Recommendations of the Nuclear and Particle Physics Program Advisory Committee
Brookhaven National Laboratory

November 7 – 8, 2024

1. Executive Summary

The Program Advisory Committee (PAC) convened on November 7 – 8, 2024, to evaluate the sPHENIX and STAR Beam Use Requests for Runs 25 – 26. The ALD requested proposals for RHIC operation for 20 and 28 cryo-weeks. STAR and sPHENIX presented reports of their Run 24 detector and data-taking performance, run goals and achievements, and operational challenges. The PAC was also presented with reports from C-AD on the RHIC machine performance and challenges in Run-24, and projected RHIC machine operations in Runs-25/26 (20/28 weeks) and the transition from RHIC to the EIC. A report on the efforts by BNL on RHIC data preservation and planning, as well as an update on the status of data preservation in PHENIX were given. The status of the ongoing analyses by the RHIC collaborations was made available to the PAC on the meeting website in the form of publications since the PAC meeting in 2023.

The PAC thanks the STAR and sPHENIX collaborations and the C-AD for their presentations and cooperation in preparing for this PAC meeting in short order (less than three weeks) after the end of Run 24. The response of the collaborations, C-AD and BNL management to the PAC's questions was appreciated and helpful in formulating our recommendations. The ALD is to be commended for the efficient handling of the issues that arose during Run 24. C-AD, STAR and sPHENIX are congratulated for their performance in making Run 24 a success. Working together, sPHENIX, C-AD and BNL management made it possible to accomplish midstream changes at the experiment (isobutane, etc) and to successfully collide pp for physics, and Au+Au for commissioning sPHENIX and for physics for both experiments. This was sufficient to also allow necessary projections for the RHIC 2025 Au+Au run. We commend the sPHENIX Collaboration for completion of their Au+Au commissioning and successful pp data taking in Run 24. Likewise, STAR accomplished very successful pp data taking that will strongly benefit their polarized pp physics program.

The PAC commends STAR for its continued success in the production of high-impact physics results and publications, the large number of PhDs awarded, and its diverse and innovative physics program. The PAC is impressed by the record-breaking number of publications in the last three years, several of which have been highlighted by the DOE Office of Science. These include the observation of the new heaviest exotic antimatter nucleus, the large nuclear suppression in J/ψ photoproduction in ultra-peripheral Au+Au collisions, triangular flow measurements in Au+Au at $\sqrt{s_{NN}}$ = 3 GeV, the development of a novel program of imaging shapes of atomic nuclei, establishing an upper limit on the chiral magnetic effect in isobar collisions, new hard-probe observables, and an extensive cold QCD program.

As we look ahead to Run 25 and its possible extension, we focus our remarks on what we see as necessary for the successful completion of the RHIC Scientific Mission, and why. In this context, it is fully clear that the top priority for Run 25 is collecting the marquee Au+Au data set that is the raison d'etre for sPHENIX, that will also allow STAR to complete an impressive suite of impactful measurements, and that is essential for the successful completion of the RHIC Science Mission.

- The PAC recommends a Au+Au run in which sPHENIX collects at least 7 nb^{-1} of data as the highest priority for Run 25.

It is the view of the PAC that in order to make sure that it is positioned to complete the RHIC Science Mission, BNL Management must – out of an abundance of caution – vigorously pursue the ability to extend the RHIC run beyond Calendar Year 2025 in case any unknown event(s), including financial, conspires to curtail Calendar Year 25 data-taking and thus jeopardizes completion of the RHIC Science Mission. Another part of hedging against unpredictable events should be starting Run 25 as early in March as possible, so as to allow as much running time as needed in Calendar Year 25.

- The PAC urges BNL Management to vigorously pursue the ability to extend the RHIC run beyond Calendar Year 2025 in case any unknown event(s), including financial hardship, conspires to curtail Calendar Year 25 data-taking.

- The PAC recommends that BNL Management in consultation with the experiment collaborations form a plan to start Run 25 as early in March as possible.

2. The Beam Use Requests

2.1 Discussion of RHIC Run 25

Au+Au:

The top priority for Run 25 is collecting the marquee Au+Au data set that has been identified by the PAC for at least the past four years and by the Nuclear Science community since the 2015 Long Range Plan as the raison d'etre for sPHENIX. The same run will also allow STAR to complete an impressive suite of impactful measurements. There is no question that this run is essential for the successful completion of the RHIC Science Mission.

sPHENIX has made a persuasive case that 7 nb^{-1} of Au+Au data in Run 25 is the minimum luminosity for this run that will enable the landmark hard probes measurements that have been stated as goals for Nuclear Science in and since the 2015 Long Range Plan. *A Au+Au run in which*

sPHENIX collects at least 7 nb^{-1} of data is the highest priority for Run 25. Based on the projections we have seen, this alone corresponds to a 28 week run.

p+p, p+Au and O+O:

The Au+Au run above is essential to the successful completion of the RHIC Science Mission but by itself is not sufficient. The PAC notes that the successful completion of the core scientific mission of RHIC poses considerable challenges in light of the foreseeable end of RHIC operations. Specifically, in addition to the request for the Au+Au run in which sPHENIX collects at least 7 nb^{-1} of data, the PAC has received beam use requests for running pp, p+Au, and O+O collision systems. *The PAC sees all three of these proposed runs as fully aligned with RHIC's core scientific mission, and in fact as key elements of completing that mission. Each of these three proposed runs is necessary to address central open RHIC Science questions in a decisive way.* We shall say more about each of the three below.

However, based on current projections, and given the uncertainties related to machine operation during Run 25, it is currently unclear to what extent an extended Run 25 may allow for pp, p+Au and O+O running. In any other PAC year, we would describe all three collision systems as "must dos", and the only question would be which gets done when. In the present circumstances, as we seek to provide the best advice regarding the optimal use of the remaining running time, the PAC is convinced that an assessment of machine performance and data-taking efficiency of the experiments after the start of Run 25 can provide decisive additional input, not yet available today.

- **The PAC proposes to meet again in the middle of the Au+Au running period, once physics data-taking is well underway and projections for the completion of the Au+Au run can be based upon experience.**

- **The PAC postpones any recommendation about the relative priority ordering of p+p, p+Au and O+O to its next meeting once an assessment of the operation and performance of the machine and experiments from the start of Run 25 has been made.**

The PAC therefore restricts itself at this time to recalling the key motivations for running pp, p+Au and O+O, and why each is necessary for the successful completion of the RHIC Science Mission.

p+p:

The sPHENIX detector was approved and built in order to make decisive hard probes measurements with the highest precision at RHIC. An eight-week pp run is necessary to achieving this goal. If sPHENIX is able to take data in a 50% streaming mode, it could possibly realize its open heavy flavor physics program with a five-week pp run; whether this is possible should be clear at the time of our next meeting. *In order to realize the*

scientific impact of the marquee 2025 Au+Au run, this pp run is essential to completing the RHIC Science Mission successfully. This is to ensure that the statistical errors in flagship hard probes measurements coming from the pp reference data are comparable to those coming from the Au+Au measurements. Such a polarized pp run would also improve our knowledge of the spin structure of the nucleons and add new measurements of spin asymmetries, such as the D^0 transverse single spin asymmetry that is expected to provide information on the gluon Sivers function.

Polarized-p+Au:

A polarized-p+Au run, with the new sPHENIX detector and STAR with its forward upgrades will produce unique, landmark measurements that will never again be possible. This has long been seen as an important element of the RHIC Science Mission. With the recent forward upgrade of STAR and the newly constructed sPHENIX, many yet unexplored kinematic regions and reaction channels in p+Au collisions will be accessible for the first time, offering considerable discovery potential.

Examples of measurements in polarized p+A collisions include the forward transverse spin asymmetries for charged hadrons, Collins asymmetries of identified hadrons in jets, and asymmetries in exclusive J/ψ production in ultraperipheral events. These measurements will allow to pin down the role of spin in the initial and final state, explore the spin dependent hadronization and effects of cold nuclear matter, as well as give first insight into the novel generalized parton distribution, which is sensitive to spin-orbit correlations and provides information about the orbital angular momentum carried by partons inside the nucleon.

The unpolarized p+A collisions will provide information on the nuclear parton distribution functions through the Drell-Yan process and direct photon measurements in a region of kinematics that is complementary to that achieved presently in p+Pb collisions at the LHC. The p+A runs at RHIC also offer the unique possibility to search for non-linear QCD effects at small x. This can be achieved through the processes of the di-hadron correlations in the forward region in a wide range of transverse momenta, which can be measured very precisely thanks to the upgraded forward instrumentation of the STAR experiment. This instrumentation allows also for precise measurements of the direct photon-jet and photon-hadron correlations in a novel kinematic regime.

RHIC has an outstanding scientific opportunity to complete unique, must-do, measurements in p+Au collisions that will be essential if we are to fully realize the scientific promise and impact of the future EIC. RHIC can provide a suite of measurements in p+A collisions that, when combined with future data from eA collisions from the EIC, will establish the validity and limits of factorization and universality. Data from the p+Au

run proposed for Run 25 will be of considerable value in planning for the EIC physics program, as well as in realizing the impact of future EIC data.

In addition, the p+Au collisions, together with the pp and Au+Au collisions, represent three complementary and closely-related colliding systems, whereby comparisons between them are crucial for optimizing our understanding of new results obtained in all these collisions. While a longer run would be desirable, *even a five-week p+Au run will allow for measurements that are unique and essential to completing the RHIC Science Mission successfully and that will contribute integrally to the science impact of future measurements from the EIC.*

O+O:

The two most impactful discoveries from the RHIC program are collective flow and jet quenching. The central open question that must be addressed in order to complete the story, even the paradigm, is whether jet quenching is also seen in Oxygen+Oxygen. While previous O+O running at RHIC has established collective flow, a two-week O+O run at RHIC with today's capabilities will provide sufficient integrated luminosity to address the fundamental question of whether jet quenching and collective flow are complementary aspects of the same QGP physics across all system sizes. This will allow RHIC to address a key open problem related to the two main RHIC discoveries of perfect fluidity and jet quenching. Both phenomena are understood as consequences of final-state interactions in the strongly coupled fluid, so if there is collective dynamics there must also be jet quenching on some scale.

A two-week O+O run at RHIC would realize the only possibility to make comparisons of hard probe measurements in identical nucleus-nucleus collision systems at RHIC and the LHC, i.e. keeping the geometry fixed but greatly varying the collision energy and thus QGP properties. However, only collective flow has been observed to date in small collision systems. O+O is optimal to resolving this puzzle, since it is a small system but still large enough to expect a measurable amount of jet quenching if our current understanding is correct. *This makes a brief O+O run, with the detectors and luminosity needed to make the requisite measurement in place for the first time, a unique opportunity for RHIC to address a central question posed by its two biggest discoveries and hence an essential element of completing the RHIC Science Mission successfully.*

Other Opportunities:

STAR has also presented two further opportunities for additional brief runs, each motivated by scientific questions from other fields. The first is to investigate the shapes and radial profiles of deformed atomic nuclei utilizing various new beam combinations, specifically to investigate the triaxiality of the well-deformed rare earth nuclei ^{154}Sm and

^{166}Er. The possibility of gaining information about the shapes of nuclei via analyzing their ultra-relativistic collisions has previously been demonstrated via analyses of the Ru+Ru and Zr+Zr data from RHIC and the extraction of constraints on the neutron skin depth of ^{208}Pb from measurements of Pb+Pb collisions at LHC energies. The second originates from the space radiation community. It is to utilize three different beams (C, Al and Fe) with energies between 6 and 50 GeV on fixed targets (also C, Al and Fe) to address their need for nuclear data for space radiation protection. There is scientific merit to both proposals, and we support pursuing them if the opportunity to do so were there without infringing upon the completion of the RHIC Science Mission.

3. RHIC Collaboration Reports

3.1 sPHENIX

The PAC commends the sPHENIX Collaboration for their outstanding efforts to make the 2024 Run a success. The experiment collected 200 GeV pp collision data sets achieving 240% of the calorimeter-based jets/photon BUR goal, 65% of the open heavy flavor goal and 30% of the Upsilon/Jet goal. The Collaboration overcame major TPC high voltage stability issues by operating the drift gas with isobutane mixture. The sPHENIX TPC experts and the Operation team demonstrated exceptional dedication and effectiveness in working with the BNL Safety Review Committee to secure approval in a relatively short time for the use of isobutane in the TPC. The other sPHENIX subsystems operated smoothly during the p+p Run. The streaming readout rate for the tracking detectors (MVTX, INTT and TPC) exceeded the original goal of 10% by a factor of three on average during the run enabling acquisition of a significant amount of data for open heavy flavor physics.

For the three-week Au+Au commissioning, the sPHENIX experiment operated all detector subsystems in the heavy-ion collision environment. The TPC achieved very stable operation in the Au+Au run and the operation is expected to be under better control when the CAEN HV supplies are fully deployed for all sectors in Run 25. A possible TPC gas contamination in the last 10 days of Au+Au commissioning was noted by sPHENIX. The PAC suggests that sPHENIX establish procedures at the beginning of Run 25 for monitoring the issue closely. During the Au+Au commissioning, beam-related “big-splash” background events were observed in the MVTX creating large deadtime that limited operation of the detector in streaming read-out mode. sPHENIX and C-AD have collected needed diagnostic data and formed a task force to evaluate options to mitigate the beam background. The PAC supports the continuing efforts of sPHENIX and C-AD to enhance the detector performance and data quality during Run 25, which had been critically important for the success of pp data-taking in Run 24. The impact of the MVTX auto-recovery dead time due to the splash background is expected to be significantly reduced when the data acquisition is run in a triggered mode instead of the streaming read-out mode.

The PAC eagerly looks forward to the first physics results from the Run 24 data taking.

- The PAC recommends that the sPHENIX Collaboration develop the necessary hardware/firmware to increase the streaming readout rate in anticipation of possible pp or p+Au data-taking in Run 2025-2026.

- The PAC recommends that BNL Management provide C-AD, working with sPHENIX, with the resources to complete their analysis and reduction of the background causing the "big-splash" events that impact the MVTX operation in untriggered Au+Au running and possibly in p+Au collisions.

3.2 STAR

The PAC congratulates the STAR collaboration for achieving its data taking goal for Run 24, both in pp and in Au+Au, despite challenges in schedule and operations during the summer months. The PAC congratulates STAR for the successful operation of the recent forward detector upgrade and DAQ5k. We are looking forward to the analysis of these data and their unique physics impact.

We commend STAR for their continued success in high-impact physics analyses and publications, the number of awarded PhDs, and their diverse and innovative physics program. The PAC is impressed by the record-breaking number of publications in the last three years, several of which have been highlighted by the DOE Office of Science. These publications include the observation of the new heaviest exotic antimatter nucleus, the large nuclear suppression in J/ψ photoproduction in ultra-peripheral Au+Au collisions, triangular flow measurements in Au+Au at $\sqrt{s_{NN}}$ = 3 GeV, the development of a novel program of imaging shapes of atomic nuclei, establishing upper limit on the chiral magnetic effect in isobar collisions, new hard-probe observables, and extensive cold QCD program.

The PAC is pleased to see the release of high-precision proton and net-proton multiplicity cumulants data in the Spring of 2024, and is looking forward to the publication, which is currently in collaboration review. The PAC was excited to learn that the analysis of the FXT BESII data is well underway, and looks forward to the results being shown at the first opportunity.

The PAC is pleased to see the continuous progress in the analysis of the different pp transverse spin asymmetries over a wide kinematic region, that are complementary to the SIDIS measurements, allow for better determination of the Sivers and the transversity functions and provide essential new insight into universality, factorization and TMD evolution.

The data collected in Run 24 will allow for multidimensional measurements of transverse spin asymmetries with increased precision. The new data, thanks to the Forward Upgrade, together

with the data collected in the previous runs, will provide valuable information about evolution effects and will establish the most precise benchmark for future comparisons to ep data from the EIC.

- The PAC recommends that STAR continue its efforts to analyze their pp and Au+Au data that were collected with the Forward Upgrade in Runs 22 and 23. Results from these data would provide important input for optimizing the run plan for Run 25.

4. Data Preservation

The RHIC's scientific mission would be incomplete without comprehensive data and analysis preservation (DAP). The PAC commends BNL Management for developing a comprehensive DAP plan first presented at the meeting. The components of the plan include software and knowledge preservation, adherence to FAIR principles, and the creation of a dedicated portal. All these are vital for successful DAP.

- PAC recommends that BNL provide the necessary infrastructure and resources for implementing the Data and Analysis Preservation (DAP) plan.

All collaborations are commended for their work on DAP. PHENIX collaboration has already accumulated significant expertise in DAP. Both STAR and sPHENIX have developed DAP plans and are taking steps towards implementation.

- The PAC recommends that BNL ensure that coordination between STAR, sPHENIX and PHENIX on DAP takes full advantage of the various lessons learned and that the necessary infrastructure and resources are available for data preservation now and in the future.

5. Off-Line and On-Line Computing for Runs 25 and Beyond

BNL's planned computing and storage upgrades for Run 25 will allow sPHENIX to take and store data, as well as perform online data processing. The PAC has now heard that orders for both the CPU and storage upgrades for Run 25 will be placed this month. These upgrades are expected to be installed before the planned start of Run 25, however the timing of installation could become an issue were the run to start sooner than early March.

Even though the BNL-STAR group was able to hire a new postdoc, their computing workforce remains an issue. The new hire has been instrumental in processing the backlog of embedding requests. However, there are concerns about the long-term availability of the general support for

STAR's software environment at BNL, and the workforce and computing resources that it depends on.

The software and computing workforce remains an issue at BNL. Attempts to maximize effectiveness of the limited workforce at BNL by sharing across experiments have had mixed success, mostly due to differences between the differing needs of the experiments. BNL is attempting to mitigate this by targeted hiring.

RHIC data analysis support (software and computing) after RHIC shuts down will continue to be a major activity throughout the decade. Success in completing the RHIC Science Mission requires sustained support beyond Run 25. BNL management reports that workforce planning for this effort is underway.

- The PAC urges BNL management to maintain a clear and strong focus on providing the computing and personnel support needed for the analysis of sPHENIX and STAR data being taken now for at least half-decade after the completion of RHIC running. This is a necessity for completing the RHIC Science Mission.

- For the next PAC Meeting, the PAC requests that BNL Management provide a detailed report on the status and plans for long-term RHIC data analysis and data preservation, including workforce, computing resources, and with possible timelines.

6. Better Facilitating Collaboration with the Theory Community

The breadth, scope, discovery potential – and complexity – of the RHIC data sets from Runs 24 and 25 from sPHENIX with its unprecedented capabilities and from STAR with its enhanced forward instrumentation, as well as from the STAR Beam Energy Scan (first results shown earlier this year) and its fixed target program (first results anticipated soon) all demand a commensurate effort from theory in terms of theoretical analysis and modeling, if the scientific potential of these investments is to be realized. Theoretical simulations of the formation and evolution of the droplet of hot matter produced in a heavy-ion collision and the hadrons that emerge involve sophisticated three-dimensional modeling, using kinetic theory and hydrodynamics, over a wide range of baryon densities. Theoretical modeling of jets, including their wakes, and heavy quarks and quarkonia requires adding the dynamics of the interaction between these hard probes and the aforementioned hot matter. Experimentalists and theorists together are investigating the discriminating power of new energy correlator observables arising from recent theoretical advances that have the potential to teach us much. An intensive cold QCD collaboration is also underway, to fully exploit the complementarity and impact of the data taken at RHIC to the physics accessible with the future EIC. In order to optimize progress in our understanding of RHIC physics given the expanded experimental capabilities (coverage and statistics), the integration of advances in modeling and

theory to address the key scientific issues will require tight coordination between sPHENIX, STAR and the theory community over the coming half-decade.

In order to fully realize the scientific impact of the completion of the RHIC Science Mission, the implications of, and connections between, the discoveries that will be made from Runs 24 and 25 data will need to be understood. To foster this progress and realize the scientific impact of these discoveries, BNL should pursue strategic involvement of the theoretical community -- whether it be through workshops, visitor programs, or sabbatical support — throughout the half-decade after RHIC operation ends.

- The PAC recommends that BNL pursue a strategy to better facilitate the progress of RHIC physics over the coming half-decade through strategic involvement of the theoretical community. Such a strategy is needed in order to fully realize the scientific impact of the completion of the RHIC Science Mission.

7. PAC Recommendations

- The PAC recommends a Au+Au run in which sPHENIX collects at least 7 nb^{-1} of data as the highest priority for Run 25.

- The PAC proposes to meet again in the middle of the Au+Au running period, once physics data-taking is well underway and projections for the completion of the Au+Au run can be based upon experience.

- The PAC postpones any recommendation about the relative priority ordering of p+p, p+Au and O+O to its next meeting once an assessment of the operation and performance of the machine and experiments from the start of Run 25 has been made.

sPHENIX:

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STAR:

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BNL Lab Management:

- The PAC urges BNL Management to vigorously pursue the ability to extend the RHIC run beyond Calendar Year 2025 in case any unknown event(s), including financial hardship, conspires to curtail Calendar Year 25 data-taking.

- The PAC recommends that BNL Management in consultation with the experiment collaborations form a plan to start Run 25 as early in March as possible.

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- The PAC urges BNL management to maintain a clear and strong focus on providing the computing and personnel support needed for the analysis of sPHENIX and STAR data being taken now for at least half-decade after the completion of RHIC running. This is a necessity for completing the RHIC Science Mission.

- The PAC requests that BNL Management provide at the next PAC Meeting a detailed report on the status and plans for long-term RHIC data analysis and data preservation, including workforce, computing resources, and with possible timelines.

- PAC recommends BNL to provide the necessary infrastructure and resources for implementing the Data and Analysis Preservation (DAP) plan.

- The PAC recommends that BNL ensure that coordination between STAR, sPHENIX and PHENIX on DAP takes full advantage of the various lessons learned and that the necessary infrastructure and resources are available for data preservation now and in the future.

- The PAC recommends that BNL pursue a strategy to better facilitate the progress of RHIC physics over the coming half-decade through strategic involvement of the theoretical

community. Such a strategy is needed in order to fully realize the scientific impact of the completion of the RHIC Science Mission.

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