RIKEN BNL Research Center
Experimental Group

1. Abstract
RIKEN BNL Research Center (RBRC) Experimental Group studies the strong interactions (QCD) using RHIC accelerator at Brookhaven National Laboratory, the world first heavy ion collider and polarized $p + p$ collider. We have three major activities: Spin Physics at RHIC, Heavy ion physics at RHIC, and detector upgrades of PHENIX experiment at RHIC.

We study the spin structure of the proton using the polarized proton-proton collisions at RHIC. This program has been promoted by RIKEN's leadership. The first focus of the research is to measure the gluon spin contribution to the proton spin. Results from PHENIX π^0 measurement and STAR jet measurement has shown that gluons in the proton carry about 30% of the proton spin. This is a major milestone of the RHIC spin program. The second goal of the spin program is to measure the polarization of anti-quarks in the proton using $W \to e$ and $W \to \mu$ decays. The results of $W \to e$ measurement was published in 2016. The final results of $W \to \mu$ was published in 2018. The focus of the RHIC spin program is moved to study of transverse spin measurement.

The aim of Heavy ion physics at RHIC is to re-create Quark Gluon Plasma (QGP), the state of Universe just after the Big Bang. Two important discoveries, jet quenching effect and strong elliptic flows, have established that new state of dense matter is indeed produced in heavy ion collisions at RHIC. We measured direct photons in Au + Au collisions for $1 < p_T < 3$ GeV/c, where thermal radiation from hot QGP is expected to dominate. The comparison between the data and theory calculations indicates that the initial temperature of 300 MeV to 600 MeV is achieved. These values are well above the transition temperature to QGP, which is calculated to be approximately 160 MeV by lattice QCD calculations.

We had major roles in detector upgrades of PHENIX experiment, namely, the silicon vertex tracker (VTX) and muon trigger upgrades. The VTX is the main device to measure heavy quark (charm and bottom) production and the muon trigger is essential for $W \to \mu$ measurement. The results from the first run with VTX detector in 2011 was published. The results show that electrons from bottom quark decay is strongly suppressed at high p_T, but the suppression is weaker than that of charm decay electron for $3 < p_T < 4$ GeV/c. PHENIX recorded 10 times as much Au + Au collisions data in each of the 2014 run and 2016 run. A paper on the suppression of electrons from charm and bottom decays in the 2014 run was submitted for publication. The data shows clear different of the suppression of $b \to e$ and ce.

PHENIX completed its data taking in 2016 to be upgraded to a new detector and experiment, sPHENIX. sPHENIX measure jets, photons, and Upsilon particles to complete the scientific mission of RHIC. We constructed an intermediate-silicon tracker INTT for sPHENIX. INTT was completed in 2022 and it was installed in sPHENIX in March 2023. The commissioning of the INTT was complete during the engineering run of sPHENIX in 2023 along with most of the subsystems of sPHENIX. sPHENIX and the INTT started taking physics data in the 2024 polarized $p + p$ run. The INTT detector worked very well in the 2024 run. In 2025, sPHENIX will take Au + Au collision data, and RHIC will complete its operation.

2. Major Research Subjects
(1) Experimental Studies of the Spin Structure of the Nucleon
(2) Study of Quark-Gluon Plasma at RHIC
(3) sPHENIX INTT detector

3. Summary of Research Activity
We study the strong interactions (QCD) using the RHIC accelerator at Brookhaven National Laboratory, the world first heavy ion collider and polarized $p + p$ collider. We have three major activities: Spin Physics at RHIC, Heavy ion physics at RHIC, and detector upgrades of PHENIX experiment. Y. Akiba is the Spokesperson of PHENIX experiment since 2016.

(1) Experimental study of spin structure of proton using RHIC polarized proton collider
How is the spin of proton formed with 3 quarks and gluons? This is a very fundamental question in Quantum Chromodynamics (QCD), the theory of the strong nuclear forces. The RHIC Spin Project has been established as an international collaboration between RIKEN and Brookhaven National Laboratory (BNL) to solve this problem by colliding two polarized protons for the first time in history. This project also has extended the physics capabilities of RHIC.

The first goal of the Spin Physics program at RHIC is to determine the gluon contribution to proton spin. It is known that the spin of quark accounts for only 25% of proton spin. The remaining 75% should be carried either by the spin of gluons or the orbital angular momentum of quarks and gluons. One of the main goals of the RHIC spin program has been to determine the gluon spin contribution. Before the start of RHIC, there was little experimental constraint on the gluon polarization, ΔG.

PHENIX measures the double helicity asymmetry (ALL) of π^0 production to determine the gluon polarization. Our most recent publication of $\pi^0 A_{LL}$ measurement at 510 GeV shows non-zero value of A_{LL}, indicating that gluons in the proton is polarized. Global analysis shows that approximately 30% of proton spin is carried by gluon spin. PHENIX measured the parity-violating single spin asymmetry A_L of the W boson production in $p + p$ in wide rapidity range. The results of the W boson measurements were published in 2016 and 2018, and these results give constraints on the anti-quark polarization in the proton. The focus of the spin physics is now moved to the measurements of the single transverse spin asymmetry A_N.

PHENIX measured double spin asymmetry A_{LL} of direct photon in $p + p$ collisions at 510 GeV. This is one of the main goal of RHIC spin program when it was started more than three decades ago. Figure 1 shows the measured A_{LL} and comparison with theories.

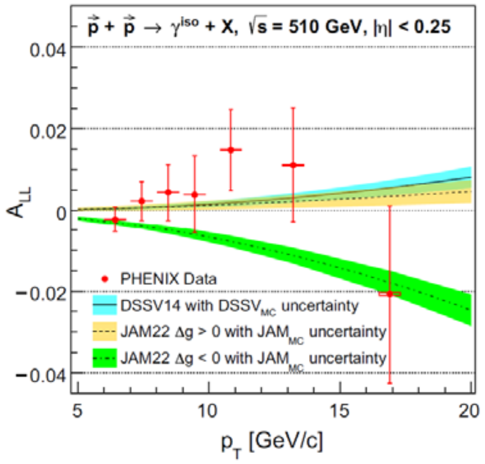

Fig. 1. The double spin asymmetry A_{LL} of direct photon is compared with theory predictions. The theories assuming that the gluon spin is aligned in opposite direction of the proton spin is excluded. Published in Phys. Rev. Lett. 130, 251901 (2023)

Theories assuming that the gluon spin in aligned in the opposite direction of the proton spin is excluded by the data. Thus it is shown that the spin of gluons is aligned in the same direction of the proton. The paper of this result is published in Physical Review Letters. News releases were issued by RIKEN and BNL regarding the results. It was also selected as a DOE Science Highlight in February 2024.

(2) Experimental study of Quark-Gluon Plasma using RHIC heavy-ion collider

The goal of high energy heavy ion physics at RHIC is study of QCD in extreme conditions *i.e.* at very high temperature and at very high energy density. Experimental results from RHIC have established that dense partonic matter is formed in Au + Au collisions at RHIC. The matter is very dense and opaque, and it has almost no viscosity and behaves like a perfect fluid. These conclusions are primarily based on the following two discoveries:

- Strong suppression of high transverse momentum hadrons in central Au + Au collisions (jet quenching);
- Strong elliptic flow.

These results are summarized in PHENIX White paper, which has more than 3800 citations to date. The focus of the research in heavy ion physics at RHIC is now to investigate the properties of the matter. RBRC have played the leading roles in some of the most important results from PHENIX in the study of the matter properties. These include (1) measurements of heavy quark production from the single electrons from heavy flavor decay (2) measurements of J/ψ production (3) measurements of di-electron continuum and (4) measurements of direct photons.

Our most important result is the measurement of direct photons for $1 < p_T < 5$ GeV/c in $p + p$ and Au + Au through their internal conversion to $e + e^-$ pairs. If the dense partonic matter formed at RHIC is thermalized, it should emit thermal photons. Observation of thermal photon is direct evidence of early thermalization, and we can determine the initial temperature of the matter. It is predicted that thermal photons from QGP phase is the dominant source of direct photons for $1 < p_T < 3$ GeV/c at the RHIC energy. We measured the direct photon in this p_T region from measurements of quasi-real virtual photons that decays into low-mass $e + e^-$ pairs. Strong enhancement of direct photon yield in Au + Au over the scaled $p + p$ data has been observed. Several hydrodynamical models can reproduce the central Au + A data within a factor of two. These models assume formation of a hot system with initial temperature of $T_{\rm init}$ = 300 MeV to 600 MeV. This is the first measurement of initial temperature of quark gluon plasma formed at RHIC. Y. Akiba received 2011 Nishina memorial Prize mainly based on this work.

PHENIX experiment recently measured the flow in small collision systems (p + Au, d + Au, and ^{3}He + Au), and observed strong flow in all of these systems. Theoretical models that assume formation of small QGP droplets best describe the data. These results are published in Nature Physics in 2019.

The group had major roles in several PHENIX detector upgrades, namely, the silicon vertex tracker (VTX) and muon trigger upgrades. VTX is a high precision charged particle tracker made of 4 layers of silicon detectors. It is jointly funded by RIKEN and the US DOE. The inner two layers are silicon pixel detectors and the outer two layers are silicon strip detectors. Y. Akiba is the project manager. The VTX detector was completed in November 2010 and subsequently installed in PHENIX. The detector started taking data in the 2011 run. With the new detector, we measure heavy quark (charm and bottom) production in $p + p$, A + A collisions to study the properties of quark-gluon plasma. The final result of the 2011 run was published. The result show that single electrons from bottom quark decay is suppressed, but not as strong as that from charm decay in low p_T region ($3 < p_T < 4$ GeV/c). This is the first measurement of suppression of bottom decay electrons at RHIC and the first observation that bottom suppression is smaller than charm. We have recorded 10 times as much Au + Au collisions data in each of the 2014 run and 2016 run. The results of bottom/charm ratios in $p + p$ collisions at 200 GeV from the 2015 run was published (Phys. Rev. D **99**, 092003 (2019)). A paper reporting measurements of the nuclear suppression factor R_{AA} of charm and bottom in Au + Au collisions from the 2014 data was published (Phys. Rev. C **109**, 044907 (2024)).

Highlights of PHENIX results in 2024

PHENIX completed data taking in 2016 to be upgraded to a new and the last detector of RHIC, sPHENIX. PHENIX continue publish physics results from the large amount of data recorded.

Figure 2(b) showed PHENIX measurement of the yield ratio of high p_T π^0 relative to direct photon in d + Au collision at $\sqrt{s_{NN}}$ = 200 GeV. The data clearly showed that in central d + Au collisions (corresponding to large N_{coll}^{EXP}) π^0 is suppressed relatively direct photon. This result provides strong evidence for a small QGP formed in small collision system. This result was highlighted as a DOE Science highlight in May 2025.

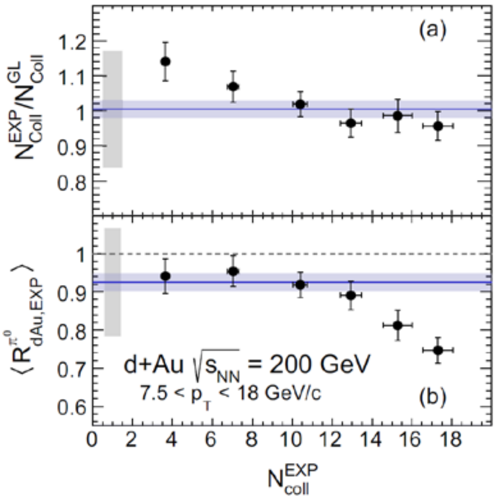

Fig. 2. The yield ratio of π^0 relative to direct photon for $7.5 p_{\rm T} < 18$ GeV/c as function of N_{coll}^{Exp} in d + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Published in Phys. Rev. Lett. **134**, 022302 (2025).

PHENIX measured direct photons in wide $p_{\rm T}$ range in Au + Au collisions. A paper of high statistics measurement from the 2014 run was published (Phys. Rev. C **109**, 044912 (2024)). A paper of high statistic v2 measurement of direct photon from the 2014 run was submitted to publication in Phys. Rev. C.

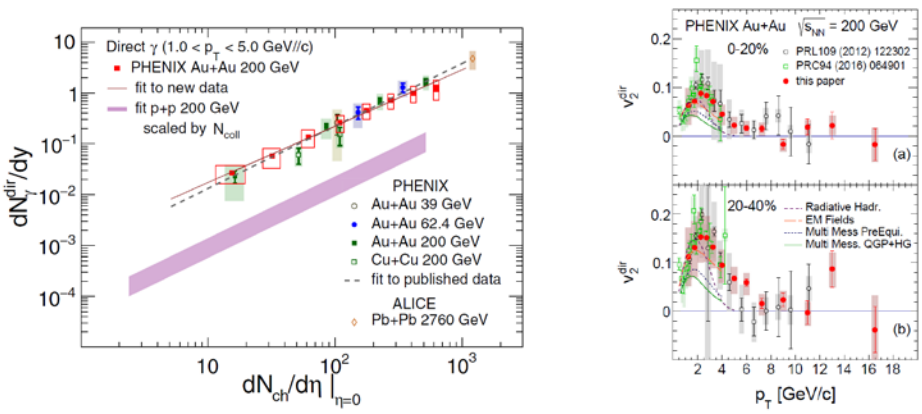

Fig. 3. Direct photon measurements in Au + Au collisions at 200 GeV. Left: Yield of direct photon as function of $dN_{ch}/d\eta$ in Au + Au collisions at 200 GeV. Published in Phys. Rev. C **109**, 044912 (2024). Right: Direct photon v2 (strength of elliptic flow) in Au + Au collisions at 200 GeV. ArXiv:2504.02955 (2025)

(3) sPHENIX INTT detector

PHENIX completed its data taking in 2016. We constructed an intermediate silicon tracker INTT for sPHENIX, a new experiment at RHIC that started operation in 2023. The construction of the INTT was completed in fall 2022 and it was installed in sPHENIX in March 2023. The INTT detector and the sPHENIX detector was commissioned with beam in the 2023 run. The commissioning of the INTT was completed in the run and the detector was working very well. Figure 4 shows the ADC distributions of 2912 read-out chips of the INTT. All chips except for those marked by red were working. Approximately 99% of the detector was working.

sPHENIX had its first physics data in the 2024 run with polarized $p + p$ collisions at $\sqrt{s}$ = 200 GeV. Figure 5 shows an event

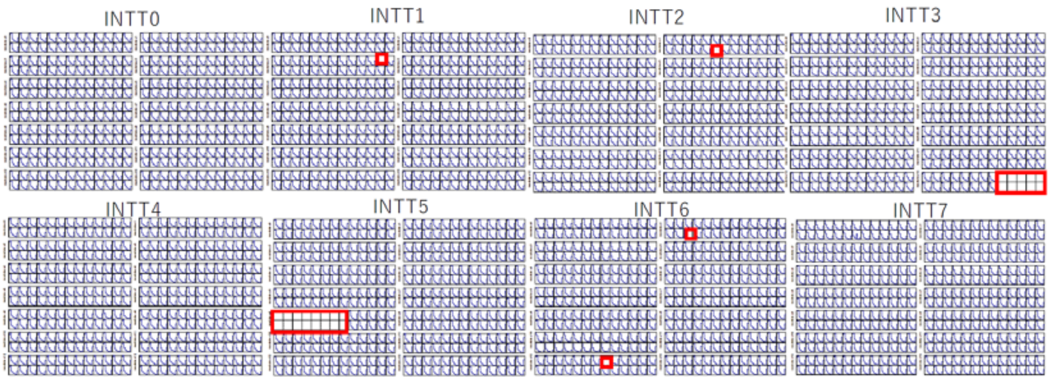

Fig. 4. ADC distributions of read-out chips of INTT detector. Red part shows the dead chips. 99% of the detector is working.

display of a $p + p$ collision event at $\sqrt{s} = 200$ GeV recorded by the INTT. Hits in the INTT and the INTT tracklets formed by the collision vertex and two INTT hits are shown. Four tracks of this collision event is reconstructed, demonstrating that the INTT can function well as a stand-alone tracking detector in $p + p$.

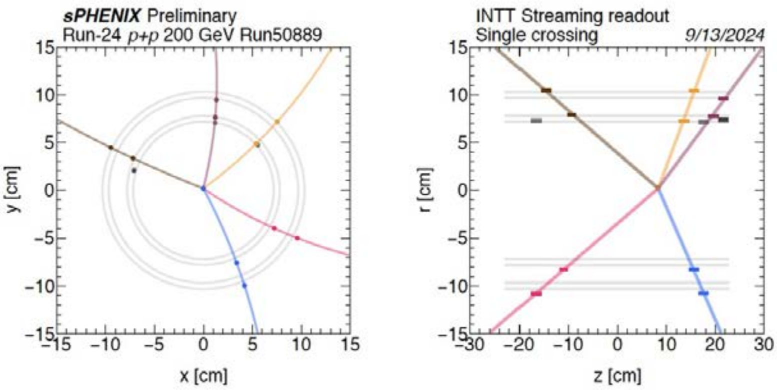

Fig. 5. Event display of $p + p$ collisions at 200 GeV recorded by the INTT detector.

In the later half of the 2024 run, the INTT was operated in "streaming read-out mode." In this novel data taking mode, the INTT recorded continuously all hits during a data taking period. This allows to record all $p + p$ collision events. In conventional "triggered-mode," only event that fires a "trigger" is recorded. Since the maximum trigger rate (15 kHz) of sPHENIX is much smaller than the minimum-bias $p + p$ collision rate (more than 1 MHz), most of the $p + p$ collisions are not recorded in the "trigger" mode.

Figure 6 shows that the INTT was working well in the streaming read-out mode. The left panel of Fig. 6 demonstrates that the INTT worked well in the streaming read-out mode. This figure shows the number of recorded hits in INTT in each beam crossing timing (BCO). The red histogram at BCO = 45 corresponds to the timing of a trigger. In this triggered event, more than 250 INTT hits are recorded, reflecting that a violent $p + p$ collision event took place in the beam crossing. In addition to this triggered event, there are several spikes indicating more than 100 INTT hits. Each of these spikes indicates that a $p + p$ collision event actually occurred in the beam crossing, but it doesn't produce a trigger. The INTT in the streaming mode recorded these untriggered events. The right panel of Fig. 6 showed the z-coordinate (along the beam) of reconstructed vertex by the INTT with 0 mrad beam crossing angle (blue) and with 1.5 mrad beam crossing angle (dark yellow). Reduction of Zvtx distribution with finite crossing angle is observed by the INTT.

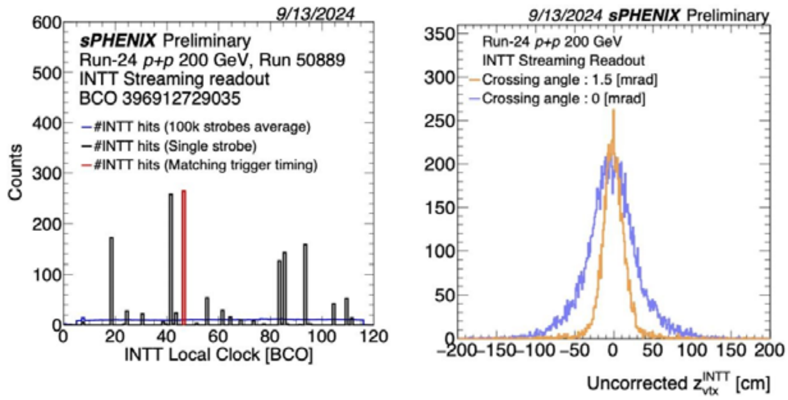

Fig. 6. The left panel shows timing of INTT hits recorded in streaming mode. See the text for the explanation. The right panel shows the distribution of $p + p$ collision vertex position Z_{vtx} reconstructed by the INTT with beam crossing angle 0 mrad (blue) and 1.5 mrad (dark yellow).

Members

Group Leader
Yasuyuki AKIBA

RBRC Researchers
Yuji GOTO
Maureen MCNEILL-SHEA
Itaru NAKAGAWA
Ralf SEIDL

Special Temporary Research Scientist
Yasushi WATANABE

Senior Visiting Scientist
Rachid NOUICER (BNL)

Visiting Scientists
Minho KIM (Argonne Nat'l Lab.)
Takao SAKAGUCHI (BNL)
Milan STOJANOVIC (Purdue Univ.)

Student Trainees
Joseph T. BERTAUX (Purdue Univ.)
Jaein HWANG (Korea Univ.)

List of Publications & Presentations

Publications

[Original Papers]

N. J. Abdulameer *et al.*, "Disentangling centrality bias and final-state effects in the produciton of high p_T Neutral Pions Using Direct Photon in d + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV," Phys. Rev. Lett. **134**, 022302 (2025).

N. J. Abdulameer *et al.*, "Centrality dependence of Levy-stable two-pion Bose-Einstein correlations in $\sqrt{s_{NN}}$ = 200 GeV Au + Au collisions," Phys. Rev. C **110**, 064909 (2024).

N. J. Abdulameer *et al.*, "Jet modification via π^0-hadron correlations in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV," Phys. Rev. C **110**, 044901 (2024).

N. J. Abdulameer *et al.*, "Identified charged-hadron production in p + Al, ^{3}He + Au, and Cu + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and in U + U collisions at $\sqrt{s_{NN}}$ = 193 GeV," Phys. Rev. C **109**, 054910 (2024).

N. J. Abdulameer *et al.*, "Nonprompt direct-photon production in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV," Phys. Rev. C **109**, 044912 (2024).

N. J. Abdulameer *et al.*, "Charm- and bottom-quark production in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV," Phys. Rev. C **109**, 044907 (2024).

M. H. Kim *et al.*, "Measurement of the transverse single-spin asymmetry for forward neutron production in a wide p_T range in polarized $p + p$ collisions at $\sqrt{s}$ = 510 GeV," Phys. Rev. D **109**, 012003 (2024).

Awards

Cheng-Wei ShihPoster Presentation Award in "The 12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions."

Cheng-Wei ShihThe Association of Asia Pacific Physical Societies (AAPPS) Award