Subnuclear System Research Division
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. Recent 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 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 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 matter. Recently, we have measured direct photons in Au + Au collisions for $1 < p_{\rm T} < 3$ 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. Both of the upgrade is now complete. 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 $p_{\rm T}$, but the suppression is weaker than that of charm decay electron for $3 < p_{\rm T} < 4$ GeV/c. We have recorded 10 times as much Au + Au collisions data in each of the 2014 run and 2016 run. The large dataset will produce definitive results on heavy quark production at RHIC.

PHENIX completed its data taking in 2016. We are now working on R&D of intermediate silicon tracker INTT for sPHENIX, a new experiment at RHIC that will be installed in the PHENIX IR.

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. From 2016, Y. Akiba (Experimental Group Leader) is the Spokesperson of PHENIX experiment.

(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 (A_{LL}) 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 gluons.

Figure 1 and Fig. 2 shows most recent spin physics measurement with PHENIX from our group. Figure 1 show the A_{LL} of charged pions in polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV and Fig. 2 shows $A_N(p_T)$ of very forward neutron. These results are published in Physical Review D.

Members of our group also participate in RHICf experiment, a small experiment at RHIC to measure particle production and single spin asymmetry of particles produced at very forward direction. Figure 3 shows $A_N(x_F)$ of very forward π^0 measured by RHICf compared with other experiments, published in Physical Review Letters. This is the first published results of RHICf experiment.

(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

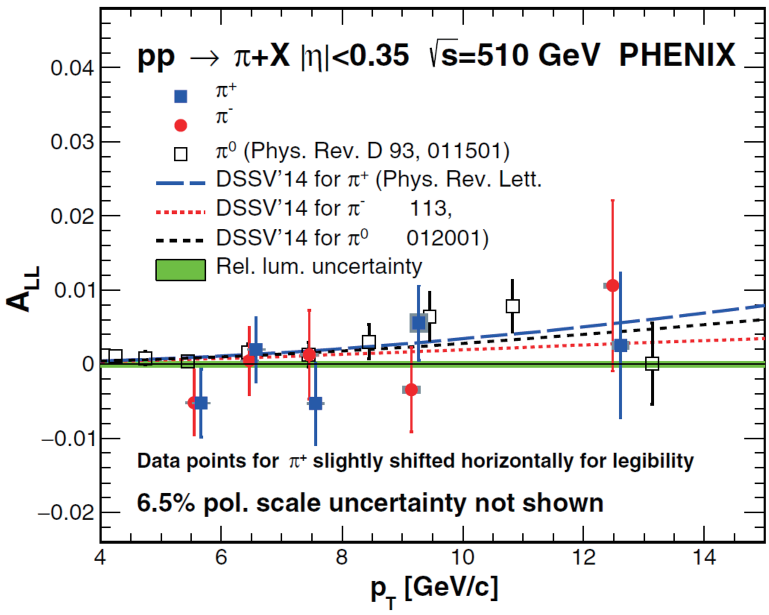

Fig. 1. Double spin asymmetry A_{LL} of charged pions in midrapidity in $p + p$ collisions at $\sqrt{5} = 510$ GeV compared with theoretical predictions of perturbative QCD. Published in Phys. Rev. D 102, 032001 (2020).

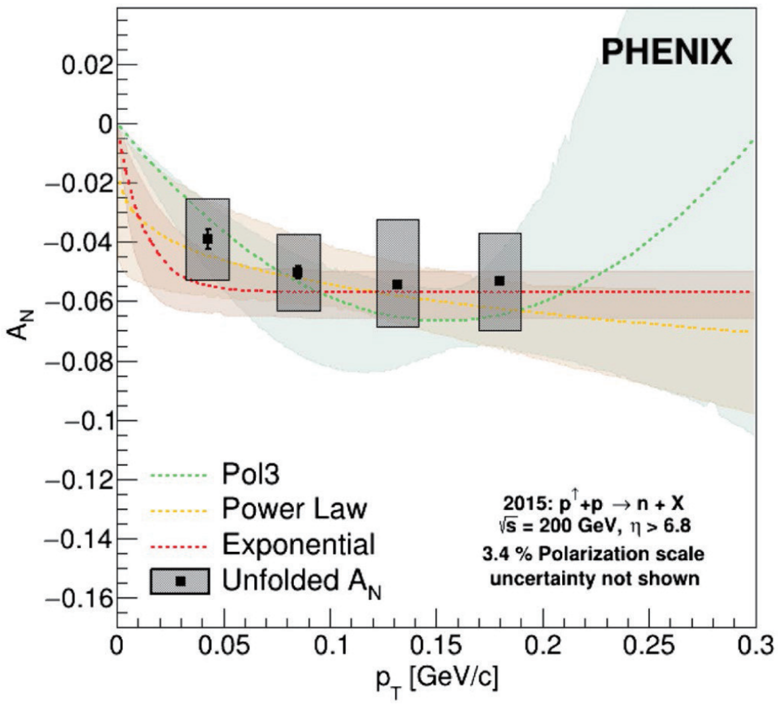

Fig. 2. Pt dependence of single spin asymmetry A_N of very forward neutron in $p + p$. Published in Phys. Rev. D 103, 032007 (2021).

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 3000 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

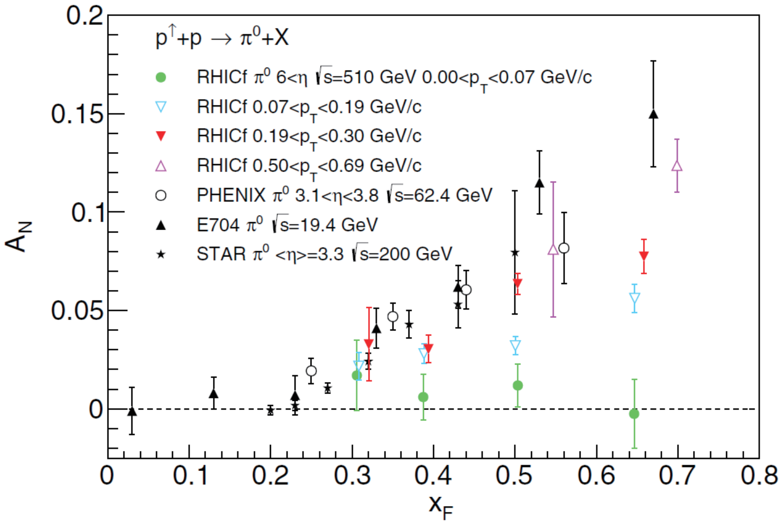

Fig. 3. $A_N(x_F)$ of very forward π^0 measured by RHICf experiment is compared with other data. Published in Phys. Rev. Lett. 124, 252501 (2020).

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 $T_{\text{init}} = 300$ 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.

(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 and A. Deshpande is the strip system 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 large dataset will produce definitive results on heavy quark production at RHIC. A preliminary results on the elliptic flow strength v_2 of $b \to e$ and $c \to e$ has been presented in Quark Matter 2018 conference. 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 is in preparation.

PHENIX completed its data taking in 2016. We are now working on construction of intermediate silicon tracker INTT for sPHENIX, a new experiment at RHIC that will start taking data in 2023. Figure 4 shows snapshot of INTT construction work. INTT consists of 56 ladders of silicon detector. So far approximately 30 ladders are produced. INTT will be completed in JFY2021.

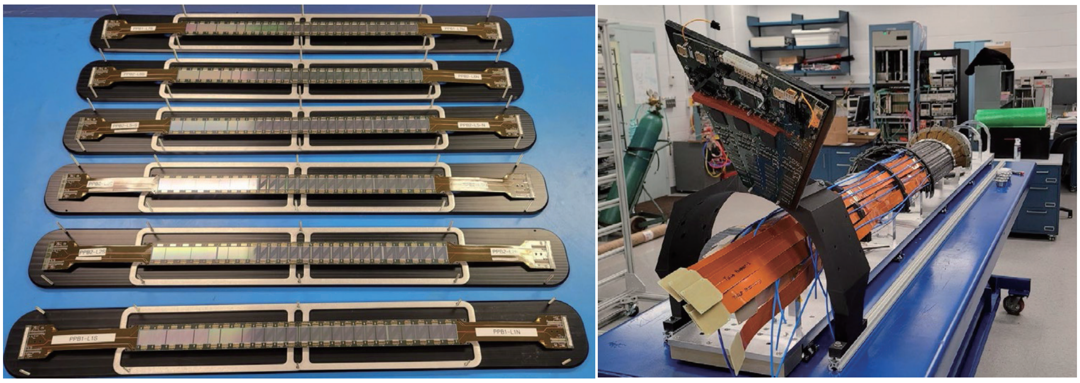

Fig. 4. Left panel shows completed INTT ladders. Right panel shows the test assembly of a half barrel of INTT detector.

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List of Publications & Presentations

Publications

[Original Papers]

U. A. Acharya *et al.*, "Transverse sngle-spn asymmetries of midrapidty π^0 and η mesons in polarized $p + p$ collisions at $\sqrt{s} = 200$ GeV," Phys. Rev. D **103**, 052009 (2021).

U. A. Acharya *et al.*, "Transverse momentum dependent forward neutron ssingle spin asymmetries in transversely polarized $p+$ collisions at $\sqrt{s} = 200$ GeV," Phys. Rev. D **103**, 032007 (2021).

U. A. Acharya *et al.*, "Nuclear dependence of the transverse single-spin asymmetry in the production of π^0 and η mesons in U+U collisions at $\sqrt{s_{NN}} = 192$ GeV," Phys. Rev. C **102**, 064905 (2020).

A. Adare *et al.*, "Production of $b\bar{b}$ at forward rapidity in $p + p$ collisions at $\sqrt{s} = 510$ GeV," Phys. Rev. D **102**, 092002 (2020).

U. A. Acharya *et al.*, "Polarization and cross section of J/ψ production in $p + p$ collisions at $\sqrt{s} = 510$ GeV," Phys. Rev. D **102**, 072008 (2020).

M. H. Kim *et al.*, "Transverse single-pin aymmetry for very forward neutral pion production in polarized $p + p$ collisions at $\sqrt{s}$ = 510 GeV," Phys. Rev. Lett. **124**, 252501 (2020).

U. A. Acharya *et al.*, "Measurement of jet-medium nteractinos via direct photon-hadron correlations in Au + Au and d + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV," Phys. Rev. C **102**, 054910 (2020).

U. A. Acharya *et al.*, "Measurement of charged pion double spin asymmetries at midrapidity in longitudinally polarized $p + p$ collisions at $\sqrt{s}$ = 510 GeV," Phys. Rev. D **102**, 032001 (2020).

U. A. Acharya *et al.*, "J/ψ nd $\psi(2S)$ production at forward rapidity n $p + p$ collion at $\sqrt{s}$ = 510 GeV," Phys. Rev. D **101**, 052006 (2020).

U. A. Acharya *et al.*, "Measurement of J/ψ at forward and backward rapidity in p_p, p + Al, p + Au and ^{3}He + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV," Phys. Rev. C **101**, 014902 (2020).

C. Aidala *et al.*, "Nuclear-modification factor of charged hadrons at forward and backward rapidty in p + Al and p + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV," Phys. Rev. C **101**, 034910 (2020).

Presentations

[International Conferences/Workshops]

M. Connors (poster), "Jets modification with two-particle correlations in Au+Au collisions at PHENIX," 10th international conference on Hard and Electromagnetc Probes of High Energy Nuclear Collisions (Hard Probe 2020) (Online) May 31–June 5, 2020.

T. Hachiya (poster), "PHENIX results on quark flavor dependence of low in AuAu colliisions," 10th international conference on Hard and Electromagnetc Probes of High Energy Nuclear Collisions (Hard Probe 2020) (Online) May 31–June 5, 2020.

Press Releases

New research deepens mystery of particle generation in proton collisions, RIKEN, June 23, 2020.