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Status and Performance of sPHENIX Experiment

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Abstract. sPHENIX is a state-of-the-art experiment at the Relativistic Heavy Ion Collider. Hard probes are to be measured in p+p, p+Au and Au+Au collisions to understand the properties of the quark-gluon plasma. sPHENIX covers a wide range of physics programs: jet correlations and substructure, upsilon spectroscopy, open heavy flavor and cold quantum chromodynamics. It provides unique opportunities in the low transverse momentum region and also offer kinematic overlap with the Large Hadron Collider experiments. In these proceedings, the scientific mission of sPHENIX, detector design and key performance parameters are described, and expected projections of some measurements under consideration are presented.

1 Introduction

The ultra-relativistic nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have revealed the existence of a new form of matter called the quark-gluon plasma (QGP) [1]. While the macroscopic properties of the QGP have been measured in detail, such properties are not apparent from the fundamental interactions governed by the quantum chromodynamics (QCD). The sPHENIX experiment will provide a crucial insight to one of the two highest priorities in Hot QCD: to understand the inner workings of the QGP via measurements of hard probes in heavy-ion collisions at RHIC [2].

sPHENIX was proposed as the upgrade and replacement of the PHENIX experiment in 2010. Detailed physics cases and detector design proposals have been developed in the following years [3, 4]. The sPHENIX Collaboration was formed in early 2016, and has more than 360 members from 82 institutions in 14 countries as of 2022. The detector construction is nearly complete, and the first data taking will take place in early 2023.

2 sPHENIX Physics

The scientific mission of sPHENIX is to probe the QGP at multiple length scales and can be achieved with three years of operation. Table 1 presents an overview of data that are expected to be obtained in the first three years [5]. The run plan is consistent with the currently envisioned schedule of the Electron Ion Collider (EIC).

More than 50% of the Year-1 (2023) data are planned to serve for the commissioning of the detector and its operation as well as to validate the calibration and reconstruction. Year-2

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Table 1. Summary of the sPHENIX Beam Use Proposal for years 2023–2025. The values in parentheses correspond to the 28 cryo-week scenario.

Year	Species	$\sqrt{s_{\rm NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert < 10$ cm	Samp. Lum. $\lvert z\rvert < 10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

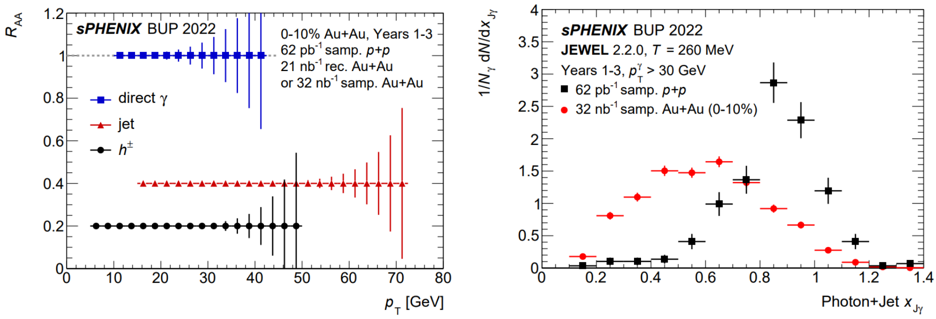

Figure 1. Statistical projections of the nuclear modification factor $R_{\rm AA}$ for photons, jets and charged hadrons (left) and the jet-photon momentum balance $x_{J\gamma}$ (right).

(2024) will collect large datasets of p+p and p+Au collisions, which are the critical references for the heavy ion physics and will also offer new opportunities for the cold QCD. Year-3 (2025) will collect a significantly large dataset of Au+Au collisions, which will provide unprecedented statistical precision in jet and heavy flavor measurements. With the three years of operation, a total of 141 billion Au+Au events is expected to be recorded. If any opportunity arises, additional runs would continue to recoup benefits from the sPHENIX investment [5].

sPHENIX has four main physics programs: (1) jet structure to probe various momentum and angular scales, (2) upsilon spectroscopy to vary the size of the probe, (3) open heavy flavor to probe with various momentum scales and parton masses, and (4) cold QCD to study proton spin, transverse momentum, and cold nuclear effects. The high data rates, precision trackers and hermetic calorimeters offer access to a wide $p_{\rm T}$ range of up to around 50 GeV for hadrons, 40 GeV for photons and 70 GeV for jets (Figure 1 (left)). sPHENIX will offer kinematic overlap with the LHC, which is possible for the first time at RHIC.

2.1 Jet structure

The jet-photon momentum balance $x_{J\gamma}$ is a “flag-ship” observable at sPHENIX (Figure 1 (right)). It is expected to have a dramatic difference between the LHC and RHIC energies [6], and such a comparison would only be possible with sPHENIX.

The jet substructure will provide another probe to measure the QGP properties and an insight to the connection to the fundamental QCD. For example, the groomed momentum sharing will allow for exploring the parton shower development in the QGP.

sPHENIX has unique opportunities for the jet measurements, being able to precisely measure down to the low-$p_{\rm T}$ region, which is challenging at the LHC. The dependence of the

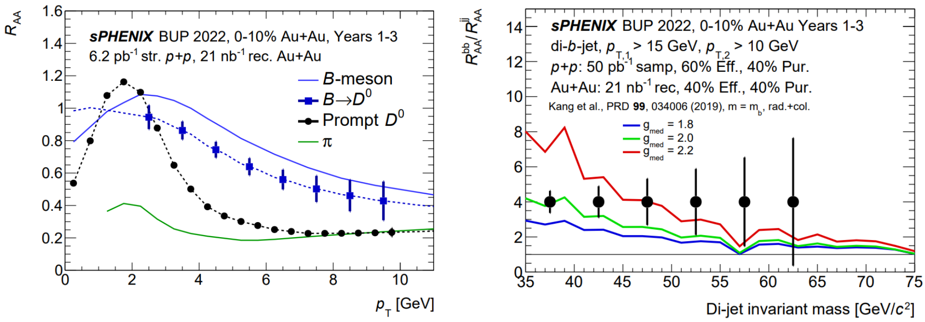

Figure 2. Statistical projections for the R_{AA} measurements of prompt/non-prompt D^0 mesons as a function of p_T (left) and of the b-jet-light-jet-super-ratio as a function of the dijet invariant mass (right).

nuclear modification factor $R_{\rm AA}$ on the jet distance parameter $R^{\rm jet}$ will probe the interplay of the out-of-cone energy loss and the medium response. Currently, there is a tension between the ALICE and ATLAS measurements. The elliptic flow v_2 is a crucial observable to understand the properties of the QGP, but modeling it simultaneously with the suppression has not been successful so far in most cases. Its precision measurement at sPHENIX may provide an insight in further understanding the QGP.

2.2 Open heavy flavor & parton energy loss

The heavy-flavor quarks are unique probes as their initial productions can be predicted from the perturbative QCD, and they are conserved from the initial hard scattering, experiencing the full evolution of the QGP.

A precise measurement of non-prompt D^0 suppression will be possible, thanks to the performance of the Monolithic Active Pixel Sensor Vertex Detector (MVTX). Furthermore, the streaming readout allows for collecting an enormous amount of minimum bias data for unbiased heavy-flavor mesons down to almost $p_{\rm T}$=0 as shown in Figure 2 (left). The determination of b-quark $R_{\rm AA}$ and v_2 will provide clean access to the diffusion at RHIC.

The MVTX and full calorimeter implementation will offer the first b-jet tagging at RHIC. The current b-jet tagging algorithms exploiting the track distance of closest approach (DCA) and the secondary vertices respectively, show compatible performance to CMS [7, 8]. sPHENIX provides outstanding precision in the low-jet-$p_{\rm T}$ region, which is challenging at the LHC. In addition, making use of the di-b-jet mass for the $R_{\rm AA}$ measurement enhances the sensitivity to the transport property, and taking the ratio to the light-jet-pair mass will particularly offer strong sensitivity to the parton mass effect (Figure 2 (right)). Sufficient statistics at sPHENIX will also allow for measuring the b-jet substructure [5, 9], which is another approach to quantify the role of the parton mass.

2.3 Upsilon spectroscopy

Measuring the centrality and $p_{\rm T}$ dependence of the nuclear modification factor of the upsilons is crucial to compare with the LHC. sPHENIX can reconstruct the upsilon states with excellent mass resolution $\delta M < 125$ MeV using the electrons. Recently, the Υ(3S) state has been observed for the first time in the Pb-Pb collisions by CMS [10]. sPHENIX has the unique opportunity to precisely measure the three separated states at RHIC (Figure 3 (left)).

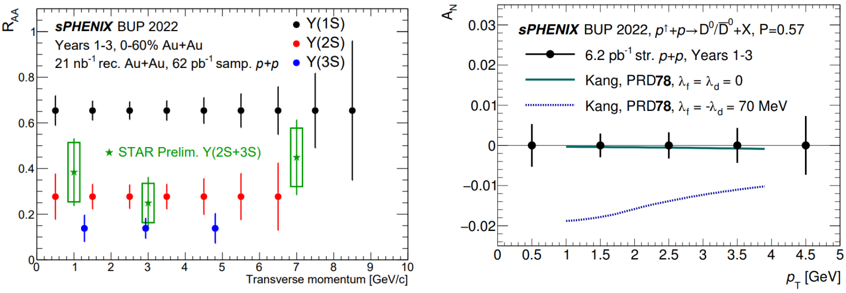

Figure 3. Statistical projections for the upsilon R_{AA} as a function of p_{T} (left) and the transverse spin asymmetry (A_N) for the D^0 mesons (right).

2.4 Cold QCD

The capability of sPHENIX to pursue measurements with jets, photons and heavy-flavor particles provides exciting programs for the cold QCD as well. In p+p collisions, the transverse single spin asymmetry (TSSA) can be accessed via prompt photons and D^0 mesons (Figure 3 (right)), which would deepen understanding about the gluon dynamics in transversely polarized nucleons with the tri-gluon correlations. In p+Au collisions, measuring the nuclear dependence of TSSA will offer insight to its origin with much improved precision from the PHENIX experiment.

3 sPHENIX detector

sPHENIX is the first new detector at RHIC at Brookhaven National Laboratory in over 20 years of operation (Figure 4). It has the capability to utilize the full delivered luminosity of RHIC with the high data rates of 15 kHz for all the subdetectors and large hermetic coverage of 2π in azimuth and pseudo-rapidity of $|\eta|<1.1$. The trigger capability includes the streaming readout, which will be described in Section 3.4. The sPHENIX detector consists of a precision tracking system, electromagnetic and hadronic calorimeters, and minimum bias and event plane detectors. The 1.4 T superconducting solenoid from the BaBar experiments surrounds the tracking system, electromagnetic and inner hadronic calorimeters. The sPHENIX detector will allow for full, unbiased jet reconstruction, b-jet tagging, and measurements of the three upsilon states separating in both Au+Au and p+p collisions.

3.1 Tracking Detectors

The tracking system consists of four components: MVTX, Intermediate Silicon Tracker (INTT), Time Projection Chamber (TPC) and TPC Outer Tracker (TPOT). The MVTX, the inner-most tracking detector (2.3 < radius < 3.9 cm), provides the precision vertexing. It has three layers of MAPS using the ALICE Pixel Detector (ALPIDE) [11]. The DCA resolution in xy and z reaches below 40 μm at p_{T}>0.5 GeV (Figure 5 (left)), which is crucial for the open heavy flavor program. The INTT consists of two layers of silicon strips with 86 μm in pitch. It has a fast integration time of $\mathcal{O}$(100ns), which can resolve one beam crossing and provide the pileup suppression. The TPC is based on Gas Electron Multiplier and has 48 layers with gateless and continuous readout. It has an outer radius of 78 cm, leading to only 1/30 of the ALICE TPC volume. The tracking efficiency is around 90% for the p+p collisions (Figure 5

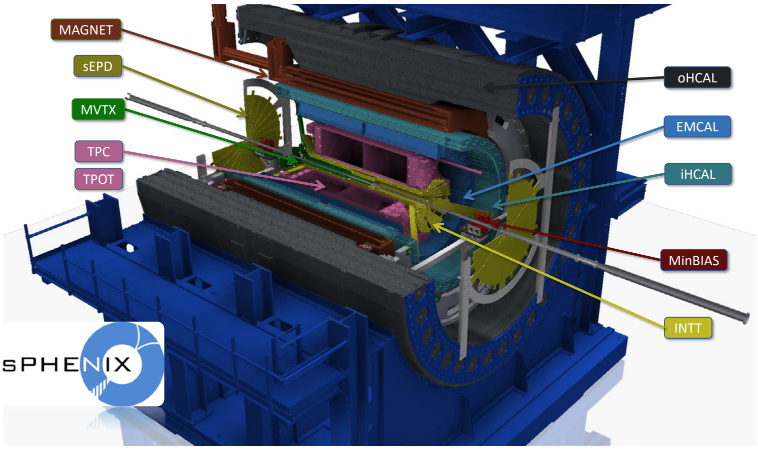

Figure 4. The engineering drawing of the sPHENIX detector with its support structure.

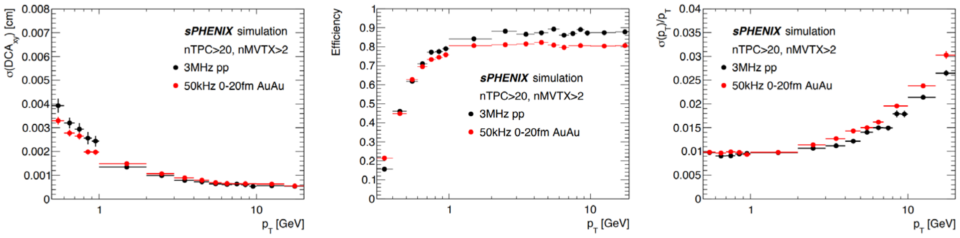

Figure 5. Tracking performance for the DCA resolution in the transverse direction (xy) (left), reconstruction efficiency (middle), and the p_{T} resolution (right) as a function of track p_{T}.

(middle)) and the p_{T} resolution is below 2% for p_{T}<10 GeV (Figure 5 (right)), which allows for measuring and discriminating the three upsilon states. The TPOT has eight modules of Micromegas inserted between the TPC and the electromagnetic calorimeter (EMCal). It offers calibration of beam-induced space charge distortions.

3.2 Calorimeters

The calorimeters consist of the EMCal, inner hadronic calorimeter (IHCal), and outer hadronic calorimeter (OHCal) with a common light collection and readout using silicon photomultipliers. The EMCal and IHCal are housed inside the solenoid.

The EMCal provides the electron identification for the upsilons and the photon measurements. It adopts a Tungsten-scintillating fiber sampling technique with a sampling fraction of 2.3%. It has a highly granular segmentation of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$. The energy resolution has been measured in testbeams to be less than $16\%/\sqrt{E} \oplus 5\%$ [12, 13].

The Inner (Outer) HCal exploits aluminum (steel) absorber plates and scintillating tiles with embedded wavelength shifting fibers. The OHCal is also used as a return yoke for the solenoidal magnetic field. Both the IHCal and OHCal have a granular segmentation of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. The energy resolution of the overall HCal has been measured in a testbeam [12] and meets the requirement for the jet energy resolution to be around $20\%/\sqrt{E}$.

3.3 Minimum Bias and Event Plane Detectors

The Minimum Bias Detector (MBD) is a reuse of the PHENIX Beam-Beam Counter, consisting of 3 cm-thick quartz radiator on the mesh dynode photomultipliers. It has the timing resolution of 120 ps.

The sPHENIX Event Plane Detector (sEPD) exploits 1.2-cm-thick scintillators with wavelength shifting fibers. It consists of two wheels of 12 sectors with 31 optically-isolated tiles. The sEPD provides significant improvement in the event plane resolution: $\mathrm{Res}(\Psi_2) = 0.14$ (MBD only) and 0.55 (with sEPD).

3.4 Hybrid Data Acquisition Structure

sPHENIX adopts a hybrid system of a streaming readout from the inner trackers (MVTX, INTT, and TPC) and the calorimeter triggers for the high-p_T objects. The streaming readout is a triggerless configuration recording 10% of all collisions. It will increase the amount of minimum bias data in the p+p and p+Au collisions by orders of magnitude. It is crucial for track-only measurements in open heavy-flavor physics as well as cold QCD.

4 Conclusions

sPHENIX is a state-of-the-art experiment at RHIC. Hard probes are to be measured in p+p, p+Au and Au+Au collisions to understand the properties of the QGP and cover a wide range of physics: jet correlations and substructure, upsilon spectroscopy, open heavy flavor and cold QCD. sPHENIX provides unique opportunities in low-p_T measurements and also offer kinematic overlap with the LHC experiments.

sPHENIX has entered the detector construction phase since September 2019. The detector construction and installation as well as the data taking preparation are on schedule. The detector will be ready for commissioning with beam in early 2023, and sPHENIX will complete the scientific mission of RHIC.

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