

PHENIX Overview

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Abstract. The PHENIX experiment at RHIC has accumulated a comprehensive dataset spanning a wide range of collision systems from small systems such as $p+p$ and $d+Au$ to large systems including Au+Au and U+U and a broad range of center-of-mass energies per nucleon pairs from 7.7 to 510 GeV. Utilizing these datasets, PHENIX has conducted systematic measurements of light- and heavy-flavor hadrons, direct photons, and jet-related observables. These measurements have yielded significant insights into the properties of the quark-gluon plasma and the proton spin structure. This paper presents a selection of recent results from the PHENIX experiment.

1 Introduction

The PHENIX experiment, conducted at the Relativistic Heavy Ion Collider (RHIC), is designed to investigate the properties of the quark-gluon plasma (QGP) and the spin structure of the proton. Over the past sixteen years, the experiment has collected extensive data across a wide range of collision systems, from small systems such as $p+p$ and $d+Au$ to large nuclei collisions including Au+Au and U+U, at center-of-mass energies from 7.7 to 200 GeV for heavy-ion collisions and up to 510 GeV for $p+p$ collisions.

During this period, the PHENIX experiment has produced a wide range of important results, including the observation of high p_T suppression for both light- and heavy-flavor hadrons, substantial elliptic flow signals, and evidence for QGP droplet formation in small-system collisions. Although PHENIX concluded data collection in 2016, the collaboration continues to actively analyze the extensive dataset. In this article, we present a brief overview of recent results reported at this conference as well as the other contributions from PHENIX [1–4].

2 Di-electron mass spectrum in $p + p$ collisions

The invariant mass spectrum of lepton pairs exhibits a complex structure and contains a wealth of information about the nature of QGP. In particular, the thermal radiation in the intermediate mass region ($1.1\text{-}2.7 \text{ GeV}/c^2$) is an important probe of the parton phase of the medium. However, this region is also subject to a large background contribution from semileptonic decays of the charm and bottom quarks. This component is statistically identified by measuring the distance of closest approach (DCA) with the PHENIX silicon vertex detector (VTX). In addition, background electrons originating from photon conversions are

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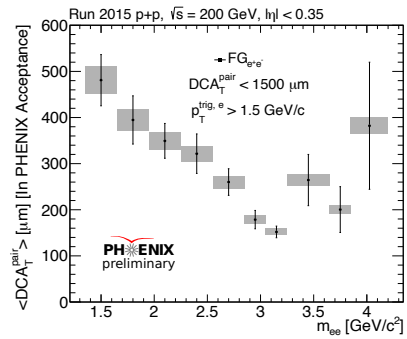
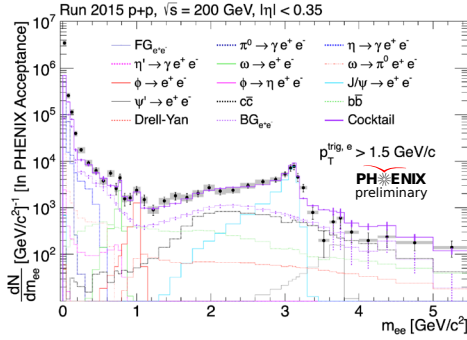


Figure 1. Invariant mass spectrum of di-electron pairs in $p + p$ collisions at $\sqrt{s} = 200$ GeV [4].

Figure 2. DCA as a function of the invariant mass [4].

effectively suppressed utilizing the VTX. Recently, a refined analysis technique has been developed to enhance the signal-to-background ratio in the $p + p$ dataset [4].

Figure 1 shows the invariant mass spectrum of di-electron pairs in $p + p$ collisions at $\sqrt{s} = 200$ GeV. By employing the newly developed analysis method, the statistical precision of the di-lepton measurement has been improved by one order of magnitude. The measured spectrum exhibits good agreement with the cocktail calculation, which includes contributions from photon conversions, Dalitz decays of light neutral mesons, open heavy-flavor (charm and bottom) decays, quarkonia, and Drell-Yan processes. Figure 2 shows the DCA as a function of the invariant mass. The DCA reaches a minimum near the J/ψ mass region and increases at lower masses due to the significant contribution from heavy-flavor decays. This behavior indicates that DCA information is effective in separating signal and background sources.

3 Nuclear modification in the small system collisions

The suppression of high p_T particle yields in the heavy-ion collisions was first observed as a signal of the QGP formation. In contrast, the absence of the suppression in small collision systems has also been observed, providing an essential baseline for comparison. The nuclear modification is quantified by the nuclear-modification factor ($R_{AA} = \frac{Y_{AA}}{N_{coll} Y_{pp}}$), where Y_{AA} and Y_{pp} are the particle yields in A+A and $p + p$ collisions, and N_{coll} is the number of binary collisions in A+A collisions. The value of N_{coll} is typically estimated using a Glauber model. However, in small collision systems, the event selection is biased by the presence of hard-scattering process, and the bias increases the uncertainty in the N_{coll} determination. To address this limitation, PHENIX has developed a novel, data-driven method to experimentally determine N_{coll}^{Exp} based on the ratio of high- p_T direct photon yields [5]. Figure 3 shows the R_{AA} of neutral pion yields as a function in N_{coll}^{Exp} in $d + A$ collisions [5]. A clear suppression is observed in the most central collisions, while the R_{AA} remains consistent with unity in peripheral events. The observed suppression in central collisions is qualitatively consistent with theoretical calculations incorporating parton energy loss in small collision systems [6, 7].

4 Heavy flavor flows and Jet modification in Au + Au collisions

Charm and bottom quarks experience distinct interactions with the QGP compared to light quarks because of their substantial masses. Therefore, the elliptic flow of heavy-flavor

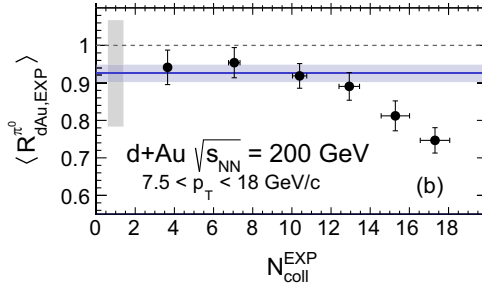


Figure 3. Nuclear modification factor of neutral pion yields as a function of N_{coll}^{Exp} [5].

hadrons is a particularly sensitive probe of the properties of QGP. Furthermore, since the QGP properties—such as temperature and pressure gradients— may exhibit rapidity dependence, measurements at the different rapidity enable systematic studies of the QGP’s space-time evolution and transport characteristics.

Figure 4 shows the elliptic flow parameter v_2 as a function of p_T of μ from heavy flavor decays at the forward rapidity [8]. The heavy flavor muon is consistent with heavy flavor electron v_2 at the mid-rapidity. This indicates that there is no strong longitudinal dependence of QGP. In contrast, a clear mass ordering of flow strength is found from the comparison with charged hadron v_2 at the forward rapidity. Figure 5 shows the v_2 of J/ψ at the forward rapidity [9]. It is found that the magnitude of the v_2 is consistent with zero. This result is clearly inconsistent with the model with coalescence of thermalized $c\bar{c}$.

The suppression of high p_T particles is a consequence of the energy loss of patrons due to their interaction with the QGP. PHENIX measured the $\Delta\phi$ angular correlation function between high p_T neutral-pion triggers and associated charged hadrons. The π^0 is used as jet proxies. The correlation functions are normalized by the number of trigger π^0 ’s. This is denoted as “per-trigger yields of the associated charged hadrons”. The difference of the per-trigger yields between A+A and $p+p$ collisions is utilized to study parton energy loss and the medium response in more detail [10]. Figure 6 shows the difference of the per-trigger yields as a function of $\Delta\phi$ at the away side of the triggered π^0 ’s. These panels correspond to the three different p_T intervals of the associated hadrons. A clear transition was observed from a low- p_T enhancement to a high- p_T suppression. This result is consistent with theoretical models that incorporate medium-induced responses to parton energy loss with particularly the formation of a hydrodynamic wake of soft particles.

5 Summary

The recent PHENIX results from $p+p$, $d+A$, and $Au+Au$ collisions provide additional insights into the properties of the QGP. In $p+p$ collisions at $\sqrt{s} = 200 \text{ GeV}$, the di-electron invariant mass spectrum demonstrates a significant improvement in the signal-to-background ratio utilizing the refined analysis method. In small collision systems, a clear suppression of high- p_T neutral pions was observed using an experimentally determined number of binary collisions. In $Au+Au$ collisions, a significant elliptic flow (v_2) of heavy-flavor hadrons is observed at forward rapidity, whereas the v_2 of J/ψ remains consistent with zero. Furthermore, two-particle correlation measurements reveal a distinct transition from low- p_T enhancement to high- p_T suppression. Collectively, these results place additional constraints on theoretical models and contribute to a deeper understanding of the QGP properties.

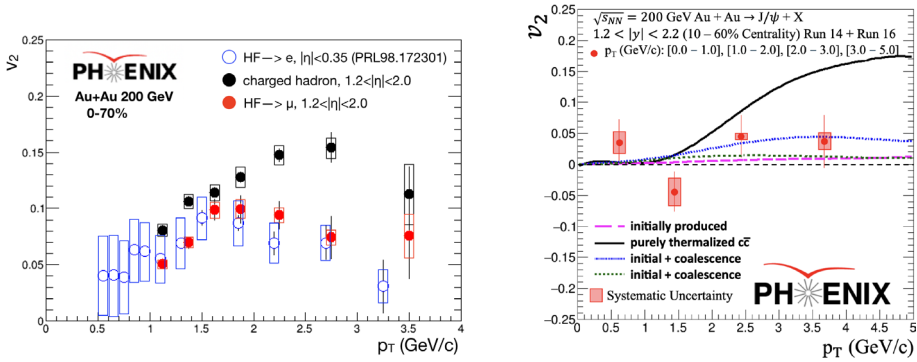


Figure 4. Heavy flavor muon v_2 as a function of p_T at the forward rapidity [8]. **Figure 5.** v_2 of J/ψ as a function of p_T at the forward rapidity [9].

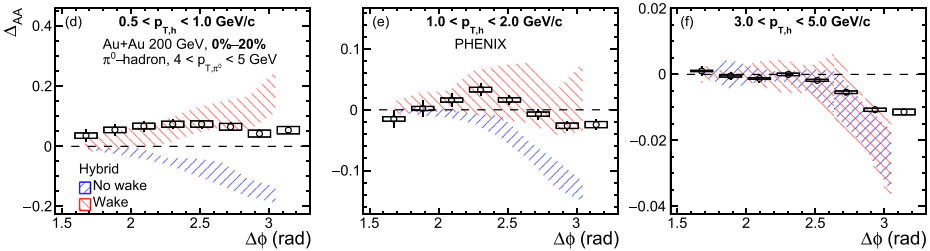


Figure 6. The difference of per-trigger yields of associated charged hadrons as a function of $\Delta\phi$ between A+A and $p+p$ collisions [10]. These panels corresponds to three difference p_T regions for the associated charged hadrons.

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