PHYSICS at PHENIX, 15 years of discoveries

PHENIX: Beyond 15 years of discovery

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Introduction

The PHENIX experiment at Brookhaven National Laboratory’s Relativistic Heavy Ion Collider (RHIC) was designed to uncover properties of the quark–gluon plasma (QGP) via rare penetrating probes. Over the past 15 years, the collaboration has delivered on its promised measurements, often with exciting results beyond those originally foreseen. That the QGP behaves as a nearly perfect fluid and that non-photonic electrons are substantially suppressed has led to the use of heavy quarks as probes of the medium. The PHENIX silicon vertex detectors are opening a new arena for QGP studies, and the MPC-EX, a novel forward calorimeter with silicon readout, accesses low-χ physics via direct photons with unprecedented precision. PHENIX has proposed sPHENIX, a major upgrade using the recently acquired BaBar solenoid and full calorimetric coverage and high rate capabilities. sPHENIX will reconstruct jets and extend observables to higher transverse momentum, where comparisons to results from the Large Hadron Collider (LHC) heavy-ion program will provide the most insightful. Following the RHIC program, the nuclear physics community has identified an electron ion collider (EIC) as crucial to the next generation of QCD investigations. The BaBar magnet and sPHENIX calorimetry will be an excellent foundation for a new collaborative pursuit of discovery.

Subject Index

C20, D30, D31, D33
with the selection aimed at seeing how these paradigm-shifting measurements have given us a road map to future discoveries.

**Knowledge gained points the path forward**

A common picture of heavy-ion collisions prior to the availability of RHIC data was of a rather static QGP consisting of a weakly interacting gas of quarks and gluons. One would be able to glean information about the QGP via penetrating probes (fast partons moving through the system or direct photons giving an image of the initial configuration), as these probes were not part of the equilibrated medium. There was also significant emphasis on signals of phase transitions, as questions of the order of the transition remained open. Very early in the RHIC program, it was clear that the QGP was anything but static or weakly interacting. Measurements from all four RHIC experiments—BRAHMS, PHENIX, PHOBOS, and STAR—indicated strong collective behavior that was only describable in terms of nearly inviscid hydrodynamics. By 2005, there was already a major paradigm shift and the QGP was now the perfect fluid; see, e.g., Ref. [4].

Although PHENIX was designed to focus on the penetrating probes, through ingenuity (e.g., using the beam–beam counters to measure reaction plane) and small coverage detectors (the fast time-of-flight), key constraints on the perfect fluid were accurately measured [5]. The experiment also found the expected suppression of fast partons traversing the medium, referred to as jet quenching [6]. First measurements of non-photonic electrons from the decay of charm and beauty quarks also indicated large modifications in the medium [7]. A new picture of the QGP was beginning to emerge.

Some of these are clear examples of exactly what PHENIX was designed to measure and others are surprises reflecting the changing landscape in our theoretical understanding of the QGP and the ingenuity of the collaboration. Another theme that emerged was the understanding of how critical it was to couple this discovery physics with sophisticated quantitative modeling in order to be able to extract medium properties [8].

**Heavy-quark probes**

The use of heavy quarks as probes of the QGP has emerged as one of the most important physics observables. Over a decade ago it was proposed that, instead of just probing the QGP, perhaps the heavy quarks approached equilibrium and flowed with the perfect fluid [9]. As shown in Fig. 1, more precise measurements showed not only a suppression of high transverse momentum electrons coming from the semi-leptonic decays of $D$ and $B$ mesons, but also strong elliptic flow [10]. These measurements were particularly surprising as the suppression was seen to persist even at the highest transverse momenta, where the electron yields were expected to be dominated by beauty quark decays.

These surprising results led to a set of RHIC upgrades to measure charm and beauty more directly and with the ability to separate the two contributions. The PHENIX collaboration constructed two silicon vertex detectors: a barrel VTX to match identified electrons with displaced vertices, and an FVTX to do the same for identified forward-rapidity muons. The VTX (FVTX) had its first commissioning operation in 2011 (2012) and this year, 2014, we are taking a large Au + Au at $\sqrt{s_{NN}} = 200$ GeV data set to directly answer the question of what happens to charm and beauty quarks in the QGP. A projection for utilizing the VTX results from the 2014 data sample to unfold back to a $D$ and $B$ meson spectrum is shown in Fig. 2.

Recent measurements of reconstructed $D$ mesons from STAR [11] and ALICE [12] give further credence to the idea that charm quarks do thermalize, at least at lower momentum. This makes the
Fig. 1. Two results showing the behavior of non-photonic electrons in nuclear collisions. (Upper panel) The nuclear modification factor, $R_{AA}$, for non-photonic electrons vs $p_T$ showing suppression that is similar in magnitude to that of light hadrons. (Lower panel) The elliptic flow coefficient, $v_2$, vs $p_T$.

PHENIX results at mid- and forward-rapidity all the more important with the full separation of charm and beauty over a broad momentum range. The VTX and FVTX also open up many new exciting physics possibilities including extending the PHENIX quarkonia program [13–15], back-to-back heavy-quark correlations, and more. We are excited to learn the true underlying physics of heavy quarks.

**Geometry engineering and small QGPs**

In 2003, there was a critical control experiment run at RHIC with $d + Au$ collisions. The first results showing the relative suppression of hadron yields in $Au + Au$ collisions were obtained at relatively
low transverse momentum [6], and there was speculation that initial-state gluon saturation physics might be responsible for the effect rather than jet quenching in the quark–gluon plasma. The measurement in \( d + A \) collisions [17] showing final-state hadron yields that were not suppressed appeared to settle the issue, and the paradigm of no medium or QGP in small systems seemed settled.

However, the high-statistics 2008 run of \( d + A u \) at RHIC started to reveal cracks in this simple picture. The yield of non-photonic electrons was seen to be enhanced (i.e., \( R_{dAu} > 1 \)) in central \( d + Au \) collisions [18]. These results are very challenging to explain in terms of cold nuclear matter effects and may find a resolution in a picture of charm quarks being pushed around even in a small QGP [19]. The yield of \( J/\psi \) is suppressed in \( d + Au \) collisions, with low-\( x \) gluon shadowing and breakup providing explanations. However, the recent measurement of significantly larger \( \psi' \) suppression again raises the question of final-state effects [15]. In a great example of the constructive interplay between RHIC and LHC (Large Hadron Collider) data, the \( p + Pb \) run at the LHC shows strong hints of collective effects [20–22]. The new data have sparked an exciting debate within the field with successful qualitative descriptions being given by scenarios involving glasma diagrams from the initial state and by hydrodynamics from the final state (Fig. 3). This led PHENIX to once again utilize the detector in new ways and discover that the “speculated to be” flow was larger at RHIC in \( d + Au \) compared to flow measured at the LHC in \( p + Pb \). We appear to be in the midst of another paradigm shift regarding the minimum size necessary for rapid equilibration and QGP formation.

The PHENIX collaboration has proposed utilizing once again the great flexibility of RHIC, in this case to collide \( 3He + Au \). Shown in Fig. 4 is an example of hydrodynamic modeling of such collisions [23]. The unique geometry should lead to substantial triangular flow if rapid equilibration is achieved followed by perfect fluid flow. We are excited to add these measurements to the world’s data set.

**Best probes of the initial state**

In order to understand the QGP, one needs to have a clear picture of the initial hadronic state, especially that of a heavy nucleus. Existing results already tell us that the initial state of a nucleus is not just a scaled-up version of the initial state of a proton. For instance, the European muon collaboration effect, which manifests itself as a strong depletion in \( F_2(A)/F_2(D) \) for \( x \sim 0.7 \) [24], shows structure

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**Fig. 3.** The elliptic flow coefficient, \( v_2 \), vs \( p_T \) in \( d + Au \) collisions [16]. Also shown are several hydrodynamic calculations.
in the nuclear initial state not present in the proton (or deuteron) wavefunction. The hadronic wavefunction becomes increasingly gluon-dominated at lower and lower values of Bjorken $x$, a trend that cannot continue unabated. The regulation, or saturation, of gluon density in the initial state is best observed through probes sensitive to the very lowest $x$ partons in the nucleus. PHENIX has employed forward–forward correlations [25] in its muon-piston calorimeters (MPC) to look for evidence of saturation. Figure 5 shows $J_{dA}$, the ratio of the yield of forward di-hadron pairs in $d + Au$ to the same yield, appropriately scaled, in $p + p$ collisions. In peripheral $d + Au$, $J_{dA}$ shows no dependence on $x$ (determined through a proxy $x_{\text{frag}}$) and has a value consistent with one. Central $d + Au$ collisions, on the other hand, deviate strongly from one at the lowest values of $x$.

The cleanest probe of low-$x$ processes in hadron–hadron collisions involves direct real or virtual photons since there are no final-state interactions. The MPC-EX adds precision separation of single photons from photon pairs via decays. The detector configuration is shown in Fig. 6. Measurements of single photons compared between $p + p$ and $p + A$ collisions are projected to constrain the nuclear modified gluon parton distribution function, as shown in Fig. 7. In addition, with transversely polarized proton–proton collisions, the MPC-EX provides key information with tantalizing hints at orbital angular motion of partons in the proton. In yet another prime example of the out-of-the-box thinking by theorists and the flexibility of RHIC, collisions of polarized protons on nuclei are planned in 2015–2016 and give a completely unique connection to gluon saturation physics [26]. This program
Fig. 6. The PHENIX detector (upper right), showing the location of the existing muon-piston calorimeters inside the muon magnet piston. The MPC-EX (upper left) will consist of eight measurement layers of absorber, sensors, and readout. The “minipad” sensors themselves (lower right) will consist of a readout card bonded to an Si sensor. The orientation of the long direction of the minipads will alternate between layers.

Fig. 7. Eskola, Paukkunen and Salgado (EPS09) nuclear parton distribution functions for gluons in Au nuclei [27]. The gray range shows the current band consistent with existing data. The dark blue and light blue bands show the one and two standard deviation constraints from the direct photon measurements proposed here.
Fig. 8. (Left) The ratio of shear viscosity to entropy density, $\eta/s$, normalized by the conjectured Kovtun, Starinets and Son (KSS) bound as a function of the reduced temperature, $T/T_c$, for water, nitrogen, and helium [28]. The cusp for helium as shown corresponds to the case at the critical pressure. (Right) Calculation of hot QCD matter (quark–gluon plasma) for a weakly coupled system. Dashed lines show the scale dependence of the perturbative calculation.

over the next few years provides very complementary information to that projected in the longer-term future from an electron ion collider.

**Next phase: sPHENIX**

Full understanding of the physics of the quark–gluon plasma requires observables that can probe the dynamics of the medium. PHENIX has employed several of these probes—direct photons, quarkonia, high $p_T$ hadrons—very successfully to provide a partial picture of these dynamics. The heavy-ion physics program at the LHC has shown the value of fully reconstructed jets for this investigation [29,30]. The strongly coupled quark–gluon plasma undergoes a phase transformation in the vicinity of temperatures achieved in RHIC collisions, which can cause rapid changes in the properties of the medium, as shown in Fig. 8.

Extending to RHIC the capability of measuring fully reconstructed jets is therefore key to advancing the physics understanding of the medium. The questions we aim to answer include the following:

- How does a partonic shower develop and propagate in the quark–gluon plasma?
- How does one reconcile the observed strongly coupled quark–gluon plasma with the asymptotically free theory of quarks and gluons?
- What are the dynamical changes in the quark–gluon plasma in terms of quasiparticles and excitations as a function of temperature?
- How sharp is the transition of the quark–gluon plasma from the most strongly coupled regime near $T_c$ to a weakly coupled system of partons known to emerge at asymptotically high temperatures?

The PHENIX collaboration is planning a major upgrade to provide these capabilities for the first time at RHIC. Figure 9 (left) shows an engineering rendering of sPHENIX, consisting of a 1.5 T superconducting solenoid (the BaBar solenoid), large acceptance electromagnetic and hadronic calorimetry, and tracking. The hadronic calorimetry is a novel design comprising tilted steel plates...
parallel to the beam line with interleaved scintillator embedded with wavelength-shifting fibers that are subsequently read out with silicon photomultipliers. This design with the steel being continuous along the magnet allows the detector to also serve as the magnetic field flux return. The electromagnetic calorimeter is envisioned as a very compact design with tungsten absorber and again a fiber readout with silicon photomultipliers.

One needs sufficient jet rates in order to carry out the sPHENIX physics program. Figure 9 (right) shows cumulative jet rates above a specified minimum $p_T$, as determined in a next-to-leading order (NLO) pQCD calculation (W. Vogelsang, private communication). In a nominal 20 week RHIC Au + Au run at $\sqrt{s_{NN}} = 200$ GeV, one would see $10^6$ jets above 30 GeV, and the dijet partner of 80% of these jets would be contained in an acceptance of $|\eta| < 1$. In addition, there would be $10^4$ direct photons above 20 GeV.

The full calorimetric coverage and high rate capability enables this comprehensive jet physics program. The large acceptance and additional charged particle tracking makes sPHENIX the tool for a much broader program, including measurements of the three Upsilon states sensitive to the medium temperature, open heavy-flavor measurements, direct photons and neutral pions at high transverse momentum, global event shape analyses, and more. As with the previous experience of the PHENIX collaboration, a powerful well designed detector will often lead to surprising things.

Next QCD facility: Electron ion collider

As the RHIC program matures, the role of precision measurement becomes increasingly important. The natural direction to pursue, following the hadron–hadron program, is to augment RHIC with an electron accelerator and provide electron–hadron collisions in a facility called eRHIC. The advantage of these collisions is the precise knowledge of the leptonic part of the initial state. PHENIX plans to further evolve its detector, from sPHENIX to instrumentation suitable for measuring eRHIC collisions.
Fig. 10. The ePHENIX detector in the PHENIX experimental hall.

Figure 10 shows an engineering rendering of the detector from a letter of intent [31] with additional capabilities for measuring the scattered electrons and hadrons. The configuration utilizes the BaBar solenoid together with shaping of return flux to provide adequate bending power at forward angles. There is key R&D underway to develop a RICH detector with the erenkov photons reflected and read out entirely within the magnetic volume to maintain hermeticity and to keep within tight spatial constraints at ±4.5 m for the interaction region with accelerator magnets.

Fig. 11. The projected reduction in the uncertainty (black) on the gluon longitudinal spin distribution based on simulated Pythia events corresponding to an integrated luminosity of 10 fb$^{-1}$ at a 10 GeV × 250 GeV beam energy configuration. A 1% systematic uncertainty in beam and target polarization is applied. The yellow area shows the uncertainty from current data based on the analysis in Ref. [32].
As a specific example of the performance from this powerful accelerator including polarization, the constraints on the quark and gluon spin contributions to the proton are shown in Fig. 11; see Ref. [31] for details.

Summary
As detailed in this journal edition and this article, the past decade of heavy-ion and spin physics at the Relativistic Heavy Ion Collider, and specifically for the PHENIX experiment, have been marked by discoveries and major paradigm shifts in our understanding of QCD matter. There is an exciting future of physics in the short, mid, and long terms with an evolution to the sPHENIX detector that may then serve as the foundation for a new collaboration at an electron ion collider. This program adds new capabilities with direction from past discoveries and is broad enough for new unexpected discoveries.

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