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

June 15 – 16, 2017

1. Introduction

The Program Advisory Committee (PAC) convened on June 15 – 16, 2017, to evaluate the STAR Beam Use Request for Runs 18 and 19. There were also presentations from STAR and PHENIX on their data-taking, analysis progress and key publications from Runs 15 and 16. The PAC heard a presentation on BNL's Computing Strategy for the RHIC Experiments, and separate presentations on the Physics of the Beam Energy Scan II and the Isobar Comparison Run. A Status Report on sPHENIX and Modest Forward Upgrade Options for STAR and for sPHENIX were reported in separate presentations.

The PAC thanks the collaborations for their work and presentations, and the collaborations and CA-D for their input and cooperation in responding to questions. It congratulates STAR and the CA-D for effective operation for physics this year. The refurbished FMS and the new FMS post-shower detector worked well. Run 17 has been successful with the $\sqrt{s} = 500$ GeV p+p data-taking having exceeded the integral luminosity goal for the $W^{\pm}$ and Z^0 data taking, 130% of that goal, and approaching the goal for the Drell-Yan (DY) data-taking with 93% of that. The data should yield significant results on evolution of the transverse momentum distributions and the sign change of A_N in these channels, as well as other spin observables. With the end of Run 17 a week away, STAR projects to collect between 1.0 – 1.3 billion $\sqrt{s_{NN}} = 62$ GeV Au+Au minimum bias events meeting their goals for data taking for measurements of jets, non-photonic electrons, and thermal photons in that system.

The PAC commends both the PHENIX and STAR collaborations for maintaining outstanding scientific productivity in terms of the number of published papers, number of Ph.D. graduates and the high impact of papers in the nuclear physics community. The collaborations continue to maintain a strong contingent of students and post-docs working on data analysis for RHIC physics. STAR has secured external financial contributions that enable important detector upgrades necessary for the BES-II program; the iTPC, EPD and eTOF upgrade projects are on schedule. Growth in the STAR collaboration membership is a strong indication that STAR has a vigorous scientific program and RHIC continues to be a national facility at the frontier of nuclear science.

RHIC published papers continue to have very high impact in the nuclear physics community. Notable papers in the last year include the first RHIC measurements of D^0 elliptic flow using the STAR HFT [PRL 118 (2017) 212391], and B meson production via its decay to J/ψ using the PHENIX FVTX [PRD 95 (2017) 092002 and arXiv:1702.01085], the PHENIX measurement of collective flow in high-multiplicity p+Au collisions [PRC 95 (2017) 034910] that concludes the RHIC small-systems geometry scan, and the STAR discovery of global hyperon polarization in nuclear collisions, which provides evidence for the most vortical fluid [to appear in Nature].

The PAC commends the STAR collaboration for successfully securing external computing resources, such as the high-performance computing at the CORI supercomputer at NERSC. The 25 M CPU hours allocated to STAR at CORI in the last year have significantly increased the data production throughput and, along with high-efficiency utilization of RCF, eliminated the backlog of datasets awaiting reconstruction. The PAC commends the STAR collaboration for successfully implementing a new pico-DST data format that led to 6.5 times reduction in needed storage space and ensured that the current storage can handle the projected needs up to FY20.

The PHENIX experiment has completed data taking in 2016. The present computing resources can meet their goals of completing data production in a year. The PAC is concerned about PHENIX maintaining adequate manpower supporting both data production and analysis needs.

1.1 Beyond the Beam Use Request

The PHENIX collaboration has completed its data-taking mission and decommissioning of the PHENIX detector is well underway. STAR is the only detector taking data at RHIC for the next three years. As a result, the newly acquired data will be unique without comparison results for the foreseeable future.

It is recognized that the RHIC results on the global Lambda polarization, kurtosis in the search for a critical point, and the CME from the isobar running add discovery potential to the RHIC program and are critically important to the field. Therefore, for new results on these three high-profile topics the PAC recommends that the STAR Collaboration eliminates preliminary release of the data and proceeds directly to journal publication. Prior to journal submission and any public release, STAR should present to BNL's Associate Laboratory Director the proposed paper and sufficient (confidential) documentation for scientific feedback on the findings, to which STAR will respond. In addition, the PAC recommends implementation of double-blind analyses for the Isobar run.

The PAC congratulates the STAR collaboration and RHIC management for finding new computing resources and new funding sources to support the iTPC and EPD upgrade projects and to carry out their future upgrades that should enable a strong BES-II physics program. BNL Management is commended for having quickly commissioned after the last PAC meeting a panel of local computing experts that evaluated STAR’s needs for computing resources and helped to optimize the use of computing resources.

The PAC views DY measurements as important for future forward physics and puts high priority on the analysis of the 2017 STAR DY data. Likewise, the 2017 RHIC Spin run must be analyzed quickly and as completely as possible, and requires maintaining at least the present effort on spin analyses.

The PAC congratulates the sPHENIX collaboration for their progress in obtaining CD-0 approval in the last year. sPHENIX continues to optimize their detector configurations through prototyping, beam tests and more realistic computer simulations, as well as their physics capabilities and rates.

The PAC commends sPHENIX for identifying its MIE detector components and finding experienced research groups to take responsibility for some of these, as well as seeking external funding beyond the MIE for the inner tracking components (silicon strip and MAPs systems).

The PAC heard presentations from STAR and sPHENIX for modest upgrades for forward physics. The PAC commends both the sPHENIX and STAR collaborations for their significant effort in preparing their forward detector upgrade plans. The physics case for the forward upgrade is compelling, is important for the future EIC program and the expanded pseudo-rapidity reach adds to the heavy-ion program.

2. RHIC Runs 2018 and 2019

2.1 Executive summary

The PAC recommends for Run 18 the following:

- $\sqrt{s_{NN}}$ = 200 GeV $^{96}Ru+^{96}Ru$ and $^{96}Zr+^{96}Zr$, 1.2 billion minimum bias events in each system. This program has the potential to clarify a question of major significance in the field – can a signal of the chiral magnetic field be extracted from charge separation measurements in two isobaric systems. This is the highest priority for Run 18.
- 3 weeks of $\sqrt{s_{NN}}$ = 27 GeV Au+Au collisions accumulating 1 billion events to measure effects of global polarization of Lambdas and anti-Lambdas with high statistics, assuming RHIC operates with 15 weeks of cryogenic running in 2018.
- 2 days of $\sqrt{s_{NN}}$ = 3 GeV Au+Au collisions in fixed-target mode to accumulate approximately 100 million events in order to investigate net proton fluctuations at an energy between its BES I run and the lower energy HADES runs.

The experimental isobar (Ru+Ru and Zr+Zr) program proposed by STAR two years ago, reinforced last year by simulations and the Report of the Chiral Magnetic Effect (CME) Task Force is a compelling program that takes advantage of the flexibility of RHIC and the capabilities of the STAR detector. It should be able to unravel a signal from the CME out of background contributions from flow, if the CME signal exceeds 20% of the magnitude of the correlation observable.

Building on the recent discovery of the vortical fluid, there are hints of a possible Faraday fluid extending throughout the plasma and thus the proposed Lambda and anti-Lambda global polarization measurement is important to investigate the features of the QCD fluid formed in non-central heavy-ion collisions.

The PAC sees that the $\sqrt{s_{NN}}$ = 3 GeV fixed-target run in STAR affords the opportunity to investigate net-proton fluctuations with good statistics and large acceptance in the energy gap between its BES I run and the lower energy HADES runs. It is important to have this first fixed-target run before the BES II, which includes six short fixed-target runs.

The PAC recommends for Run 19:

Commencement of the first half of Beam Energy Scan II with the following runs:

- $\sqrt{s_{NN}}$ = 11.5, 14.5 and 19.6 GeV Au + Au minimum bias collisions with a goal of accumulating 230 million, 300 million and 400 million events, respectively, starting at the highest energy and working down. This is the first priority for data acquisition in Run 19. In addition, once low energy electron cooling is commissioned a run at $\sqrt{s_{NN}}$ = 9.1 GeV should be undertaken.
- Interleaving between the above runs a *fixed-target run* with 100 million minimum bias events at each RHIC Au beam energy listed above, corresponding to fixed-target runs at $\sqrt{s_{NN}}$ = 4.5, 3.9, 3.5 GeV Au + Au.
- *Fixed-target runs* collecting 100 million Au+Au minimum bias events each at $\sqrt{s_{NN}}$ = 7.7, 6.2, and 5.2 GeV.

Run 19 will initiate the BES II program with minimum bias measurements in Au + Au collisions with $\sqrt{s_{NN}}$ = 19.6 GeV, 14.5 GeV and 11.5 GeV. This sequence of operation allows the simultaneous commissioning of the low energy electron cooling, critical to the measurements at $\sqrt{s_{NN}}$ = 9.1 GeV. The PAC concurs that these collider measurements, including a start on the 9.1 GeV run at the end of Run 19 are the *top priority* for Run 19. In the following year, with the low energy cooling commissioned and operating, RHIC will be positioned to make the flagship measurements at $\sqrt{s_{NN}}$ = 7.7 and 9.1 GeV that will complete the BES II program.

The PAC supports the proposed Run 19 plan of six fixed-target runs, each accumulating 100 million events, at six center-of-mass energies ranging from $\sqrt{s_{NN}}$ = 3.5 to 7.7 GeV as a strongly motivated *second priority* for Run 19.

2.2 Summary Discussion of Run 18 and Priorities

Run 18 requests address three separate fundamental questions facing the relativistic heavy-ion community. Each of these three runs carries significant discovery potential, and in each case exploits new capabilities of the RHIC accelerator and/or the STAR detector. The ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr runs represent the opportunity to obtain a definitive answer to a central question in the field, and thus is of the highest priority. If nature yields an affirmative answer to the question on the table this will demonstrate that the chiral anomaly – a fundamental feature of quantum field theory – has macroscopic consequences. Observing or constraining chiral effects may also shed light on the restoration of chiral symmetry. Restoring chiral symmetry involves melting the scalar quark condensate responsible for generating quark masses, and chiral phenomenology depends critically on mass. The $\sqrt{s_{NN}}$ = 27 GeV Au+Au run represents the opportunity to turn what is currently a hint of the possible detection (via global Lambda polarization) of a trapped magnetic field in the quark-gluon plasma produced in these collisions into either a discovery or an interesting limit. The Au+Au fixed-target run at 3 GeV center-of-mass energy will be the first physics run in the STAR fixed-target program and as such will set the stage for, and demonstrate the viability of, a newly developed component of the Beam Energy Scan II program that will begin in Run 19.

The PAC recommends that the ^{96}Ru+^{96}Ru and ^{96}Zr+^{96}Zr runs, each of sufficient length to accumulate 1.2 billion events, be given highest priority. This would represent the first comparison of systems with identical sizes but differing charges in highly relativistic heavy-ion collisions. This comparison provides the leverage to differentiate effects based on their *Z*-dependence. Most importantly, the principal observable for identifying the existence of the chiral magnetic effect (CME) is plagued by background. If same-sign pairs are more likely to be observed in the same direction than opposite-sign pairs when the pairs are perpendicular to the reaction plane, as in the CME, this contributes to the observable γ_p. Chiral effects are driven by the large magnetic fields from the incoming nuclei and the spectator matter, and γ_p scales as the square of the field, and thus scales as Z^2. Thus, the ten percent difference in *Z* of the Ru and Zr isotopes translates into a 20% difference in the magnitude of the CME contribution to γ_p. In contrast, the background, which involves local charge conservation superimposed onto elliptic flow, is largely independent of *Z*. Differentiating these contributions would provide the first clear demonstration of collective anomalous chiral currents in heavy-ion environments, and provide the first demonstration of coupling between chiral charge in the electromagnetic and QCD sectors in any context.

The PAC also strongly endorses STAR's request for a 3 week high-statistics $\sqrt{s_{NN}}$ *= 27 GeV Au+Au run aimed at establishing the existence of a Faraday fluid*. STAR has published a landmark analysis, which for the first time measured a non-zero "global polarization" of nuclear spins for hadrons emitted from a high-energy heavy-ion collision. A collective effect like this must come from a macroscopic collective rotation of the droplet of quark-gluon plasma. By observing final-state global polarization of Lambda baryons, STAR has made a compelling case for large rotational velocities existing in equilibrated hot QCD matter. The mechanism for converting the large angular momentum of the incoming nuclei to rotational angular momentum of the fluid is currently far from understood. The possibility of observing a *Faraday fluid* would represent a major discovery for the RHIC program, both as an experimental tour-de-force, and by establishing the existence of strong coherent magnetic fields in the equilibrated stages of heavy-ion collisions. The EPD (event-plane detector) upgrade to the STAR detector is needed in order to reduce the error bars in the global polarization measurement as proposed. This upgrade is on schedule to be fully installed for Run 18, making possible the proposed run.

The PAC also recognizes the unique potential of the 2-day fixed-target run. STAR proposes to run a single fixed-target beam energy, Au+Au at 3 GeV center-of-mass energy for two days that will establish the feasibility of a substantial fixed-target program proposed for Run 19. This follows previously successful short pilot tests in 2014 and 2015. The PAC recognizes the value of a 2-day fixed-target run in Run 18 to accumulate the first physics in this mode and establish the viability of the proposed Run 19 program. By measuring and analyzing data from one fixed-target energy in Run 18, STAR will be better able to optimize the setup and analysis of future fixed-target runs. The fixed-target collisions proposed by STAR in Runs 18 and 19 fill an important energy gap between HADES and SPS measurements. It is expected that sufficient data will be collected in each of these runs to make fluctuation and correlation measurements, e.g. kurtosis, related to critical phenomena and phase separation. (The data sets collected in each 2-day run are expected to contain approximately four orders of magnitude more events than those from the EoS TPC in the AGS era; thus they will have the statistics needed for these analyses.) Establishing, or constraining, the existence of a first-order phase transition in hot matter at supra-normal baryon densities has represented a principal goal of high-energy heavy-ion physics since its inception. Given the discovery potential of this program, the PAC recommends that this portion of the request be completed even if it infringes on the ability to accomplish fully the 27 GeV Au+Au run statistics.

2.3 Summary Discussion of Run 19 and Priorities

The PAC looks forward with considerable anticipation to the first year of the two-year Beam Energy Scan (BES) II program in Run 19. BES II was identified as a high priority in the 2015 NSAC Long Range Plan. The plan for Run 19, as proposed to the PAC by STAR, will begin the exploration of the phase diagram of QCD that is the purpose of the BES II program by making definitive measurements at center-of-mass energies $\sqrt{s_{NN}}$ = 19.6 GeV, 14.5 GeV and 11.5 GeV. Beginning the BES II program with these higher BES energies is well-motivated: it will allow the simultaneous commissioning of the low energy cooling that is critical to completing the program with measurements at $\sqrt{s_{NN}}$ = 9.1 GeV and 7.7 GeV. With 24 cryo-weeks in Run 19, it will also be possible to begin the $\sqrt{s_{NN}}$ = 9.1 GeV measurements at the end of Run 19. These collider measurements in sum are the top priority for Run 19. In the following year, with the low energy cooling commissioned and operating, RHIC will be positioned to make flagship measurements at $\sqrt{s_{NN}}$ = 7.7 and 9.1 GeV that will complete the exploration promised in the Long Range Plan, and that will give RHIC the opportunity to find a critical point in the QCD phase diagram if there is one in the region with baryon chemical potential up to 400 MeV.

The PAC commends STAR for its pilot fixed-target measurements. This program can extend the Beam Energy Scan to lower collision energies, meaning extending the exploration of the QCD phase diagram to even higher baryon doping, albeit at lower temperatures. With the first physics run in fixed-target mode anticipated in Run 18, the PAC anticipates that next year it will be able to make a fully informed recommendation in support of the proposed Run 19 plan for six 2 day fixed-target runs yielding 100 million events at six center-of-mass energies ranging from $\sqrt{s_{NN}}$ = 3.5 to 7.7 GeV as a strongly motivated second priority for Run 19. Including the highest of these energies is important as it will allow cross-checking the new and challenging fixed-target measurements against the now well-developed collider analyses.

2.4 Discussion of Run 18 (2018)

The PAC recommends that the $^{96}Ru+^{96}Ru$ and $^{96}Zr+^{96}Zr$ runs, each of sufficient length to accumulate 1.2 billion events, be given highest priority. STAR first suggested this isobar run to the PAC in 2015. At its 2015 meeting, the PAC recommended that BNL "convene a working group that includes experimentalists from STAR as well as theorists with expertise relevant to understanding CME and related phenomena and who are familiar with the challenges related to separating its observable consequences from possible backgrounds" and asked that the working group provide a "critical assessment of the present state of understanding and map out a strategy", including sharpening the case for isobar collisions. At its 2016 meeting, the PAC reviewed the report of the Chiral Magnetic Effect Task Force that had been convened by BNL and that had done its work over the preceding year. The 2016 PAC highly commended the Task Force for rising to the challenge that it was given, in full, including providing the requested critical assessment and strategies for how best to use current data, and for having "made a considerable effort to develop a compelling case for isobar collisions." It was the simulations, analysis, and report of this Task

Force that persuaded the PAC of the feasibility of this challenging endeavor, and convinced it that "it represents an opportunity to use the unparalleled flexibility of the RHIC accelerator and the capabilities of the STAR detector to clarify a central puzzle in the field". This favorable report, and the solid analysis on which it was based, has clearly played a significant role in the development of this year's STAR beam use request, and it continues to play a critical role in forming the recommendations of this year's PAC.

The PAC was convinced that the requested compilation (1.2 billion events in collisions of each of the two isobars) was necessary, and that BNL should try to ensure that amount of data is collected even if it requires a reduction of the runs described below. As described in the STAR beam use request, and as last year's Task Force concluded in its report, if this many events are collected and analyzed the proposed isobar run will yield a 5 sigma difference between γ_p in Ru+Ru and Zr+Zr collisions if 20% or more of the effect presently seen in this observable is in fact due to the chiral magnetic effect. This means that STAR will settle the puzzle that we are faced with today either via clinching a major discovery (of the CME in heavy-ion collisions, which requires chiral symmetry restoration, a trapped magnetic field, and a macroscopic manifestation of the chiral anomaly from quantum field theory) or via showing convincingly that more than 80% of what we are puzzling over today can be understood in terms of background effects.

We note that CME effects are expected to be larger in lower-energy collisions due to the lesser Lorentz contraction of the magnetic field from the incoming nuclei, meaning that although the initial magnetic field is not as large in magnitude it persists longer, making it more likely that it is trapped in the quark-gluon plasma. STAR has requested that the isobar collisions be done at the highest possible energy, $\sqrt{s_{NN}}$ = 200 GeV. This choice was motivated by the need to accumulate 1.2 billion events for both the Ru+Ru and Zr+Zr runs, the fact that lowering the collision energy lowers the luminosity, and the fact that the plan is to use naturally occurring Ru, which contains only a small percentage of the ^{96}Ru isotope. We understand that if a sufficient quantity of isotopically enhanced Ru, containing more ^{96}Ru, can be obtained it may become possible to accumulate 1.2 billion events in collisions at a lower energy. During its meeting the PAC discussed 62 GeV as a potential option. *The PAC recommends that BNL, the CA-D and STAR consider running the isobar collisions at lower energy should the issue of isotope availability be overcome.*

The leverage provided by varying the isotopic composition of the beams (changing Z while keeping A fixed) can also be exploited in the physics of ultra-peripheral collisions. For very soft momentum transfer, the nuclei can be excited coherently with the cross sections scaling as Z^2 for γ-N processes or Z^4 for gamma-gamma channels. Coherent processes have been identified for excitations of the rho meson. In many instances competing processes create the same or similar final states, and determining the reaction mechanism is problematic. By comparing the same processes with ^{96}Ru or ^{96}Zr beams, STAR will be able to distinguish competing reaction channels. Isobaric variation may also prove useful in evaluating the relative role of electromagnetic and isospin-dependent mean fields in regards to other classes of observables, such as differential collective flow.

The PAC strongly endorses STAR's request for a 3 week high-statistics $\sqrt{s_{NN}}$ = 27 GeV Au+Au run aimed at establishing the existence of a Faraday fluid. In the last year, STAR has published a landmark analysis, which for the first time measured a non-zero "global polarization" of nuclear spins for hadrons emitted from a high-energy heavy-ion collision. Global polarization refers to a net polarization of all the hadrons of a given type in a given collision in a common direction, here perpendicular to the reaction plane. A collective effect like this must come from a macroscopic collective rotation of the droplet of quark-gluon plasma. By observing final-state global polarization of Lambda baryons, STAR has made a compelling case for large rotational velocities existing in equilibrated hot QCD matter. This has inspired the moniker *vortical fluid.* The large rotation, $\sim 10^{22}$ radians/s, is forcing a rethinking of the initial pre-equilibrium, or stopping, stage of heavy-ion collisions. The mechanism for converting the large angular momentum of the incoming nuclei to rotational angular momentum of the fluid is currently far from understood.

Even more remarkably, the same analysis was able to independently extract polarizations for both Lambda and anti-Lambda baryons. If the source of both polarizations were determined by the thermal equilibration of spin degrees of freedom with the medium's vorticity, both polarizations would be equal. However, if the difference were due to coupling with magnetic field, polarizations would be opposite. STAR has observed a small, ~ one-half sigma, difference that appears to persist across all the beam energies. By increasing the statistics, STAR has the potential to establish a statistically significant, > 3 sigma and possibly > 5 sigma, difference between the Lambda and anti-Lambda polarizations. This would make a compelling case for strong magnetic fields persisting throughout the expansion and cooling of the fireball. If not for the existence of matter, the magnetic field would decay on the scale of a few tenths of one fm/*c*. A long-lasting field requires the Faraday effect, the delayed decay of the initial magnetic field pulse produced by the spectator matter due to the rotating currents induced in the QGP as the initial field "tries to" decay. This possibility of observing a *Faraday fluid* would represent a major discovery for the RHIC program, both as an experimental tour-de-force, and by establishing the existence of strong coherent magnetic fields in the equilibrated stages of heavy-ion collisions. If the existence of a long-lived magnetic field is established it would enable theory and experiment to consider wholly new classes of questions. Just to give one example, the existence of persistent magnetic fields is critical for building CME or CMV effects in heavy-ion collisions to measurable levels.

The EPD (event-plane detector) upgrade to the STAR detector is needed in order to reduce the error bars in the global polarization measurement as proposed. The PAC commends the STAR collaboration for having this upgrade on schedule to be fully installed for Run 18, making this proposed run the opportunity that it is.

The PAC was enthusiastic in endorsing a 3 week $\sqrt{s_{NN}}$ = 27 GeV Au+Au run, with the goal of recording 1 billion events. However, the PAC noted that it anticipates STAR collecting 400 million events in Au+Au collisions at $\sqrt{s_{NN}}$ = 19.6 GeV in Run 19, as proposed, and that this future run would allow the same global Lambda polarization measurement to be made, albeit less definitively due to the lower statistics. Given the high scientific impact and discovery potential of this measurement, the PAC was convinced that this measurement should be pursued via 27 GeV collisions in Run 18 as long as the unique isobaric runs that are the highest scientific priority for Run 18 have first collected sufficient statistics to meet their goals. If a high-statistics 27 GeV run is completed in Run 18 yielding a difference between polarizations of the Ω and Ω-bar, and if comparison with models points to the existence of a trapped magnetic field, i.e. the discovery of the Faraday fluid, then there is a chance that the 19.6 GeV collisions in Run 19 could provide some initial evidence for how the strength of the trapped magnetic field changes with energy.

The PAC also recognizes the unique potential of the 2-day fixed-target program. After successful pilot tests in 2014 and 2015 (only a few hours of data taking each) STAR proposed running fixed-target collisions at a 3 GeV center-of-mass energy for two days. Only a single fixed-target beam energy was proposed for Run 18, Au+Au at 3 GeV. This will set the stage for, and establish the viability of, the substantial fixed-target program proposed for Run 19. For this reason, the PAC is persuaded of the value of investing 2 days from Run 18 to perform the first physics run of the STAR fixed-target program. Beginning with the lowest planned energy makes good sense because in Run 18 the iTPC and eTOF upgrades to STAR will not yet be fully installed. These upgrades improve STAR's forward capabilities, and in fixed-target collisions with even slightly higher energies more and more of the produced particles are emitted in sufficiently forward directions as to make these detectors necessary. They are on schedule to be fully installed for Run 19. The STAR presentation to the PAC described how given that in fixed-target collisions with $\sqrt{s_{NN}} = 3$ GeV the center of mass of the collision is only at a rapidity of 1.05, and given the off-center placement of the target, at this low collision energy the majority of the mid-rapidity particles are within the current (pre-iTPC) STAR detector, making it possible for STAR to measure the fluctuation observables that are of considerable interest in a 2 day run that accumulates 100 million events. By measuring and analyzing data from this one low fixed-target energy in Run 18, STAR will be better able to optimize the setup and analysis of fixed-target experiments for the coming years, including verifying the required conduct of operations and optimizing triggers and software. The fixed-target collisions being studied over Run 18 and Run 19 fill an important gap between HADES and SPS measurements. Compared to AGS measurements with the EoS TPC, just two days of data collection will surpass the EoS data set by perhaps four orders of magnitude. This enables the analysis of fluctuation and correlation measurements, e.g. the kurtosis observable, related to critical phenomena and phase separation. Establishing, or constraining, the existence of a first-order phase transition in hot matter at supranormal baryon densities has represented a principal goal of the high-energy heavy-ion physics program since its inception. Given the discovery potential of this program, combined with the fact that only two days of beam time are requested to initiate it in Run 18, the PAC recommends this portion of the request be completed even if it impinges on the ability to accomplish the 27 GeV Au+Au run described above.

2.5 Discussion of Run 19

The plan for Run 19, as proposed to the PAC by STAR, constitutes a major scientific opportunity. It represents the first year of a two-year effort (BES II) to use heavy-ion collisions at RHIC to provide a definitive survey of the phase diagram of QCD, building upon the exploratory phase of the Beam Energy Scan program (BES I) conducted in 2010-2014. Experimental data show that QGP with low baryon doping (low excess of quarks over antiquarks; low baryon chemical potential (μ_B)) is produced in heavy-ion collisions at top RHIC and LHC energies. Lattice QCD calculations, together with the experimental data, indicate that as this QGP cools and forms hadrons it does so via a continuous crossover. Much less is known about the phase diagram of strongly-interacting matter with larger baryon doping. With QCD the only strongly-interacting theory in our fundamental description of Nature (the Standard Model), mapping the transition region of its phase diagram is a scientific goal of the highest order. In the long term, successfully connecting a quantitative, empirical understanding of its phases and the transitions between phases to theoretical predictions obtained from the QCD Lagrangian could have ramifications in how we understand phases of strongly-coupled matter in many other contexts.

Lattice calculations of the properties of QCD matter with substantial μ_B are either indirect, or very challenging, or both. It is thought that the crossover may become a first-order phase transition above some critical point, but there is at present no calculation that can tell us reliably whether such a critical point exists and, if so, at what μ_B it is located. *Experimental discovery of a first-order phase transition or a critical point on the QCD phase diagram would be a landmark achievement.* The first step in this program should be the quantitative study of the crossover region of the phase diagram as a function of increasing baryon doping, with quantitative comparison between theory and experiment in a regime where both are more tractable. Success in this, in and of itself, would constitute a major and lasting impact of the RHIC program. Questions that can be addressed include quantitative study of the onset of various signatures of the presence of quark-gluon plasma and the onset of chiral symmetry restoration, as one traverses the crossover region.

A major effort to use heavy-ion collisions at RHIC to survey the phase diagram of QCD is now underway. Doped QGP is produced by colliding large nuclei at lower energies, where the excess of quarks over antiquarks in the incoming nuclei dominates. The flexibility of the RHIC collider has allowed it to dial its collision energy downward from $\sqrt{s_{NN}}$ = 200 to 7.7 GeV, meaning that RHIC can study collisions that freeze out at points on the phase diagram with μ_B ranging from 20 to 400 MeV. The PAC has commented on the physics results obtained from the exploratory (low statistics) BES I phase of this program by the STAR and PHENIX collaborations, and their implications, at length in previous years. Here, we will employ quotes from the 2015 NSAC Long Range Plan to provide a brief perspective: “RHIC is uniquely positioned in the world to discover a critical point in the QCD phase diagram if nature has put this landmark in the” region of the phase diagram with μ_B up to 400 MeV. With its newly demonstrated capability of taking data on fixed-target collisions, it can also explore regimes with even higher baryon doping, albeit at lower temperatures. “Data from BES I provided qualitative evidence for a reduction in the QGP pressure … in collisions that form QGP not far above the crossover region.” “The experimental search for the QCD critical point hinges on the fact that matter near such a point exhibits well understood critical fluctuations.” The data from BES-I collisions with $\sqrt{s_{NN}}$ between 19.6 and 7.7 GeV on the “collision energy dependence of a fluctuation observable that is particularly sensitive to the critical point” namely the kurtosis of the net-proton multiplicity fluctuations, “are tantalizing … and may be indicative of the presence of a critical point in the phase diagram of QCD, although the uncertainties at present are too large to draw conclusions.” Overall, “the trends and features in BES-I data provide compelling motivation for experimental measurements with higher statistical precision from BES-II.” This is the two-year program that STAR has proposed to begin in Run 19. The PAC looks forward to this program with great anticipation, and finds the proposal for Run 19 both exciting and compelling.

As the PAC discussed at length several years ago, realizing the scientific potential of the BES-II program relies upon the low energy electron cooling capability being developed by the CA-D and on several upgrades to the STAR detector, namely the iTPC, EPD and eTOF. In particular, two years ago the PAC noted that the sensitivity to the net-proton multiplicity fluctuations whose energy-dependence is a key signature of the QCD critical point is "sharply enhanced with the increased number of net protons per event provided by the increased rapidity coverage" made possible by the iTPC. The EPD is scheduled to be fully installed for Run 18; its capabilities are important to achieving the scientific goals for that run as well as for BES-II. The EPD, eTOF, and iTPC are scheduled to be fully installed for BES-II, beginning in Run 19. The PAC commends STAR for the efforts made to advance the construction of these detector upgrades on schedule, including via complementing the support from the DOE with support from NSF-funded groups, Chinese groups, and CBM-FAIR.

The plan for Run 19, as proposed to the PAC by STAR, will launch the BES II program by making definitive measurements from data taken in collisions with $\sqrt{s_{NN}}$ = 19.6 GeV, 14.5 GeV and 11.5 GeV. Beginning at these energies will allow the simultaneous commissioning of the low energy cooling that is critical to subsequent measurements at 9.1 GeV and 7.7 GeV. The PAC concurs with STAR that these collider measurements, including making a start on the 9.1 GeV run at the end of Run 19 if it includes 24 cryo-weeks, are the top priority for Run 19. In the following year, with the low energy cooling commissioned and operating, RHIC will be positioned to make the flagship measurements at $\sqrt{s_{NN}}$ = 7.7 and 9.1 GeV that will complete the exploration promised in the Long Range Plan, and that will give RHIC the opportunity to find a critical point in the QCD phase diagram, if there is one in the region with baryon chemical potential up to 400 MeV.

The PAC commends STAR for the successful pilot fixed-target measurements that it made in 2014-15. Employing fixed-target collisions can extend the Beam Energy Scan to collisions with center-of-mass energies all the way down to $\sqrt{s_{NN}}$ = 3.0 GeV, making it possible for RHIC to explore the QCD phase diagram out to even higher baryon doping, albeit at lower temperatures. With the first physics run in fixed-target mode (at $\sqrt{s_{NN}}$ = 3 GeV) anticipated in Run 18, the PAC hopes that when it meets next year it will receive an initial report on STAR's ability to use these data to measure some of the key BES observables. The PAC anticipates supporting the proposed Run 19 plan for six fixed-target runs, each 2 days long and each yielding 100 million events, at six center-of-mass energies ranging from $\sqrt{s_{NN}}$ = 3.5 to 7.7 GeV as a strongly motivated second priority for Run 19. Including the highest of these energies (corresponding to collisions of a 31.2 GeV beam with the fixed-target) is important as it will allow cross-checking the new fixed-target measurements, including in particular the measurements of fluctuation observables which are challenging in fixed-target collisions, against the now well-developed collider analyses.

3. Status of STAR and PHENIX

The PAC commends both the PHENIX and STAR collaborations for maintaining outstanding scientific productivity in terms of the number of published papers, the number of Ph.D. graduates and the high impact of papers in the nuclear physics community.

The PAC commends the PHENIX collaboration for the efforts of keeping a strong cohort of students and post-docs active in data analysis and RHIC physics after the decommissioning of the PHENIX detector.

The PAC commends the STAR collaboration for securing many external financial contributions in addition to DOE funding, which enabled important detector upgrades necessary for the BES II program. The iTPC, EPD and eTOF upgrade projects are on schedule. Many prototypes including EPD quadrant, eTOF modules and iTPC RDO and FEE were tested in Run 2017. The growth in the STAR collaboration membership is a strong indication that STAR has a vigorous scientific program and RHIC continues to be a national facility at the frontier of nuclear science.

The PAC commends the CA-D and the STAR collaboration for a successful Run 2017. Major data-taking goals have been achieved for the run. The refurbished FMS and the new FMS post-shower detector worked well for the run. The data set of polarized p+p collisions at $\sqrt{s}$ = 510 GeV from 2017 has discovery potential for TMD evolution and the sign change in the Sivers function.

Recommendations

- For new results from STAR on global Lambda polarization, measurements of fluctuations (e.g. net-proton kurtosis) in the search for a critical point, and on the CME from the isobar run the PAC recommends that the STAR Collaboration eliminates preliminary release of the data and proceeds directly to journal publication. Prior to journal submission or any public release, STAR should present to BNL's Associate Laboratory Director the proposed paper and sufficient (confidential) documentation for scientific feedback on the findings, to which STAR will respond.
- The PAC recommends implementation of double-blind analyses for the Isobar run.

Discussion

It is recognized that the results from future data-taking by STAR on the global Lambda polarization, kurtoses of event-by-event distributions in the search for a critical point, and the CME from the isobar run add discovery potential to the RHIC program and are critically important to the field. Since STAR will be the only operating experiment in this energy range over the next few years, a more considered and deliberate approach to release of data on these topics was sought. The PAC felt that STAR should work with lab management to allow critical evaluation of discovery results prior to any (preliminary or final) release of data. In discussions with STAR management, it was agreed that the most effective means of ensuring the integrity of any discovery data prior to release was for STAR to proceed directly to journal publication and therefore eliminate any preliminary release of new data on these three topics. In addition, double-blind analyses could and should be implemented for analysis of data from the Isobar run.

Both the PHENIX and the STAR collaborations continue to maintain outstanding scientific productivity. Each experiment produces an impressive number of refereed journal papers and a large number of Ph.D. graduates. RHIC published papers continue to have very high impact in the nuclear physics community according to the citation tracking from inSPIRE. Notable papers in the last year include the first RHIC measurements of D^0 elliptic flow using the STAR HFT [PRL 118

(2017) 212391] and B meson production via its decay to J/ψ using the PHENIX FVTX [PRD 95 (2017) 092002, and arXiv:1702.01085], the PHENIX measurement of collective flow in high-multiplicity p+Au collisions [PRC 95 (2017) 034910], which concludes the RHIC small-systems geometry scan, and the STAR discovery of global hyperon polarization in nuclear collisions, which provides evidence for the most vortical fluid [to appear in Nature].

The PHENIX collaboration completed its data-taking mission and decommissioning of the PHENIX detector is well underway. PHENIX organized a school to provide instruction on PHENIX data analysis and related skills with over 30 students and post-docs in attendance. The PAC commends the PHENIX collaboration for its efforts to keep students and post-docs active in PHENIX data analysis and RHIC physics.

The STAR collaboration has made progress on the iTPC, EPD and eTOF detector upgrades. In addition to DOE funding, the iTPC and EPD projects have considerable financial contributions from Chinese funding agencies. The EPD project is managed by two NSF supported groups (OSU and Lehigh). The eTOF detector will be provided by the CBM-FAIR collaboration with additional contribution from Chinese groups. The PAC commends the STAR collaboration for successfully securing funding for these important detector upgrade projects that are critical for the BES II program. The construction of these detector upgrades are on schedule. Prototypes of upgrade detectors including the EPD quadrant, eTOF modules and iTPC RDO and FEE were tested.

Run 2017 has turned out to be another very successful run for the STAR collaboration. The STAR collaboration took data for polarized p+p collisions at 510 GeV and Au+Au collisions at 54.4 GeV. A week of RHICf data-taking is also scheduled before the end of the 2017 run. The refurbished FMS and the new FMS post-shower detector worked very well for the run. All major data-taking goals have been achieved for the run. The polarized p+p data have the potential to address the TMD evolution and the sign change in the Sivers function, arguably two of the most important and currently outstanding questions in spin physics. The PAC commends the CA-D and the STAR collaboration for the successful run and looks forward to timely physics results from the 2017 run data.

The PAC is pleased with the continued growth of the STAR institutional membership in recent years. Three new research groups (Fudan, Heidelberg and Rutgers) joined the STAR collaboration in 2017. This is a strong indication that STAR has a very vigorous scientific program and that RHIC is a national facility at the frontier of nuclear science.

4. Computing and Data Production for STAR and PHENIX

The status of the data production and release, and the associated computing resources was presented to the PAC by PHENIX and STAR, and in a dedicated BNL report.

Following last year's PAC recommendation, the BNL management convened a panel of local computing experts that evaluated the STAR computing needs, reviewed the current practices for data reconstruction and analysis, both within STAR and in the larger context of the RCF, and identified action items to help STAR overcome the bottle-necks in data production that were present for the last couple of years.

The PAC commends the STAR collaboration for successfully securing external computing resources, such as the high-performance computing at the CORI supercomputer at NERSC, based on the demonstrated high efficiency in utilizing these resources. The 25 M CPU hours allocated to STAR at CORI in the last year have significantly increased the data production throughput and, along with high-efficiency utilization of RCF, eliminated the backlog of datasets awaiting reconstruction.

The PAC commends the STAR collaboration for successfully implementing a new small-print data format that led to 6.5 times reduction in the storage space needed, ensuring that the current storage can handle the projected needs up to FY20.

The PHENIX experiment completed its data-taking program in 2016. Completion of the reconstruction of all data sets taken is projected to take 1 year, and publication of the major results is projected to take up to 4 years. The present computing resources can meet these goals. The PAC is more concerned about maintaining adequate manpower in support of both data production and data analysis needs, since there has been a recent reduction in size and redirection of effort in the BNL PHENIX group that has negatively impacted data production.

The PAC commends the BNL management and the STAR collaboration for responding quickly to last year's PAC recommendation addressing STAR computing and data production issues. The outcome has been very satisfactory. The PAC encourages the STAR collaboration to continue to seek outside resources to complement its computing resource needs. We recognize that continued support and effective management of resources from RCF, a central pillar of computing and data analysis for the RHIC community, will remain essential for the productivity of RHIC science. The PAC encourages BNL management to continue to be proactive in addressing the computing and data production needs of STAR, PHENIX and sPHENIX.

Recommendations

- The PAC recommends that the STAR experiment continues to employ external computing resources to complement the CPU available at RCF and to ensure the timely data production of the data sets taken.
- The BNL management is encouraged to provide adequate support both in computing resources and in manpower to STAR, PHENIX, and sPHENIX.

5. sPHENIX

The 2015 LRP for Nuclear Science states that in addition to mapping the phase diagram of QCD with the BES I and II, the other goal of "measurements planned at RHIC, as it completes its scientific mission, and at the LHC" is to "probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX."

Those statements in the 2015 LRP emphasize the high priority that the field has placed on future measurements and physics that will be provided by the sPHENIX detector. sPHENIX will probe the QGP on multiple length scales via 1) microscopic investigation utilizing jets and jet structure;

2) mass and flavor dependence utilizing heavy quarks; and 3) measurement of three upsilon states to determine the temperature dependence of color screening at their three length scales in the QGP. "Understanding the evolution of the microscopic substructure of QGP as a function of scale will complete the connection between the fundamental laws of nature, QCD, and the emergent phenomena discovered at RHIC" as stated in the LRP.

The PAC commends sPHENIX for the progress they have made in the last year and their success in obtaining CD-0 approval for physics. sPHENIX presented to the PAC their results of improved computer simulations demonstrating their ability to accomplish the important physics measurements they have proposed and that drive the detector requirements for the configuration of the experiment.

sPHENIX continues to optimize its detector configuration and has identified potential sources of external funding beyond the MIE to add detector components to accomplish their overall physics goals. sPHENIX is commended for identifying a strong consortium of groups responsible for and seeking external funding for a four-layer Intermediate Silicon Strip detector system and a multilayer MVTX detector system based on the MAPS technology. These groups have considerable experience and expertise in those detector technologies. The PAC heard that integration of these systems is underway, which is important.

The PAC has seen substantial progress in the implementation by sPHENIX of realistic tracking software providing more accurate estimates of efficiencies, rates and backgrounds. As a result, sPHENIX has refined its event statistics leading to an increase over previous estimates and the PAC was presented a multi-year plan based on this.

BNL must be aware that budget uncertainties and the delay of CD-1 could impact what the PAC has seen as a collaboration actively progressing to meet demands of an already tight schedule. These issues could impact the ability to attract additional groups that are needed for a concerted effort to bring sPHENIX through reviews and eventually online for operation and data-taking. They may also negatively impact the success of grant applications by existing sPHENIX groups, especially those of new faculty. Furthermore, the overall importance and interest in proceeding to an EIC expressed by the U.S. nuclear physics community in the Long Range Plan poses additional schedule pressure on the far end.

sPHENIX has developed a letter of intent for addition of a modest upgrade to undertake forward physics measurements that address aspects (forward Drell-Yan and transverse single spin asymmetries) of the program envisioned last year in the Cold QCD Report. A plan for physics with polarized p+p, polarized p+A and A+A was presented. The PAC's comments on presentation of sPHENIX forward are found in the section below.

sPHENIX has progressed with technology developments limiting choices for their calorimetry and tracking. Significant work has been accomplished on proofs-of-principle and detector prototyping utilizing test beams, and it appears that sPHENIX is on track for a CD-1 review.

The sPHENIX physics case remains strong and refinement of the case is expected to continue with the recently implemented improved software and models.

6. Modest Forward Upgrades

The PAC commends both the sPHENIX and STAR collaborations for their considerable effort in preparation of detailed Letters of Intent that describe their forward detector upgrade plans. The PAC finds that the physics case for a forward upgrade at RHIC remains compelling. The importance of the proposed measurements for the future EIC is clear. The PAC is also impressed by the added benefit to the heavy-ion program of the increased rapidity range provided by the forward detector upgrades.

The proposed polarized p+p measurement with a forward upgrade focuses primarily on the study of *Transverse Momentum Dependent parton distribution functions* (TMDs). The TMDs are the large complex of completely new physics that will be investigated by EIC. This is new because the experimental observables are directly sensitive to gauge links, i.e. to the fact that QCD, as in general relativity, has non-trivial parallel transport. This fundamental feature of QCD does not arise in any purely collinear processes. Thus, the properties of TMDs differ fundamentally from those of normal collinear PDFs. For example, their evolution involves an unsuppressed non-perturbative term whose effects are completely unknown at present, making various theoretical predictions that are needed to optimize the EIC accelerator and detector designs impossible to obtain with any accuracy.

The broad topics of *single-spin asymmetries* (in particular A_N for various reactions) and *twist-3 distribution and fragmentation functions* remain poorly understood. A better understanding of these could significantly impact the design of EIC detectors. Furthermore, in view of the complicated physics, making full use of the complementarity of p+p and e+p reactions may prove crucial to disentangle the various contributions. Therefore, utilizing the unique polarized p+p capability of RHIC with a forward upgrade to collect high-quality data would be very valuable for spin physics. For example, the A_N asymmetries increase strongly in the forward direction meaning that the proposed forward upgrades would allow them to be investigated with much greater precision.

A recurring topic is the sea quark and gluon distributions in the nucleon and in nuclei. Proton polarization and forward kinematics allow RHIC to contribute markedly to this topic. As sea quarks and gluons are dominant in the small x region, extraction of sea-quark and gluon distributions at RHIC complement very well the physics program that is planned for EIC.

The analysis of hadron-in-jet events promises to become a widely utilized tool for the investigation of hadron structure. It is expected that hadron-in-jet observables can combine the advantages of hadron production (high statistics, sensitivity to spin effects) with the reduced theoretical uncertainty for IR-safe jet schemes. Another major topic is factorization, which is a pre-requisite for any reliable QCD analysis. If both initial and final state QCD interactions occur, factorization can be broken, although it is unclear how strongly. Thus any bound on the degree of factorization breaking would be of fundamental importance. Such a bound could be obtained by comparing the results for different ways to extract the same quantity, in particular the transversity function.

A promising physics topic is the investigation of saturation, for example in measurements of forward di-hadron production. Establishing saturation is important to understanding how to model the initial stages of relativistic heavy-ion collisions. While such experiments do not require proton polarization and therefore could in principle also be performed at other accelerators, e.g. at the LHC, the additional effort for such an analysis of p+A data compared to its potential pay-off is relatively small once forward detectors are installed.

The increased rapidity coverage afforded by a forward upgrade would also enhance understanding of several puzzles currently facing the field. Correlations spanning a wide rapidity gap are sensitive to physical processes that happen in the initial stages of a heavy-ion collision. Thus, the forward upgrades would help answer questions related to how energy and charge are deposited in the pre-equilibrium stage, what role jets and mini-jets play in building fluctuations, how the quark chemistry is equilibrated, and how flow builds in the initial stages or in small systems. Furthermore, forward instrumentation will also allow for the characterization of events by multiplicity and the potential analysis at RHIC of very high multiplicity proton-proton events, where surprising breakthroughs have been established at the LHC.

The envisioned hardware solutions for forward detector upgrades are realistic, cost-effective, and relevant for EIC planning. Both collaborations are encouraged to continue their design and simulation efforts to optimize the detector performance, and to find additional groups to assume responsibility for part of the investments required to realize the forward upgrades.

In summary, a broad spectrum of important experimental investigation is proposed that depends critically on a forward detector upgrade and profits significantly from its inclusion in the RHIC program. RHIC management is encouraged to find a way to enhance and include a forward physics program at RHIC.

Recommendations:

- In view of the importance of DY reactions for the forward detector program, high priority should be given to the analysis of the 2017 STAR DY data to demonstrate the feasibility of such a measurement.

- As TMD physics is the major motivation for the forward detector upgrade program, it is of crucial importance that the 2017 RHIC Spin run be analyzed quickly and as completely as possible. This calls for an increase in the RHIC Spin effort rather than the reduction that is being considered.

- As the physics program that is foreseen for forward physics is substantial, full utilization of future polarized proton beam time must be made to realize the proposed forward physics program.

- RHIC management is encouraged to find a way to enhance and include a forward physics program at RHIC.

2017 BNL Nuclear and Particle Physics Program Advisory Committee:

John W. Harris (john.harris@yale.edu)

Huan Huang (huang@physics.ucla.edu)

Jen-Chieh Peng (jcpeng@illinois.edu)

Krishna Rajagopal (krishna@mit.edu)

Scott Pratt (prattsc@msu.edu)

Andreas Schaefer (andreas.schaefer@physik.uni-r.de)

Julia Velkovska (julia.velkovska@vanderbilt.edu)