Heavy Flavor and Quarkonia Physics at sPHENIX

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The sPHENIX detector being constructed at BNL's Relativistic Heavy Ion Collider (RHIC) will begin measuring a plethora of Heavy Flavor and Quarkonia observables with unprecedented statistics and kinematic reach at RHIC energies starting in 2023. This includes the largest recorded sample of b-hadron decays from Heavy Ion collisions at RHIC, allowing for precise probes of the QGP using charm and beauty quarks. These measurements are enabled by the excellent vertexing of the MVTX detector, timing of the INTT, precision tracking by the TPC, and the EM and hadronic calorimetry systems, the latter of which is deployed for the first time at RHIC. The sPHENIX collaboration has created the reconstruction software stack as well as realistic data simulations, which allow for testing and optimization of the software and physics selections.

Keywords: ***Open Heavy Flavor, Quarkonia, Heavy Ion Collisions, sPHENIX***

1 Introduction

The super Pioneering High Energy Nuclear Interaction eXperiment (sPHENIX) [1] is a relativistic heavy-ion experiment stationed at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL). The sPHENIX barrel consists of several layers of detectors encompassing a full 2π azimuthal coverage with a pseudorapidity range of $\eta \leq 1.1$, and allows for a 15 kHz trigger rate with additional data taken in streaming mode. It also includes a 1.4 T superconducting solenoid magnet repurposed from the BaBar experiment. Based on current projections and progress, sPHENIX is poised to begin data taking in early 2023 with an initial Au+Au sample at $\sqrt{s_{NN}} = 200$ GeV, followed by p+Au and p+p samples at the same $\sqrt{s_{NN}}$ in 2024, and a larger Au+Au sample in 2025.

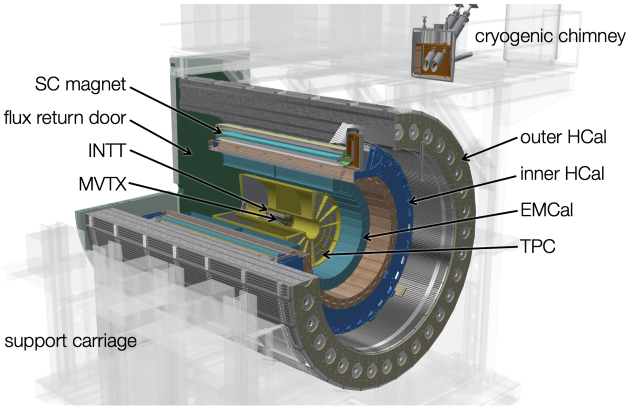

FIGURE 1. Rendering of the sPHENIX Detector with section cutaway. EPD and MBD not shown but would exist near the end caps of the barrel. [2]

The tracking system for the sPHENIX detector begins 2.3 cm from the center of the beam pipe with the MAPS-based micro-VerTeX detector (MVTX), followed radially outward by the INTermediate silicon strip Tracker (INTT), Time Projection Chamber (TPC), and TPC Outer Tracker (TPOT). Beyond the tracking detectors, the electromagnetic calorimeter (EMCal) and inner hadronic calorimeter (iHCal) systems continue outward while still within the BaBar magnet until the barrel is finally surrounded by the outer hadronic calorimeter (oHCal) outside the magnet. Additionally, sPHENIX employs Event Plane Detector (EPD) and Min Bias Detector (MBD) systems at the end caps of the barrel. A rendering of the complete detector can be seen in Figure 1.

sPHENIX aims to study in detail the quark gluon plasma (QGP) produced at RHIC as well as the nature of parton structure, parton energy loss, and mass dependent energy loss using its high precision next generation detectors. Exploring kinematic regions unavailable to and overlapping with the Large Hadron Collider (LHC), particularly at low p_T, additionally combine to establish a high level of importance for the experiment relative to the DOE/NSF NSAC 2015 Nuclear Physics Long Range Plan [3]. To accomplish its goals, the sPHENIX physics program is divided into four main components: jets and photons, open heavy flavor, upsilons, and and cold QCD physics. The open heavy flavor and upsilon physics components will be emphasized here.

2 Tracking Detectors and Performance

The sPHENIX tracking system is composed of three main detector systems: the MVTX, the INTT, and the TPC. Together these detectors are the keys to unlocking sPHENIX's heavy-flavor tagged jet and heavy-flavor physics programs.

Starting at the innermost of these three, the MVTX is based closely on the ALICE ITS inner barrel and performs precise vertexing using three layers of monolithic active pixel sensors (MAPS) ($\sim$5 μm space point precision per pixel for tracks with $p_T > 1$ GeV/c). The MAPS used in sPHENIX have a 5-10 μs integration time, which is a significant improvement over the 180 μs integration time of the previous generation of MAPS as used in the earlier runs of the STAR experiment [4] [5]. The MVTX begins 2.3 cm radially outward from the center of the beam pipe and extends to 3.9 cm.

Moving outward radially at 6 to 12 cm from the center of the beam pipe resides the INTT, a silicon strip detector surrounding the MVTX made of two rings of two silicon strip layers (one oriented in the ϕ direction, the other in the z direction). Using space point resolution between that of the finer MVTX and coarser TPC, the INTT allows for better pattern recognition and interpolation between the two. In addition, it is the only detector with single-beam-crossing timing resolution, allowing us to associate a hit with a single bunch crossing. This will be crucial to sPHENIX's ability to associate fully reconstructed tracks with the event that produced them.

Lastly, the TPC sits between 20 to 78 cm radially outward from the center of the beam pipe. Filled with a 50:50 mixture of Ne-CF4 gas with an electron drift velocity of 8 cm/μs, it operates as the primary tracker for the experiment and provides precise momentum resolution. This resolution is critical for the experiment's goal of being able to distinguish the Υ(2S) and Υ(3S) states with the $\sim$1.2% momentum resolution needed in the 4-8 GeV/c p_T range to accomplish this. Additionally, it is designed to be able to measure displaced tracks originating from a D or B meson decay, further enhancing the open heavy-flavor physics program. The TPC is currently set to operate in such a way that ion backflow is minimized which, combined with the shorter gas length compared to other larger TPCs such as at STAR, also results in reduced particle identification (PID) capabilities using dE/dx.

With this tracking system, the software is designed to be able to calibrate and reconstruct Au+Au events within a few weeks of data taking. To be able to accomplish this, sPHENIX uses the fast and experiment-agnostic A Common Tracking Software (ACTS) from the ATLAS experiment [6]. Track seeding for the silicon detectors is done separately from TPC track seeding with the former using ACTS, the latter using cellular automation and a Kalman filter developed for sPHENIX based on the algorithm developed for the ALICE TPC, and the final combined track fitting using an ACTS Kalman filter that matches tracks using η, ϕ, and position at the beam line.

Recent simulation results project tracking efficiency in the 85-90% range above a p_T of 2 GeV after requiring 3 MVTX hits for heavy flavor analysis using these methods. Momentum resolution compatible with the necessary precision needed for separating the first three Upsilon states is also observed, as well as p_T resolution below 3.5% at 20 GeV which is sufficient for making important jet physics measurements at high p_T. With continued improvements in track seeding, silicon track matching, and TPC clustering, these results are expected to continue to improve as the experiment moves towards data taking in early 2023.

3 Quarkonia Physics

Clear separation of the Υ(1S, 2S, 3S) states is a key deliverable of the sPHENIX experiment. Determining the centrality and p_T dependence of the nuclear modification factors for each of these states are critical measurements for the comparisons sPHENIX intends to make between RHIC and the LHC due to the important differences shown in temperature profiles of the states from hydrodynamic calculations at different collision energies.

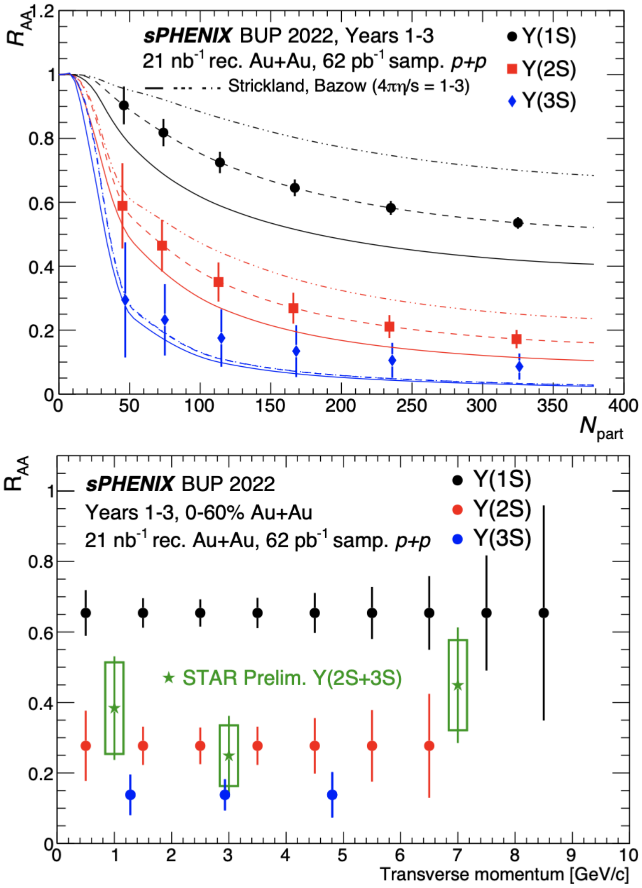

FIGURE 2. Projected statistical uncertainties for the centrality (top) and p_T (bottom) dependent R_{AA} measurements of the Υ(1S, 2S, 3S) states at sPHENIX [2] [7] [8].

Figure 2 shows the current projected statistical uncertainties for these measurements using sPHENIX simulation data. The 1S and 2S R_{AA} projected measurements in the top figure are taken from predictions from Strickland and Bazow, while the 3S measurement is taken to be approximately half that of the 2S measurement as seen in the recent CMS measurement at the LHC [7]. In the bottom figure, the current best knowledge of Upsilon suppression from STAR is also included with the projected uncertainties for R_{AA} measurements as a function of transverse momentum in 0-60% Au+Au collisions.

It is also important to note sPHENIX's unique projected ability at RHIC to separate the first three Upsilon states. This has never been done before at RHIC, and has only recently been performed by CMS at the LHC. It was previously expected that the Drell-Yan background would be comparable with the 3S signal in Au+Au collisions at RHIC energies, but the new CMS measurement suggests a heightened possibility for sPHENIX to explore the systematics of the Upsilon 3S state.

4 Open Heavy Flavor Physics

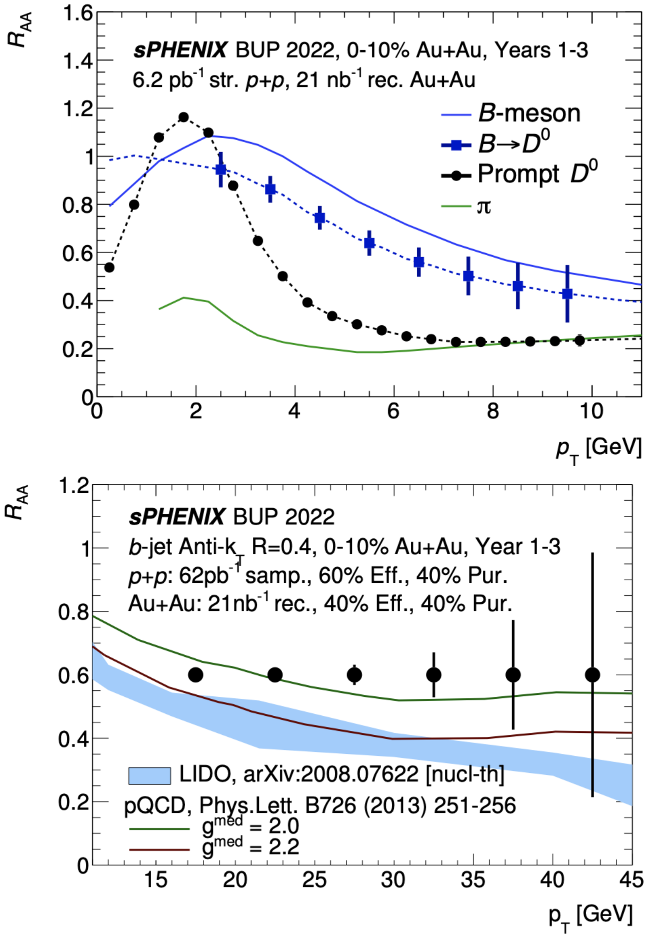

FIGURE 3. Projected statistical uncertainties for prompt and non-prompt D^0 meson (top) and b-jet (bottom) nuclear modification factor measurements as a function of p_T in 0-10% Au+Au collisions [2].

Because of their large masses, heavy-flavor quarks (c and b) are predominantly created in initial hard scattering at high Q^2 which allows for important insight into the initial stages of heavy ion collisions and comparison with calculable production rates in perturbative QCD. The high precision and high data rate of sPHENIX allows for improvements in measurements of these probes that are often limited by the rarity of heavy-flavor signals in heavy ion collisions at RHIC energies.

Figure 3 shows the projected statistical uncertainties for sPHENIX's observation of mass-dependent energy loss through D meson and b-jet R_{AA} measurements. By combining the reconstructed meson states and full jet, sPHENIX is capable of covering a broad kinematic range for probing the b-quark coupling with the QGP and providing stringent constraints on model parameters.

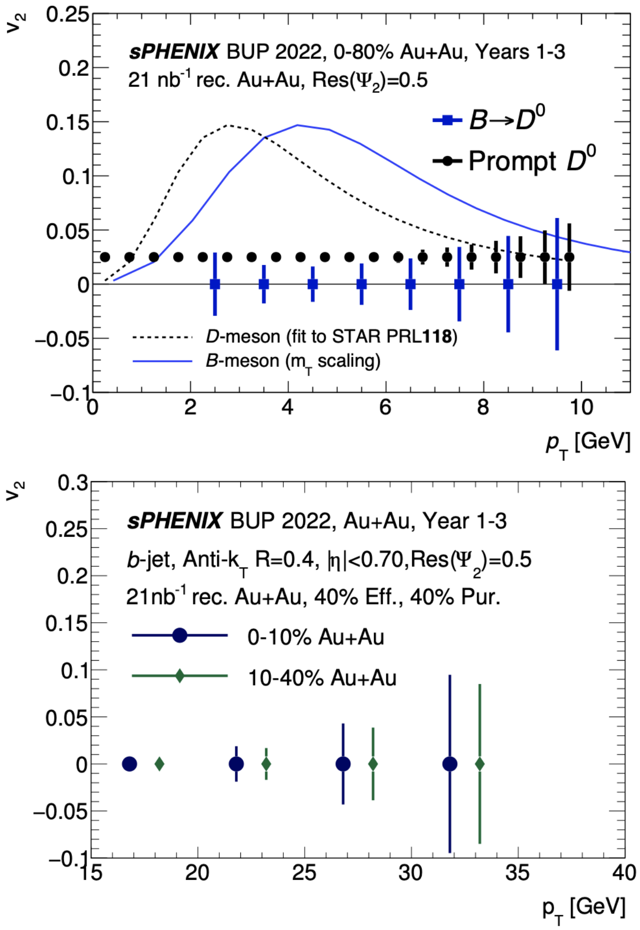

FIGURE 4. Projected statistical uncertainties for prompt and non-prompt D^0 meson (top) and b-jet (bottom) elliptic flow measurements as a function of p_T in Au+Au collisions at $\sqrt{s} = 200$ GeV [2].

In addition to these R_{AA} measurements, sPHENIX plans to make precise elliptic flow measurements for charm and bottom mesons as well as b-jets in order to obtain insight into how the heavy-flavor quark couples to the QGP medium. The current projected statistical uncertainties for these measurements can be seen in Figure 4. Due to the better constraints on bottom quarks, as opposed to lighter charm quarks, in the theoretical modeling of this measurement [9] [10], sPHENIX plans to significantly constrain the heavy quark diffusion transport parameter of the QGP as well as its temperature dependence through making very precise bottom measurements over a wide p_T range. At the higher end of the p_T spectrum above 10 GeV, the bottom plot in Figure 4 demonstrates sPHENIX's ability to examine the path-length dependent energy loss of the b-quark as well.

sPHENIX also aims to investigate charm hadronization in the QGP through production ratio measurements. Recent results at both RHIC and the LHC suggest an enhancement of the Λ_c baryon compared to the D^0 meson, but RHIC is missing a baseline p+p measurement of that ratio as well as a broad in p_T and precise Au+Au measurement. The high statistics and precision of sPHENIX will allow for these measurements to be taken at RHIC so that questions remaining regarding differences in model predictions for charm hadronization in the QGP at RHIC energies can finally resolved. Projected uncertainties for these measurements can be seen in Figure 5. It is important here to note as well that sPHENIX does not have π, K, p particle identification (PID) due to a lack of a time of flight detector and poor dE/dx resolution in the TPC, but the Λ_c baryon can still be reconstructed well enough to perform this analysis using geometric and momentum-based measurements.

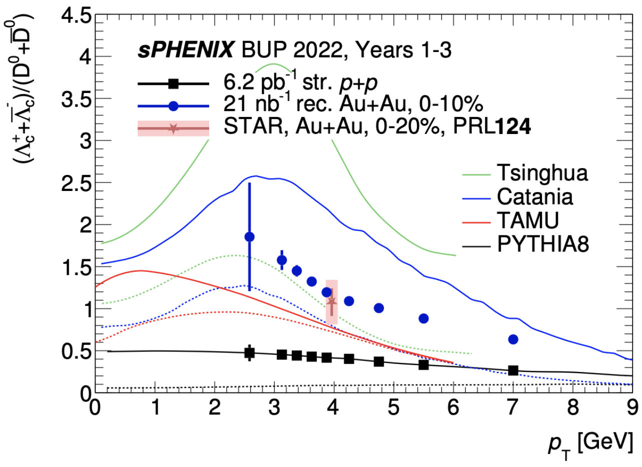

FIGURE 5. Projected Λ_c/D meson production ratio uncertainties in central Au+Au and p+p collisions at sPHENIX overlayed with STAR's recent comparable measurement [2].

4.1 HF Reconstruction with KFParticle

As mentioned in the previous section, the sPHENIX compact TPC is designed for minimizing the ion backflow in the streaming mode, which limits its capability for providing dE/dx-based hadron PID. Without these PID capabilities, sPHENIX needs a way to perform HF reconstructions; the KFParticle package is the answer. This tool is a current industry standard originally developed for the CBM experiment that is also used in other comparable experiments such as ALICE and STAR [11]. Using the pre-established external package, sPHENIX has been able to add a user interface, the ability to unpack tracks and vertices in the KFParticle format, and the selection requirements and combinatorics needed to run the package effectively.

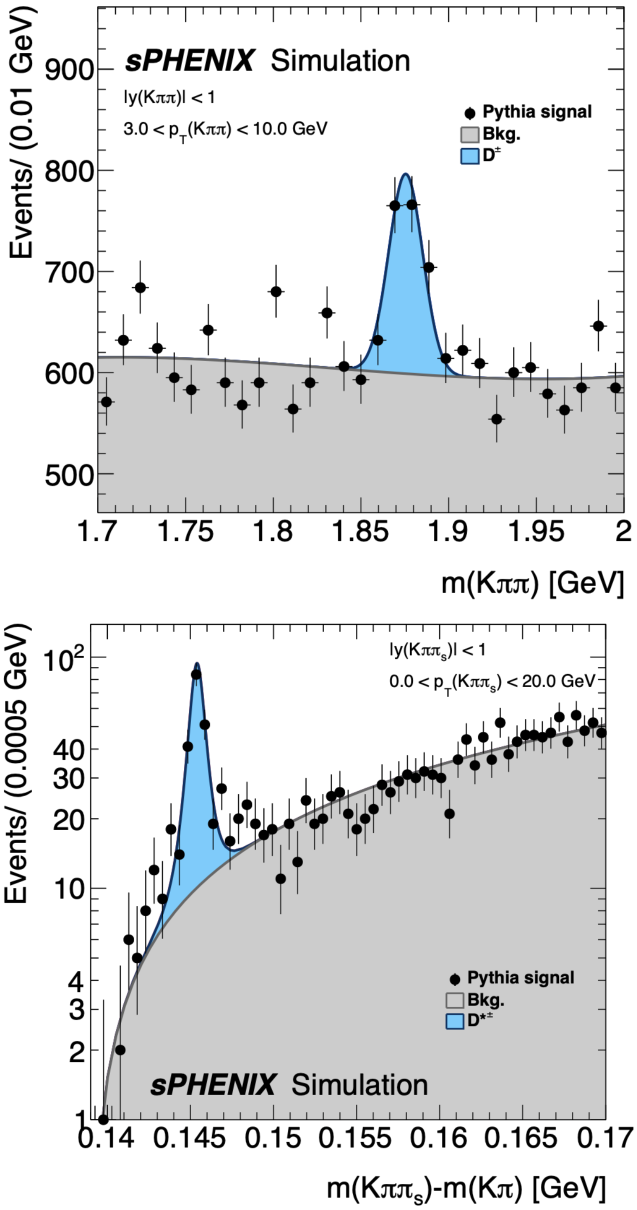

FIGURE 6. Mock Data Challenge 1 reconstruction of the $D^{\pm}$ invariant mass (top) and $D^{*\pm}$ invariant mass (bottom) using the KFParticle package implemented in the sPHENIX framework. Reconstruction performed on 50 million event $c\bar{c}$ sample from $\sqrt{s} = 200$ GeV p+p collisions without pileup [12].

In order to test the efficacy of this package in sPHENIX's software framework, a mock data challenge (MDC) was undertaken by the collaboration to evaluate the performance of its current simulation and reconstruction software. Significantly for this discussion, a reconstruction of the $D^{\pm}$ and $D^{*\pm}$ meson was performed using sPHENIX reconstruction software and the sPHENIX implementation of the KFParticle package. As can be seen in Figure 6, clear invariant mass peaks for each of these mesons were able to be reconstructed from a 50 million event $c\bar{c}$ sample from p+p collisions at $\sqrt{s} = 200$ GeV without pileup. These figures along with others that were evaluated during the MDC give the group confidence in the efficacy of the KFParticle package within the sPHENIX framework, as well as putting the group on the right track to be ready for data-taking on Day 1.

4.2 $D^0/\overline{D}^0$ Separation

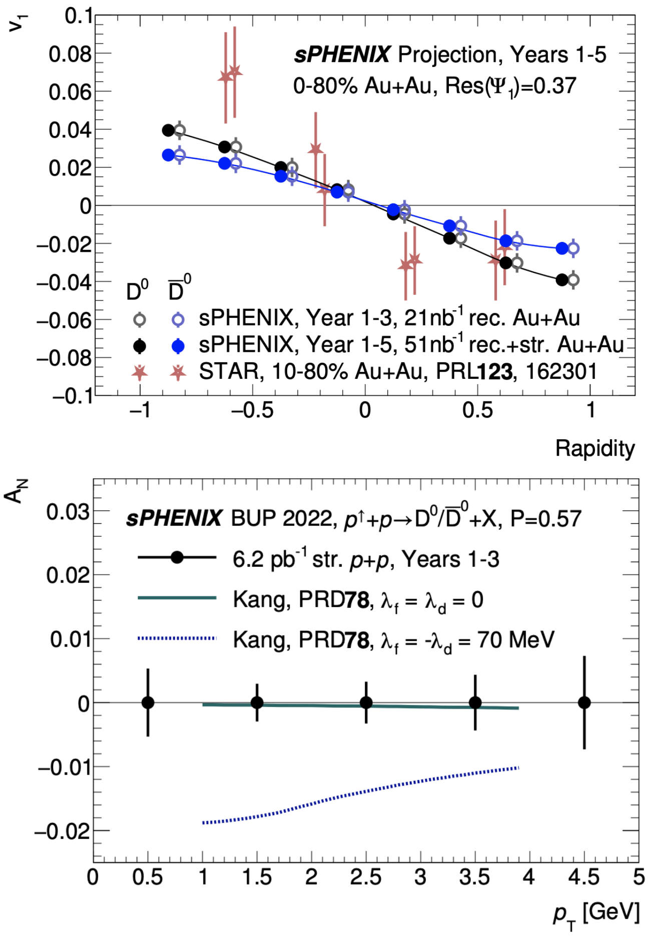

FIGURE 7. Projections of $D^0/\overline{D}^0$ uncertainties for v_1 (top) and transverse single spin asymmetry (bottom) measurements with sPHENIX [2].

The KFParticle package will additionally be critical in allowing for the separation of the D^0 and $\overline{D}^0$ mesons without effective PID. The better sPHENIX is able to separate these heavy flavor mesons, the better the measurements shown in Figure 7 can be taken and refined to determine properties of the QGP and cold QCD. In the top figure, separate measurements of D^0 and $\overline{D}^0$ v_1 are projected to show a splitting across the sPHENIX rapidity range due to a predicted transient magnetic field effect that is odd under charge conjugation. Compared to the precision of the STAR measurement shown in the same figure, sPHENIX has the potential to significantly enhance knowledge of the initial magnetic field formed in heavy ion collisions through constraining the parameters of this predicted effect. In the bottom figure, the current sPHENIX projection for transverse single spin asymmetry, A_N, is made averaged over both D^0 and $\overline{D}^0$ measurements. If sufficient separation of the mesons is possible, this measurement can instead be separated allowing for further constraints on the model parameters in the trigluon correlation function [13].

Current work on separating the D^0 and $\overline{D}^0$ mesons is ongoing through another simulated data sample using p+p collisions at RHIC energies with pileup. Without PID, the reconstructed invariant mass of the D^0 becomes a powerful tool for separation. Using KFParticle to obtain daughter candidate tracks, the $K^{\pm}$ and the $\pi^{\pm}$ mass assumption can be made for both tracks and, using the reconstructed momentum, used to create two different reconstructed mass values. Truth matched results have shown that the incorrect track mass assumptions will lead to a significant widening of mass distribution around the true mass of the D^0, allowing cuts to be made on each of the two reconstructed masses to label the mother as a D^0 or $\overline{D}^0$ candidate. Basic cuts as well as multivariate analyses are being tested using this method currently and preliminary work shows promising results which may allow sPHENIX to perform these measurements effectively.

5 Timeline and Progress

Fabrication, assembly, and installation of the sPHENIX detector systems are well underway in preparation for data-taking beginning in early 2023. In the assembly hall at RHIC, the outer support structure, outer hadronic calorimeter, and BaBar magnet are all firmly in place. This can be seen, minus the now-completed top of the support structure, in Figure 8. Outside the assembly hall, the remaining detectors are also rapidly approaching installation readiness. The inner hadronic calorimeter is completely assembled and installed in its support ring with pre-assembly-hall testing completed. All electromagnetic calorimeter sectors have been assembled and are nearly completely tested while installation practice is ongoing. The tracking detectors (MVTX, INTT, TPC, and TPOT) are all also well along the way towards being ready for installation in the coming months, and are still undergoing testing and assembly.

Although there is still significant work remaining for sPHENIX to be ready for day-1 data taking, the current progress puts the collaboration in position to be able to align with its projected commissioning and data taking schedule as shown in Figure 9.

FIGURE 8. Outer Hadronic Calorimeter completely assembled and installed in the sPHENIX assembly hall at RHIC

Year	Species	$\sqrt{s_{NN}}$ [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 9. Proposed run schedule in the sPHENIX beam use proposal. Further details given in [2].

6 Conclusion

sPHENIX is rapidly approaching data taking and first analyses coming at the start of 2023. The collaboration has made great efforts to keep assembly and installation projects on schedule, while also preparing analysis and reconstruction modules to be ready for the first data taken. With these efforts, sPHENIX is prepared to make extremely precise and accurate measurements critical to the stated goals of the 2015 Long Range Plan for Nuclear Science [3] that also encompass numerous first-ever measurements made at RHIC such as the nuclear modification factor of the Upsilon 3S state, a baseline p+p measurement of the Λ_c baryon to D^0 meson production ratio, and possible separation of D^0 and $\overline{D}^0$ v_1.

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