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The sPHENIX Experiment at RHIC

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Abstract. The sPHENIX detector is the first new detector at RHIC in over twenty years and is designed to make precise jet and heavy flavor measurements to elucidate properties of the Quark-Gluon Plasma at very fine length scales. In 2023, sPHENIX took its first, commissioning run where it made two, established, standard-candle measurements: the π^0 v_2 and $dE_T/d\eta$ in 200 GeV Au + Au collisions. In 2024, sPHENIX took baseline 200 GeV $p + p$ data with calorimeter jet and photon triggers collecting over 100 pb^{-1} of calorimeter-only hard probes data. Additionally, the tracking detectors were successfully commissioned in both triggered and streaming readout mode, with the latter being a first-of-its-kind achievement at RHIC.

1 Introduction

The sPHENIX detector is a next-generation, jet and heavy-flavor detector at the Relativistic Heavy-Ion Collider (RHIC) located at Brookhaven National Laboratory (BNL) in Upton, New York. Designed with high p_T jet, photon, and other rare-probe measurements in mind, sPHENIX boasts a large, azimuthally hermetic acceptance, covering $|\eta| < 1.1$ and 2π in azimuth about the interaction point, along with a data acquisition system capable of running at over 10 kHz in a triggered readout mode. Additionally, the tracking subsystems are capable of taking data in a zero-bias streaming and extended readout configuration. The sPHENIX detector is designed for high-statistics, precision measurements that will offer novel insight into key QCD phenomena via comparison to models and theoretical calculations [1].

sPHENIX is composed of several subsystems which provide calorimetric, tracking, and event-level information. At mid-rapidity, it contains an Electromagnetic Calorimeter (EMCal) and Inner and Outer Hadronic Calorimeters (I/OHCal), with the latter two being the first of their kind at RHIC. The combination of both electromagnetic and hadronic calorimetry gives sPHENIX the ability to both trigger on and reconstruct jets with minimal dependence on the jet's fragmentation. Track reconstruction is carried out by four tracking detectors, the Time Projection Chamber (TPC), Intermediate Silicon Tracker (INTT), MAPS-Based Vertex detector (MVTX), and the TPC Outer Tracker (TPOT). The majority of the space points used in track reconstruction and, thus, the dominant contributor to the track momentum resolution come from the TPC; meanwhile, the TPOT provides an additional space point for calibration purposes. The INTT, located between the TPC and MVTX, is a two-layer silicon-strip detector which provides timing information with sufficient timing resolution to reject pileup. Radially closest to the beam line, the MVTX is a three-layer silicon pixel detector and provides a precise determination of primary and secondary vertices which is critical for the sPHENIX

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heavy flavor program. The MVTX sensors are MAPS-based and the design of the detector itself is based on the inner three layers of the ALICE Inner Tracking System 2 (ITS2) [2]. Event characterization is handled by three subsystems positioned at forward rapidity. The Minimum Bias Detector (MBD) is composed of two arms each with 64 quartz radiator tubes read out with photomultiplier tubes placed on the north and south end of the beam line covering $3.51 < |\eta| < 4.51$ and provides the minimum bias trigger, which records an event if at least one PMT in each arm sees a hit above threshold. The sPHENIX Event Plane Detector (sEPD) is responsible for event plane reconstruction and covers $2.0 < |\eta| < 4.9$. The Zero-Degree Calorimeter (ZDC) is responsible for measuring the energy of spectator neutrons in Au + Au collisions as well as providing polarimetry data in polarized $p + p$ collisions.

2 Early Data Taking and Physics Results

sPHENIX first saw collisions in the summer of 2023 when it collected commissioning data with 200 GeV Au + Au collisions. The commissioning dataset was small, comprising only a few million events, but allowed for the successful implementation of many data production and calibration workflows for the first time in sPHENIX. In particular, the EMCal's energy scale was calibrated by using reconstructed neutral pions in data and simulation. Clusters within the EMCal, passing background rejection selections, are paired together as candidate decay products from π^0's. The invariant mass from these pairs is then calculated, the resulting mass peak fit, and the energy scale is then set to the energy scale in simulation which properly accounts for smearing due to detector effects. The hadronic calorimeters were calibrated via cosmic rays measured in simulation and in data to the minimum ionizing particle, or MIP, scale. Two calorimeter-based, standard-candle measurements, the π^0 v_2 [3] and $dE_T/d\eta$ [4] utilize these calibrations.

2.1 Neutral Pion Azimuthal Anisotropy

Collective flow is a hallmark signature of the creation of QGP in heavy-ion collisions and has been measured in many contexts at RHIC and the LHC. Neutral pion candidates are reconstructed in the EMCal using a similar procedure as for the energy scale calibration mentioned in Section 2. Charge information from the MBD PMT's is then used in combination with that from the π^0 candidates to measure the π^0 v_2 via the scalar product method [5]. The π^0 v_2 measured by sPHENIX is shown in Figure 1, and shows a v_2 which increases with centrality, a proxy for the impact parameter, until it levels off at around the 30 − 40% centrality class. Also shown is a comparison to a previously published measurement from the PHENIX experiment [6], and the two results agree well within uncertainties.

2.2 Total Transverse Energy

A measurement of the fully-corrected transverse energy as a function of psuedorapidity, $dE_T/d\eta$, was made for the EMCal and combined Inner and Outer HCals. Beginning with the baseline calibrations to the electromagnetic and MIP scales for the EMCal and HCals, respectively, additional Monte-Carlo-derived corrections correct the measurement back to the full electromagnetic plus hadronic energy scale. Figure 2 on the left shows the fully-corrected $dE_T/d\eta$ for both the EMCal and combined HCals as a function of η for several centrality bins. One can see that despite the different calorimeters have amounts and types of materials and therefore different numbers of nuclear interaction and radiation lengths, as well as different calibration processes, the subsystems are modeled in Monte-Carlo sufficiently that these

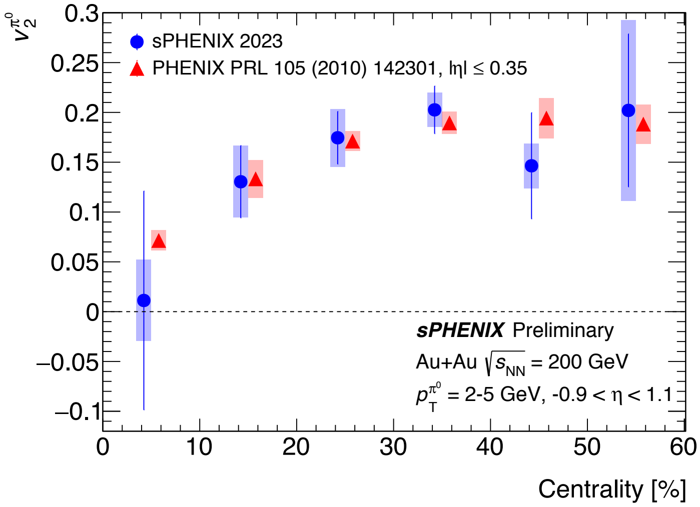

Figure 1. sPHENIX π^0 v_2 (blue circles) and PHENIX (red triangles) π^0 v_2 as a function of centrality. The skinny error bars are statistical uncertainties, whereas the bands represent the systematic uncertainties.

differences can be precisely accounted for, leading to consistent transverse energy measurements in the two calorimeter layers. Additionally, a comparison to previous PHENIX [7] and STAR [8] $dE_T/d\eta$ measurements is shown on the right hand side of Figure 2. In the peripheral and semi-peripheral centrality bins, the sPHENIX result has good agreement with both PHENIX and STAR results. In the most central bins, however, the agreement worsens slightly, though this could be due to imperfections in the centrality determination of the most central bins in the sPHENIX result.

3 Baseline p+p Data Collection in 2024

In summer of 2024, sPHENIX began data-taking operations again, collecting high luminosity 200 GeV $p + p$ data which serve as the baseline for the 2025 Au + Au running. The run had several major tasks, including but not limited to: implementation and commissioning of the calorimeter photon and jet triggers, commissioning and data taking with the full suite of sPHENIX tracking subsystems, and the commissioning of the tracking streaming readout system. Emphasis was also placed on high-rate data taking as, for many observables such as the R_{AA}, the statistical uncertainties in the $p + p$ baseline measurement can be a dominant source of uncertainty on the final measurement.

3.1 High p_T Jet and Photon Physics

To maximize the statistical impact of the 2024 $p + p$ run, a suite of high energy jet and photon triggers was implemented. The performance of these triggers relative to the minimum bias triggers is shown in Figure 3. A four-panel, single event display is shown in Figure 4. A dijet pair with leading $p_T = 26.2$ GeV and subleading $p_T = 25.3$ GeV at the electromagnetic scale can be seen separated by approximately π radians in the calorimeters. Each of the panels represents a different calorimeter layer, and one can see the largest energy depositions in the

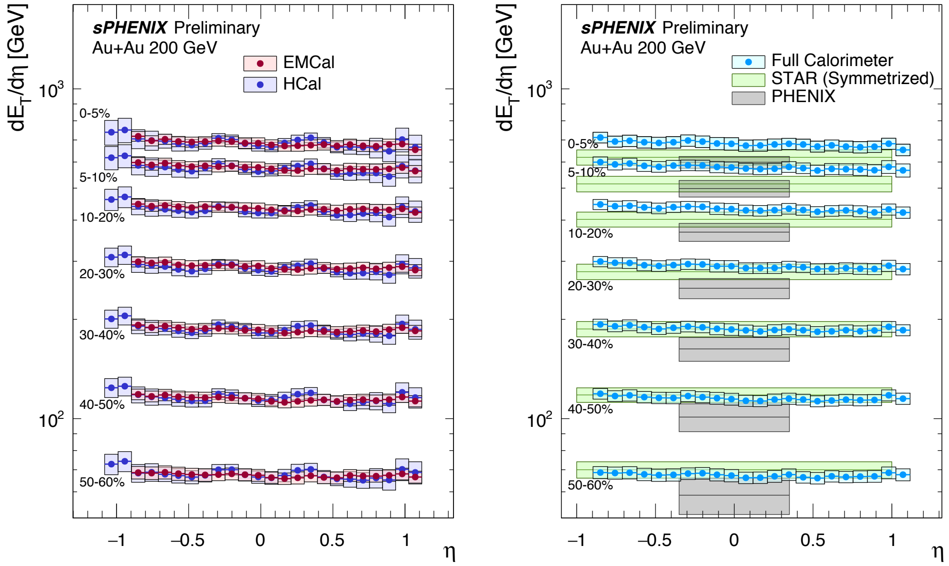

Figure 2. Left: Fully-corrected $d\mathrm{E_T}/d\eta$ as a function of η for the EMCal (red) and the OHCal (blue) in different centrality bins. Right: Fully-corrected $d\mathrm{E_T}/d\eta$ as a function of η for the combined sPHENIX calorimetry system (cyan) compared to STAR (green band) and PHENIX (grey band) results in different centrality bins.

EMCal and OHCal, and a smaller energy deposit in the IHCal, which is thinner and serves primarily to measure the start of a hadronic shower before the magnet.

3.2 Tracking Commissioning

Run 2024 began with commissioning the sPHENIX TPC, and early beam data was quickly analyzed for feedback on the TPC's performance. Two invariant mass distributions are shown in Figure 5 for reconstructed K_s^0 and Λ's with TPC-only tracks and no attempt to correct for the effects of static or dynamic distortions. However, one can still see clear peaks at approximately the K_s^0 and Λ masses of 0.497 GeV/c^2 and 1.115 GeV/c^2, respectively. The TPC's running performance was then further improved by changing its gas composition from a 60:40 Ar:CF$_4$ to a 75:20:5 Ar:CF4:Isobutane gas mixture, with the isobutane adding increased stability. The latter phase of Run 2024 saw all sPHENIX tracking subsystems collecting data simultaneously for the first time, and, additionally, the TPC, INTT, MVTX, and TPOT were run alongside the calorimeters, leading to the first datasets with information from every sPHENIX subsystem.

Additionally, commissioning of the streaming readout was successfully carried out with the tracking detectors. Unlike in a triggered readout mode, a streaming readout takes data continuously with no input from hardware triggers, allowing for zero-bias data taking and the collection of a large $p + p$ baseline for heavy flavor measurements. At the end of the run, the streaming readout was sampling $10 - 30\%$ of the delivered luminosity, a first-of-its-kind achievement at RHIC.

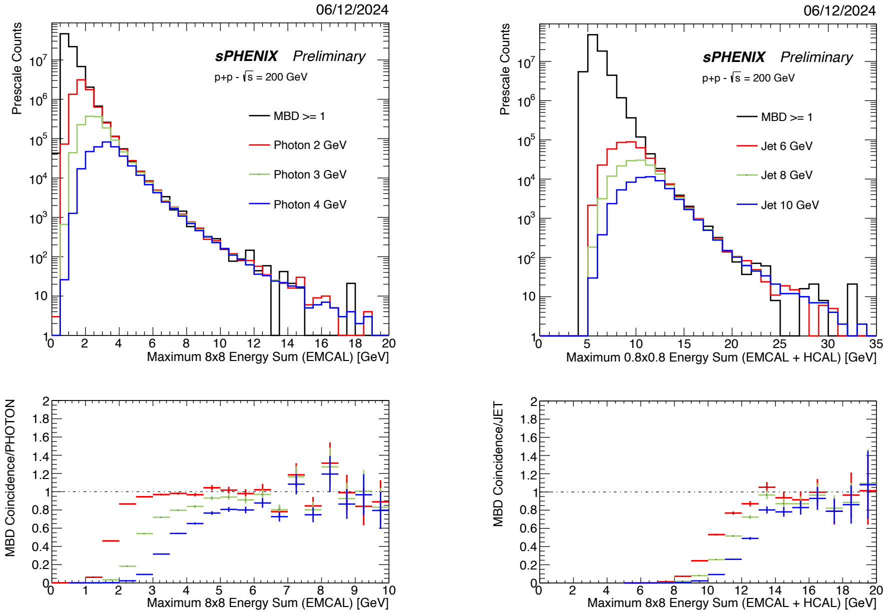

Figure 3. Left top: Pre-scaled counts vs the sum of energy in an 8 × 8 patch of EMCal towers for the minimum bias (black), 2 GeV (red), 3 GeV (green), and 4 GeV (blue) threshold photon triggers. Left Bottom: Ratio of each of the above photon triggers to minimum bias. Right top: Pre-scaled counts vs the sum of energy in an overlapping 0.8 × 0.8 region in the EMCal and HCal for the minimum bias (black), 6 GeV (red), 8 GeV (green), and 10 GeV (blue) threshold photon triggers. Left Bottom: Ratio of each of the above jet triggers to minimum bias.

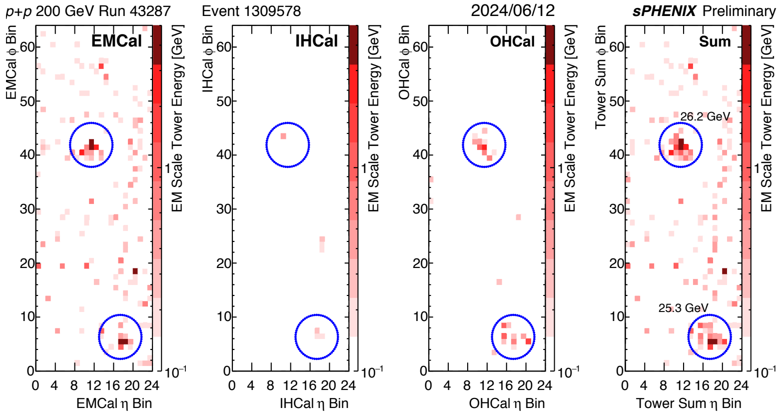

Figure 4. Energy depositions in a given calorimeter layer for the EMCal (1st panel), IHCal (2nd panel), OHCal (3rd panel), and all calorimeters combined (4th panel). The two circles represent the location in $\eta \times \phi$-space of two $R = 0.4$ anti-k_t jets that form a dijet pair.

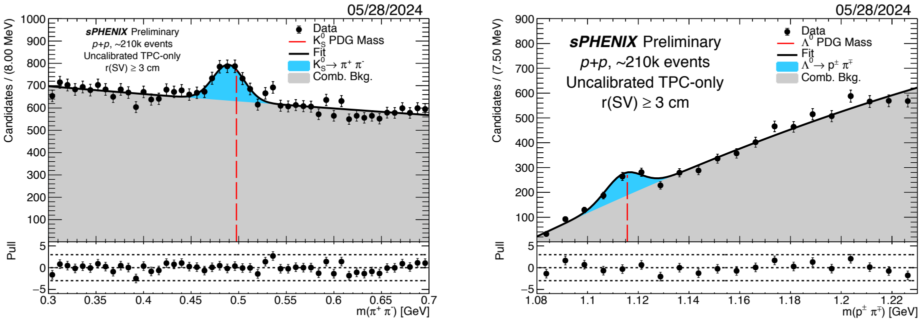

Figure 5. Left: Yield of $\pi^+\pi^-$ pairs as a function of the reconstructed invariant mass. Right: Yield of $p^\pm\pi^\mp$ pairs as a function of the reconstructed invariant mass. No calibrations have been applied to account for distortions. Each distribution is fit, and the point-to-point discrepancy to the data, the pull, is plotted in the bottom panels for both invariant mass distributions.

3.3 Collected Luminosity

According to the 2023 sPHENIX Beam Use Proposal [9], the experiment proposed to collect approximately 39 pb^{-1} of data within a z-vertex range of ±10 cm. In the early part of Run 2024 when the TPC was not operational, however, beam conditions were optimized to increase the collected luminosity for the calorimeter-only jet and photon physics programs, resulting in the collection of over 100 pb^{-1} over the course of the entire Run 2024 $p + p$ data-collection campaign as shown in Figure 6, over 200% of the original goal. Additionally, the jet and photon-triggered dataset which included the tracking detectors collected approximately 30% of its luminosity goal, and the streaming readout collected 65% of its luminosity goal for the open heavy flavor program, amounting to 2.90 pb^{-1}, an orders-of-magnitude improvement over the previous largest collected at RHIC.

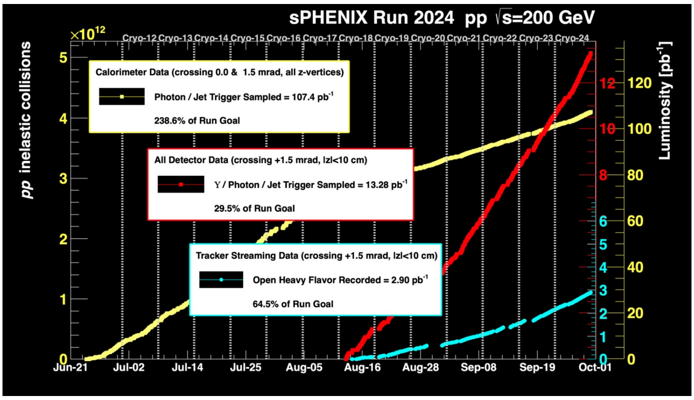

Figure 6. Total collected luminosity for three different physics programs. The yellow points indicate the luminosity collected by the calorimeter jet and photon-triggered datasets. The red points indicate the luminosity collected with the calorimeter jet and photon triggers while running with the tracking subsystems in triggered readout mode. The blue poinst indicate to the luminosity collected by the streaming readout, which serves as a zero-bias baseline for the heavy flavor physics program.

4 Au+Au Running and Future Physics

2025 will see sPHENIX take its flagship 200 GeV Au + Au dataset that will offer access to a rich set of physics observables in combination with the $p + p$ dataset taken in 2024. Figure 7 shows projections for several target measurements that will be feasible with the 2025 Au + Au data [10]. Additionally, sPHENIX is prepared for opportunities for continued data-taking beyond the 2025 Au + Au data taking campaign, and, for example, has made projections for the statistical uncertainties on observables such as the R_{pAu} and energy-energy correlations in p + Au collisions in Figure 8.

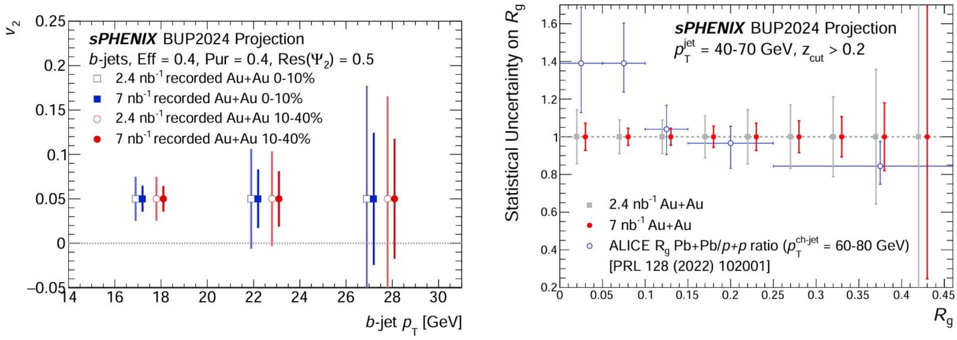

Figure 7. Left: Projected statistical uncertainties on the b-jet v_2 in the $0-10\%$ centrality class (blue) and $10-40\%$ centrality class (red) for two luminosity scenarios in Run 2025: $2.4nb^{-1}$ in the open points and $7nb^{-1}$ in the closed points. Right: Projected statistical uncertainties on the jet R_g for luminosity scenarios of $2.4nb^{-1}$ (grey squares) and $7nb^{-1}$ (red circles) compared to ALICE [11].

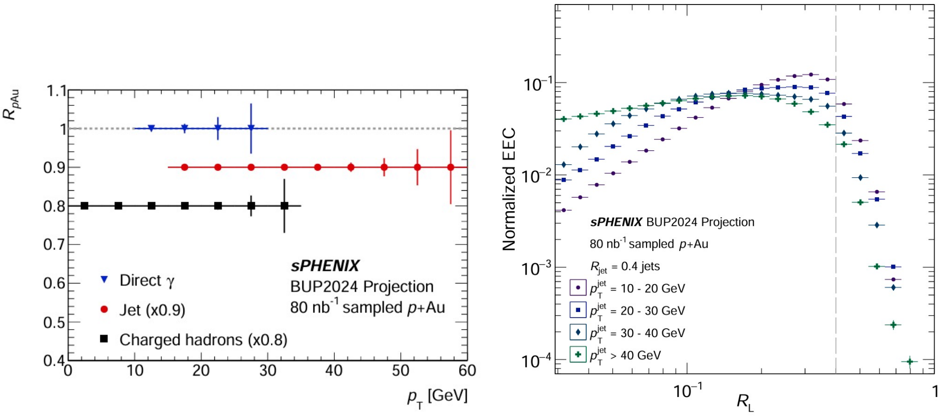

Figure 8. Left: Projections of the nuclear modification factor in p + Au collisions, R_{pAu} for direct photons (blue), jets (red), and hadrons (black) based on a sampled luminosity of $80nb^{-1}$. Right: Projected statistical uncertainties on the normalized yield of Energy-Energy Correlators of a given R_L for 4 jet momentum ranges.

5 Summary and Conclusion

In conclusion, the sPHENIX detector, the first new, full detector system at RHIC in over 20 years, has collected a small 200 GeV Au + Au commissioning dataset in 2023 and a high-statistics jet and photon dataset in the 2024 $p + p$ data collection campaign. From the 2023 Au + Au campaign two benchmark physics observables were measured using the commissioning dataset: the π^0 v_2 and the $dE_T/d\eta$, both of which compare favorably to previous RHIC measurements of the same quantities. The 2024 $p + p$ run saw sPHENIX successfully commission and deploy its calorimetric jet and photon triggers, full tracking suite, and streaming readout capabilities. Data analyses are underway for several observables such as the inclusive jet cross-section and dijet asymmetry (x_j), and the sPHENIX collaboration anticipates making many impactful measurements in the coming years that will elucidate properties of the QGP and quantum chromodynamics.

References

[1] R. Belmont et al., Predictions for the sPHENIX physics program, Nucl. Phys. A **1043**, 122821 (2024), `2305.15491`. 10.1016/j.nuclphysa.2024.122821

[2] F. Reidt, Upgrade of the ALICE ITS detector, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1032**, 166632 (2022). 10.1016/j.nima.2022.166632

[3] sPHENIX Collaboration, Measurement of π^0 v_2 in $Au{+}Au$ collisions at 200 Gev with the sPHENIX detector (2024), `https://www.sphenix.bnl.gov/sPH-CONF-BULK-2024-01`.

[4] sPHENIX Collaboration, Measurement of $dE_T/d\eta$ with the sphenix detector using run 2023 $Au + Au$ data at 200 Gev (2024), `https://www.sphenix.bnl.gov/sPH-CONF-BULK-2024-02`.

[5] C. Adler et al. (STAR), Elliptic flow from two- and four- particle correlations in Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV, Phys. Rev. C **66**, 034904 (2002), `nucl-ex/0206001`.

[6] A. Adare et al. (PHENIX), Azimuthal Anisotropy of π^0 Production in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV: Path-Length Dependence of Jet Quenching and the Role of Initial Geometry, Physical Review Letters **105** (2010). 10.1103/physrevlett.105.142301

[7] A. Adare et al. (PHENIX), Transverse energy production and charged-particle multiplicity at midrapidity in various systems from $\sqrt{s_{NN}} = 7.7$ to 200 gev, Phys. Rev. C **93**, 024901 (2016). 10.1103/PhysRevC.93.024901

[8] J. Adams et al. (STAR Collaboration), Measurements of transverse energy distributions in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. C **70**, 054907 (2004). 10.1103/PhysRevC.70.054907

[9] sPHENIX Collaboration, 2023 sPHENIX beam use proposal (2023), `https://indico.bnl.gov/event/20373/`.

[10] sPHENIX Collaboration, 2024 sPHENIX beam use proposal (2024), `https://indico.bnl.gov/event/25471/`.

[11] S. Acharya et al. (ALICE), Measurement of the groomed jet radius and momentum splitting fraction in pp and pb-pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Rev. Lett. **128**, 102001 (2022). 10.1103/PhysRevLett.128.102001