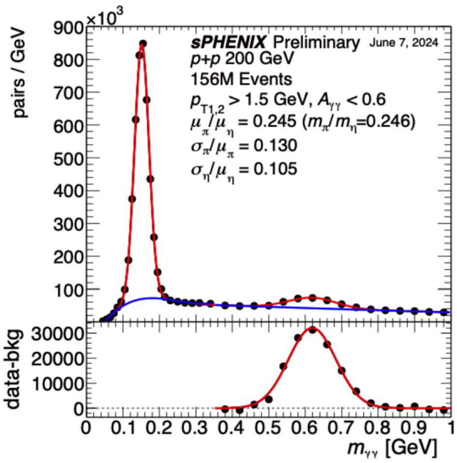


Fig. 11. The reconstructed invariant mass of π^0 and η mesons observed in $\mathrm{p+p}$ collision at $\sqrt{s} = 200$ GeV

vertical, any deviation from it would be accounted as the systematic error.

The sPHENIX local polarimeter relies on the nonzero transverse single spin asymmetry of very forward neutrons produced from collisions of transversely polarized and unpolarized protons, $p^{\uparrow}+p$. The magnitude of the asymmetry is proportional to the beam polarization, with a roughly 2–3% negative asymmetry expected at nominal beam polarization of 50–60% [11]. Shown in Fig. 8 are azimuthal modulation of the forward neutrons of the blue beam observed by the North ZDC/SMD and the yellow beam by the South ZDC/SMD detectors. The observed asymmetries are consistent with the published results.

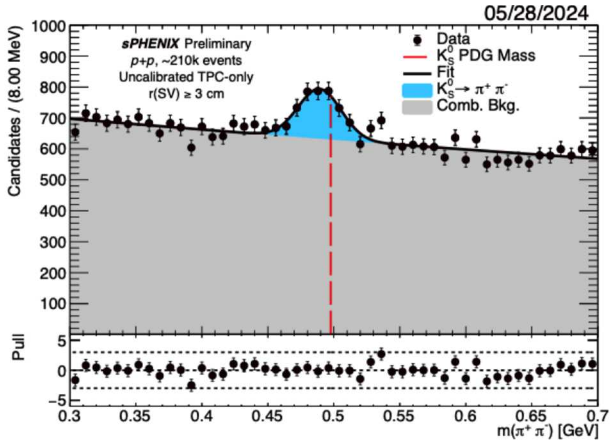


Fig. 12. The reconstructed invariant mass of K_s^0 meson observed in $\mathrm{p+p}$ collision at $\sqrt{s} = 200$ GeV

In order to accumulate high energy jet and photon events, jet and photon triggers were implemented in sPHENIX. The photon trigger was formed by the clusters in EMCAL. The photon triggers for threshold of *2* (red), *3* (green), *4* (blue) established decent rejection powers with respect to the minimum bias trigger *1* (black), respectively (Fig. 9).

Presented in Fig. 10 is the reconstructed collision vertex distribution along the beam axis using observed tracklets in INTT detector without magnetic field in sPHENIX. The collision vertex was nicely centered around zero and width of the distribution reconstructed by two independent detectors, i.e. INTT and MBD are consistent to each other within 1 cm.

Shown in Fig. 11 is the reconstructed mass spectrum of photon pairs using EMCAL. Distinctive π^0 and η mass peaks can be observed on above combinatory backgrounds which is represented by blue curve.

Figure 12 shows the invariant mass spectrum of π^+ and π^- pair detected by TPC. A clear K_s^0-meson mass peak appears as expected around 0.5 GeV, although no distortion corrections are applied yet.

1. An Upgrade Concept from the PHENIX Collaboration. arXiv:1207.6378v2 (2012).
2. Technical Design Report of sPHENIX (2019).
3. K. Adcox *et al.* PHENIX detector overview. *Nucl. Instr. Meth. A* **499**, 469 (2003).

4. B. Aubert *et al.* The BABAR detector. *Nucl. Instr. Meth. A* **479**, 1 (2002).
5. M. Anderson *et al.* The STAR time projection chamber: A unique tool for studying high multiplicity events at RHIC. *Nucl. Instr. Meth. A* **499**, 659 (2003).
6. G. Contin *et al.* The STAR MAPS-based PiXeL detector. arXiv:1710.02176 [physics.ins-det] (2018).
7. The ALICE Collaboration, CERN-LHCC-2012-013/ LHCC-P-005, ALICE-UG-002 (2012).
8. M. Wu (ATLAS TDAQ Collaboration). FELIX: Readout upgrade for the ATLAS Trigger DAQ system in HL-LHC. *Nucl. Inst. Meth. A* **1048**, 167994 (2023).
9. C. Aidala *et al.* The PHENIX forward silicon vertex detector. *Nucl. Instr. Meth. A* **755**, 44 (2014).
10. Central Au + Au data event recorded in the sPHENIX calorimeter system. In: *sPHENIX Beam Use Proposal* (2023).
11. A. Adare *et al.* PHENIX Collaboration. Inclusive cross section and single transverse spin asymmetry for very forward neutron production in polarized $p + p$ collisions at $\sqrt{s} = 200$ GeV. *Phys. Rev. D* **88**, 032006 (2013).

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І. Накагава від імені колаборації sPHENIX

ПРОГРАМА ФІЗИКИ СПІНУ
ДЛЯ ДЕТЕКТОРА sPHENIX НОВОГО
ПОКОЛІННЯ НА КОЛАЙДЕРІ RHIC

Експеримент sPHENIX – це новий експеримент на новому детекторі релятивістичного колайдера важких іонів (RHIC) у Брукхейвенській національній лабораторії. sPHENIX має завершити наукову місію колайдера RHIC – вивчення кварк-ґлюонної плазми і спінової структури протона. Детектор sPHENIX забезпечує точне визначення вершин, треків і електромагнітну та гадронну калориметрію в центральній області псевдохуткості $|\eta| \leq 1{,}1$, з повним азимутальним покриттям, при повній швидкості зіткнень на колайдері RHIC, що дає безпрецедентні набори даних для жорсткої томографії на RHIC. sPHENIX було введено в експлуатацію з використанням зіткнень $\mathrm{Au} + \mathrm{Au}$ у 2023 році, і у 2024 році на цьому детекторі отримано експериментальні дані для зіткнень поперечно поляризованих протонів із протонами з енергією центра мас $\sqrt{s} = 200$ ГеВ. В роботі обговорюється стан введення детектора в експлуатацію та досягнуті фізичні цілі в рамках програми дослідження спіну протона з використанням детектора sPHENIX.

Ключові слова: колайдер RHIC, детектор sPHENIX, холодна кварк-ґлюонна плазма, спін протона, поперечна асиметрія, кутовий момент.