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 are now studying the property of the QGP. 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 $c \to e$.

PHENIX completed its data taking in 2016, and construction of a new detector, sPHENIX, as upgrade of PHENIX was started. sPHENIX will measure jets, photons, and Upsilon particles and will complete the scientific mission of RHIC. We constructed a 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 will start taking physics data in the 2024 polarized $p + p$ run.

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 (Experimental Group Leader) 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. 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

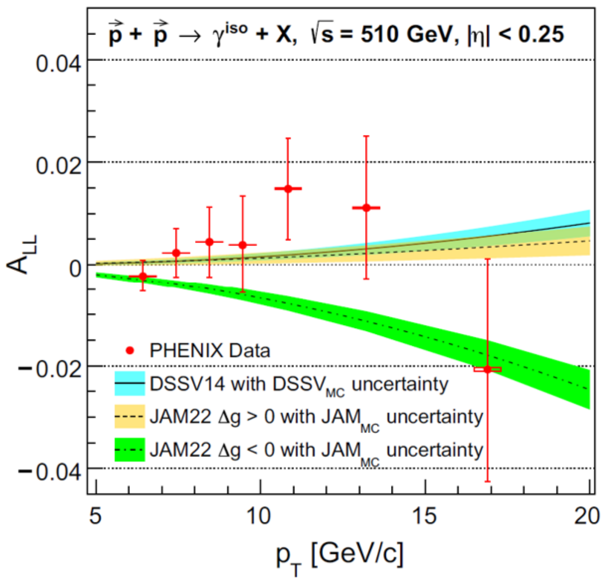

Fig. 1. The double spin asymmetry A_{LL} of direct photon is compared with theory predictions. The theories assuming that the gluon spin is aligned in opposite direction of the proton spin is excluded. Published in Phys. Rev. Lett. **130**, 251901 (2023).

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 3400 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_{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.

We constructed VTX detector of PHENIX. VTX is a 4-layer silicon tracker and it is the main device for measurement of charm and bottom quark production in PHENIX. VTX took data from the 2011 to 2016 when PHENIX completed data taking. PHENIX recorded high statistics Au + Au data, approximately 20 billion events with VTX in each of the 2014 run and the 2016 run. Figure 2 show nuclear modification factor R_{AA} of single electrons from $b \to e$ decays and $c \to e$ decays in Au + Au collisions measured in RUN14 in the most central (0–10%) collisions and peripheral (40–60%) collisions. One can see clear difference between the R_{AA} of $b \to e$ (shown in blue curves) and $c \to e$ (green curves). This indicates difference of energy loss of b quark and c quark in the QGP medium. A paper reporting these results was published in Physical Review C.

PHENIX measured direct photons in wide p_T range in Au + Au collisions. A paper of high statistics measurement from the 2014

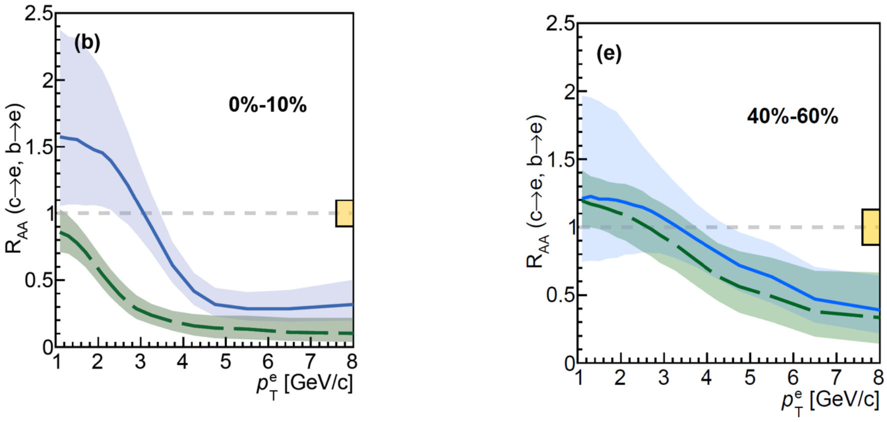

Fig. 2. Nuclear modification factor R_{AA} of b and c decay electrons in central (left) and peripheral (right) Au + Au collisions at 200 GeV. Published in Phys. Rev. C **109**, 044907 (2024).

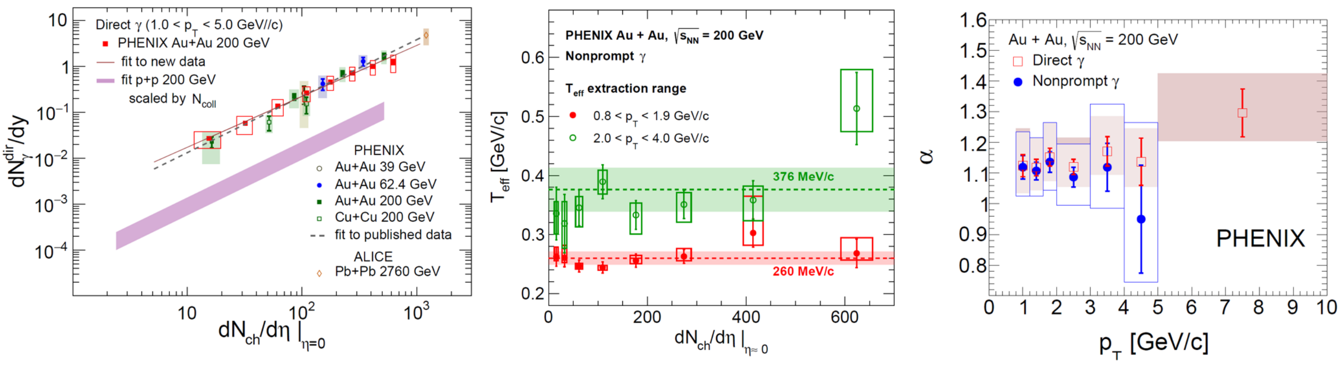

Fig. 3. Direct photon measurements in Au + Au collisions at 200 GeV. Published in Phys. Rev. C **109**, 044912 (2024).

run was published in Physical Review C.

(3) sPHENIX INTT detector

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 submitted for publication to Physical Review C.

PHENIX completed its data taking in 2016. We constructed intermediate silicon tracker INTT for sPHENIX, a new experiment at RHIC that will start taking data in 2023. 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. Figure 5 shows some performance plots obtained from the run. In the left panel, correlation of the number of hits in the INTT and the charge measured in the MBD (trigger detector) is shown. The clear correlation between the two detector indicates that both detectors were working well. The right panel shows the collision vertex position reconstructed from the tracklets of the INTT. sPHENIX will start taking physics data of polarized $p + p$ collisions from the spring 2024.

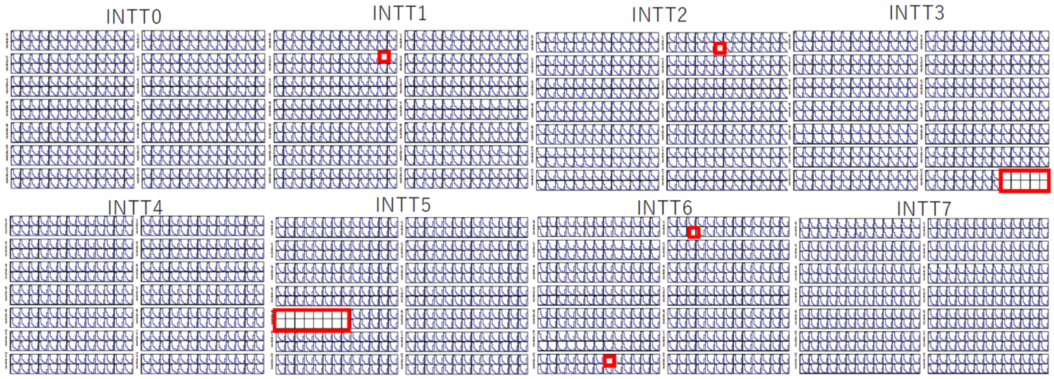

Fig. 4. ADC distributions of read-out chips of INTT detector. Red part shows the dead chips. 99% of the detector is working.

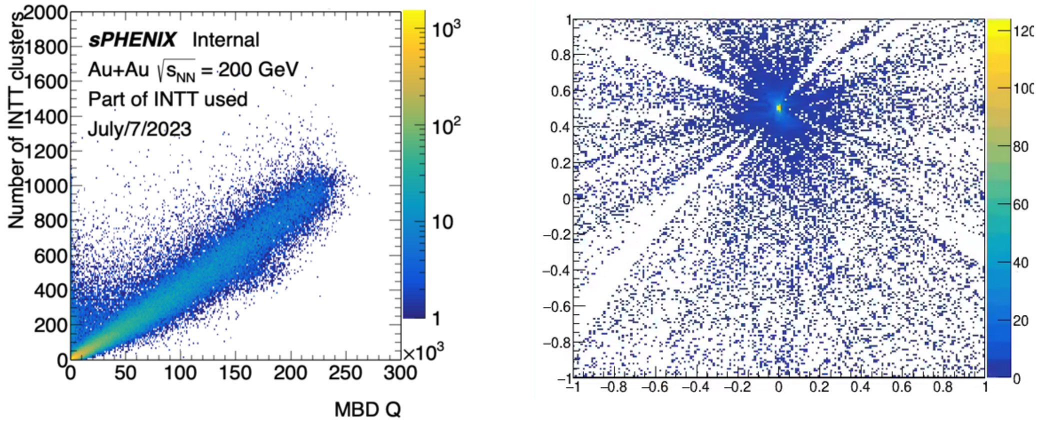

Fig. 5. ADC distributions of read-out chips of INTT detector. Red part show the dead chips. 99% of the detector is working.

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List of Publications & Presentations

Publications

[Original Papers]

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).

N. J. Abdulameer *et al.*, "Transverse signle-spin asymmetry of charged hadrons at forward and backward rapidity in polarized $p + p$, p + Al, and p + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV", Phys. Rev. D **108**, 072016 (2023).

N. J. Abdulameer *et al.*, "Measurement of direct-photon cross sectin and double-helicity asymmetry at $\sqrt{s}$ = 510 GeV in $p + p$ collisions", Phys. Rev. Lett. **130**, 251901 (2023).

N. J. Abdulameer *et al.*, "Transverse single-spin asymmetry of midrapidity π^0 and η mesons in p + Au and p + Al collisions at $\sqrt{s_{NN}}$ = 200 GeV", Phys. Rev. D **107**, 112004 (2023).

N. J. Abdulameer *et al.*, "Improving constraints oon gluon spin-momentum correlations in transversely polarized protons vias midrapidity open-heavy flavor electrons in $p + p$ collisions at $\sqrt{s}$ = 200 GeV", Phys. Rev. D **107**, 052012 (2023).

N. J. Abdulameer *et al.*, "Low p_{T} direct-photon production in Au + Au collisions at $\sqrt{s_{NN}}$ = 39 and 62.4 GeV", Phys. Rev. C **107**, 024914 (2023).

N. J. Abdulameer *et al.*, "Measurement of second-harmonic Fourier coefficients from azimuthal anisotropies in $p + p$, p + Au, d + Au, and ^{3}He + Au at $\sqrt{s_{NN}}$ = 200 GeV", Phys. Rev. C **107**, 024907 (2023).

Award

Yuji Goto and Hideto Enyo, RIKEN BAIHOU award for measurement of double spin asymmetry of direct photon and determination of gluon spin alignment.