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sPHENIX measurements of collective behavior in small and large systems

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Abstract. sPHENIX, a next-generation detector at RHIC, completed commissioning in 2023–2024 and in 2024 recorded proton–proton (p+p) collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ and gold–gold (Au+Au) collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. With large pseudorapidity coverage, full azimuth, and dedicated forward systems, the detector enables precise measurements of bulk particle production in addition to the high-p_T jet and heavy-flavor program. These proceedings present the inaugural sPHENIX results for the transverse energy density $\mathrm{d}E_\mathrm{T}/\mathrm{d}\eta$ and charged-hadron multiplicity $\mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta$ in Au+Au collisions, along with initial performance studies of neutral-pion elliptic flow and second-order event-plane measurements and long-range two-particle correlations in high-multiplicity p+p events. Together, these results validate the performance of the tracking, calorimetry, and global event-characterization systems and confirm the readiness of sPHENIX for a comprehensive QGP program at RHIC.

1 Introduction

sPHENIX is a new experiment at the Relativistic Heavy Ion Collider (RHIC), designed to complete RHIC's mission of uncovering the microscopic structure and dynamics of the quark-gluon plasma (QGP) governed by quantum chromodynamics (QCD) [1, 2]. This paper presents the inaugural sPHENIX results on transverse energy density ($\mathrm{d}E_\mathrm{T}/\mathrm{d}\eta$) and charged hadron multiplicity ($\mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta$) in gold-gold (Au+Au) collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. Preliminary performance results are also highlighted, including measurements of the neutral pion elliptic flow coefficient ($v_2^{\pi^0}$) in Au+Au collisions, event plane determination using the sEPD, and long-range two-particle correlations in high-multiplicity proton-proton (p+p) collisions.

The sPHENIX detector, purpose-built to support the experiment's physics goals, comprises a superconducting solenoid magnet and three primary subsystems: tracking, calorimetry, and global event characterization. The tracking system includes a Monolithic Active Pixel Sensor-based Vertex Detector (MVTX), an Intermediate Silicon Tracker (INTT), a Time Projection Chamber (TPC), and a TPC-Outer Tracker, delivering precise vertexing, timing, and momentum measurements, crucial for high-precision bulk property measurements. The calorimeter system consists of electromagnetic (EMCal) and a two-layer hadronic (HCal) calorimeters, providing full azimuthal coverage at mid-rapidity and playing a central role in jet physics. Global event characterization is achieved using the Minimum Bias Detector (MBD) and the sPHENIX Event Plane Detector (sEPD). Two additional forward detectors, the Zero-Degree Calorimeter and the Shower Maximum Detector, further extend the detector capabilities of event triggering and proton beam polarity determination at RHIC.

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2 Bulk Property Measurements

Measurements of the bulk properties of the QGP serve a dual purpose: probing the defining characteristic of the QGP and benchmarking the performance and capabilities of the detector subsystems. Each sPHENIX result presented in this paper corresponds directly to the commissioning purposes of one of the three primary subsystems described in Section 1. In this section we first present single-particle production observables, followed by preliminary flow and correlation measurements.

2.1 sPHENIX Inaugural Physics Results: Transverse Energy density and Charged Hadron Multiplicity

2.1.1 Measurement of Transverse Energy density

A measurement of transverse energy, $\mathrm{d}E_\mathrm{T}/\mathrm{d}\eta$, is performed using the EMCal and HCal [5]. EMCal calibration follows the $v_2^{\pi^0}$ procedure, while HCal is calibrated by aligning the minimum ionizing particle peak from cosmic-ray muons in data and simulation. Corrections based on Monte Carlo (MC) simulations are applied to account for the full electromagnetic and hadronic calorimeter responses. As shown in the left plot of Figure 1, the EMCal and HCal yield remarkably consistent $\mathrm{d}E_\mathrm{T}/\mathrm{d}\eta$ measurements despite differing sensitivities and independent calibrations. The right plot of Figure 1 compares the average $\mathrm{d}E_\mathrm{T}/\mathrm{d}\eta$ per participant pair with previous PHENIX [6] and STAR [7] results and model predictions, showing consistency and improved precision in peripheral collisions. Among the models, AMPT offers the best agreement with the measurements. This marks the first such measurement at RHIC using an HCal and demonstrates the strong performance of the sPHENIX calorimeters, an essential step toward the jet physics program.

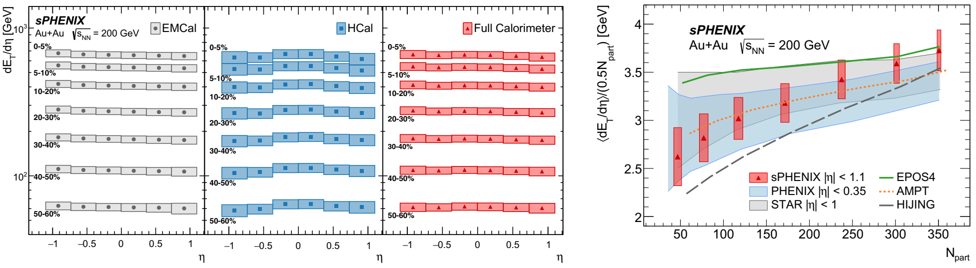

Figure 1. Left: $\mathrm{d}E_\mathrm{T}/\mathrm{d}\eta$ measurements in Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. Right: Measured $\mathrm{d}E_\mathrm{T}/\mathrm{d}\eta$ normalized by the number of participant pairs as a function of N_part.

2.1.2 Measurement of Charged Hadron Multiplicity

As a tracking-based standard candle measurement, charged hadron multiplicity $\mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta$ is measured using the INTT [8]. Data quality is ensured through a series of calibrations, including channel masking, hit timing selection, and ADC calibration. Charged particle yields are obtained by counting cluster pairs with small angular separation, corresponding to a minimum transverse momentum of 50 MeV, from the two INTT layers, with corrections for acceptance and efficiency derived from MC simulations. The left of Figure 2 shows the resulting $\mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta$ distributions as a function of η, consistent with PHOBOS results [9]. The average $\mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta$

normalized by the number of participant pairs (the right plot of Figure 2), shows a characteristic non-linear centrality dependence, consistent with previous RHIC experiments [6, 9, 10]. Among model predictions, HIJING provides the best overall agreement. This analysis highlights the performance of the INTT, essential for timing-based track association and will play a key role in future heavy-flavor measurements.

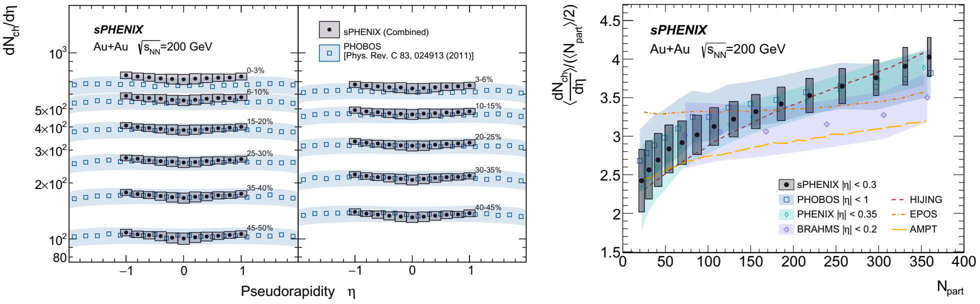

Figure 2. Left: $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ measurements as a function of η over the range of $|\eta| < 1.1$. Right: Measured $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ normalized by the number of participant pairs as a function of N_{part}.

2.2 Performance and Preliminary Results: Long-range Two-Particle Correlations, Event Plane Determination, and Neutral Pion Azimuthal Anisotropy

An effort to measure long-range two-particle correlations in high-multiplicity p+p collisions has been initiated using silicon tracklets built from MVTX and INTT. As shown in the left plot of Figure 3, no significant near-side enhancement is observed in the current dataset, though the correlation structure resembles those in previous measurements, validating the vertexing precision of MVTX and the timing capability of INTT. The ability to construct silicon tracklets is also essential to the track and high-level physics object reconstructions.

Event plane determination is a key component of anisotropic flow measurements. The right plot of Figure 3 presents the second-order event plane angle (Ψ_2) resolution, highlighting the sEPD's capability to provide a reliable event plane. This measurement will serve as a critical input to future jet and open heavy-flavor flow measurements, which are central pillars of the sPHENIX physics program.

The neutral pion elliptic flow coefficient $v_2^{\pi^0}$ is measured via the scalar product method utilizing the calorimeter system based on the initial Au+Au collision dataset [3]. Neutral pions are reconstructed via the $\pi^0 \to \gamma\gamma$ decay channel by pairing EMCal clusters, and the invariant mass of π^0 candidates is calculated. The energy scale, derived by fitting the resulting mass peak, is set to that in the simulation. The $v_2^{\pi^0}$ measured by sPHENIX is consistent with those previously reported by the PHENIX experiment [4], which analyzed a substantially larger dataset. This agreement affirms the performance of detector subsystems and calibration procedures.

3 Summary

sPHENIX's inaugural physics measurements and preliminary collective-phenomena results validate the performance of the tracking, calorimetry, and global event-characterization systems. All reported measurements are consistent with previous RHIC results. The $\mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta$

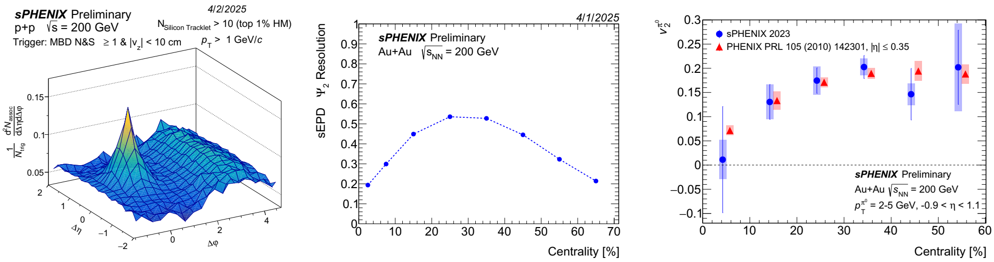

Figure 3. Left: two-particle correlation function in the top 1% of high multiplicity events in p+p collisions. Middle: The resolution of the Ψ_2 as a function of centrality. Right: $v_2^{\pi^0}$ as a function of centrality. For clarity, the sPHENIX and PHENIX data points are horizontally offset to the left and right, respectively.

measurements are best reproduced by the AMPT model, while the dN_{ch}/dη results more closely follow HIJING. This indicates that AMPT may overpredict transverse mass and momentum, whereas HIJING may underpredict them, possibly due to differences in the hadronization mechanisms implemented in the two models. Preliminary results for neutral-pion elliptic flow, event-plane resolution, and long-range correlations confirm the detector's readiness for precision studies of collective behavior. These results establish a baseline for the high-luminosity Au+Au run in 2025 and support the broader sPHENIX physics program.

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