# Recommendations
# Brookhaven National Laboratory
# Nuclear and Particle Physics
# Program Advisory Committee
# June 11-13, 2014

## 1. Introduction

On June 11, 2014, the PAC heard the PHENIX and STAR Beam Use Requests (BURs) for Runs 15 and 16 and a proposal for *Precise Measurements of Very Forward Particle Production at RHIC* (RHICf). On June 12, the PAC heard about collaboration plans for possible running in 2018/19 ("Beam Energy Scan II") and a possible p+p and p+A program for 2021/22. These plans for the future included discussion of the sPHENIX detector, as well as forward upgrades for both STAR and sPHENIX for the beginning of the next decade. Based on this input, we report our recommendations for Runs 15 and 16 and assess the RHICf proposal in Section 2, and provide our assessment of the proposed beam energy scan and pp/pA programs in Sections 3 and 4, respectively. Finally, in Section 5 we offer some thoughts on new opportunities that might make further use of RHIC's flexibility.

The PAC commends the collaborations and C-AD for the remarkably successful execution of the Run 14 Au+Au program. The PHENIX collaboration accumulated more than 2.3 $nb^{-1}$ of Au+Au collisions at 200 GeV within $|z_{vtx}|< 10$ cm, which exceeded by 55% the goal set by the experiment allowing for critical heavy flavor measurements with the new and improved VTX/FVTX detector capabilities. PHENIX also collected data during 15 GeV Au+Au run as part of the BES program. In addition, in the last two weeks of the run, PHENIX accumulated 2.2 billion minimum bias events of $^{3}$He + Au collisions (22% above the experiment projected goal), that will enable the detailed study of particle correlations and collective phenomena in small systems. The STAR collaboration completed two major HFT and MTD upgrades for Run 14. STAR reached the goal of 150 M Au+Au events for the 15 GeV run completing the BES phase I program. The 200 GeV Au+Au in Run 14 is the first year of a multi-year heavy quark physics program based on the new HFT and MTD capabilities. STAR achieved the goals of an integrated luminosity of 10 $nb^{-1}$ for the MTD and a data set of over 1 billion min-bias events for the HFT. The PAC (as well as the rest of the world) is eager to see the physics results from Run 14.

# 2. RHIC run plans

## 2.1 Executive summary

For Run 15 the PAC recommends the following (*in order of priority*):

1. 9 weeks of polarized p+p collisions at $\sqrt{s_{NN}}$ = 200 GeV, *and*
   5 weeks of p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with transverse polarization of the proton
2. 2 weeks of p+Si collisions at $\sqrt{s_{NN}}$ = 200 GeV with transverse polarization of the proton

For Run 16 the PAC recommends the following

1. 10 weeks of Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV
2. 7 weeks of Au+Au and p+p collisions at $\sqrt{s_{NN}}$ = 62 GeV, *or*
   7 weeks of polarized p+p collisions at 510 GeV

For Run 15, in a 22 cryo-weeks scenario, both p+p, p+Au and p+Si running are recommended. In the case of a shorter run, the p+p and p+Au programs would have higher priority.

For Run 16, the PAC recommends 10 week Au+Au running at 200 GeV at the highest priority as a part of the multi-year RHIC commitment to complete the heavy flavor physics program enabled by the STAR HFT/MTD detector upgrades. The PAC considered the options of p+p 510 GeV and a combination of Au+Au and p+p at 62 GeV for the rest of the 7 weeks under a run scenario of 22 cryo-weeks to both be viable. At its 2015 meeting, the PAC will reconsider these requests without prejudice; the STAR and PHENIX collaborations are each asked to present updated physics goals for both of these scenarios. The p+p goals should address the DOE milestone HP13. The PAC encourages more interactions between theory community and experimental collaborations to address the TMD evolutions which is critical for evaluating experimental sensitivities for possible p+p run at 510 GeV in 2016.

## 2.2 Discussion of Run 15 priorities

### 2.2.1 9 week p+p run

A p+p run at full energy in Run 15 is essential both for the heavy ion program and the spin program. For the heavy ion program, both STAR and PHENIX collaborations require high-statistics reference measurements in the heavy flavor sector. These measurements will utilize the new detector capabilities (VTX and FVTX in PHENIX, and HFT and MTD in STAR). The PAC recommends 9 weeks of p+p running to provide, at high $p_T$, comparable statistics in the p+p and in the central Au+Au data sets. Although this recommendation falls a little short of the STAR request, the compromise allows for additional 2 weeks of p+Si running at full energy. The exploration of a smaller colliding p+A system with both STAR and PHENIX detectors can be accomplished in Run 15 only, as CAD indicated that asymmetric colliding systems cannot be accommodated in Run 16 without major effort and at a significant beam time cost.

Several measurements are proposed in p+p collisions for the spin program. Both STAR and PHENIX will have new detector capabilities in the forward direction: refurbished Forward-Muon-Spectrometer (FMS) with an additional pre-shower detector (STAR), and the MPC-EX (PHENIX). With transverse proton spin polarization, both STAR and PHENIX propose to measure the Sivers effects with direct photons. Concurrent with that, measurements of the single spin asymmetry for identified $\pi^0$ and $\eta$ out to large transverse momentum can be performed. In addition, new measurements of the single spin asymmetry $A_N$ for exclusive J/$\Psi$ production and inclusive diffractive production in p+p collisions, and improved heavy flavor measurement of $A_N$ using single muons could be accomplished. Hadron-hadron and jet-hadron correlations with improved precision will be possible and provide further understanding of the large transverse single spin asymmetries.

Within a 12-week p+p running scenario during Run 15, the STAR collaboration proposed a six-week run of p+p collisions with longitudinal polarization to improve the precision in measurements of the double-spin asymmetry $A_{LL}$ in inclusive jet and coincident di-jet production. These measurements would provide a definitive answer about the gluon contribution to the total spin of the proton if the current central value for $\Delta g$ holds. Based on present day knowledge, the PAC expresses a preference for the improved $\Delta g(x)$ measurement relative to the proposed transverse physics measurements.

The PAC recommends the 9 weeks of p+p running with the same priority as the 5 weeks of p+Au running. Both of these programs are recommended with higher priority than the two-week run with p+Si collisions.

### 2.2.2 5 week p+Au run

Proton-nucleus collisions with a transversely polarized proton beam provide key measurements both for the heavy ion program and for the spin program. A 5 week p+Au run at full energy would allow the collaboration to collect reference data for the heavy flavor and quarkonia measurements to constrain cold nuclear matter effects utilizing new detector capabilities. The proposed direct photon measurements at forward rapidity would provide constraints on the gluon distribution at low-x and significantly reduce the uncertainties in the nuclear PDFs. These measurements are important for disentangling the initial and final state effects in AA collisions, and the PAC endorses them.

In addition to the study of initial state effects in the nucleus, the recently discovered correlation phenomena in p+Pb collisions at the LHC and d+Au collisions at RHIC call for further investigations with a variety of collision geometries to pin down the possible collective nature of these effects. The PAC endorses these measurements and gives high priority to the proposed p+Au run.

It was proposed by the PHENIX collaboration that the beam directions be switched from p+Au to Au+p in the middle of the running period to achieve a better understanding of the systematic uncertainties. CAD indicated that such a switch will require considerable setup time. In view of the limited running time and the asymmetric configuration of the STAR detector, the PAC recommends against the switch in beam directions in order to optimize the accumulated statistics.

The polarized p+Au collisions would allow the exploration of saturation effects in the Au target through measurement of the ratio of single spin asymmetries $A_N^{pA}/A_N^{pp}$ for identified $\pi^0$ . The PAC notes that while this is an exciting possibility, the theoretical foundation of these effects is not sufficiently well-established and that a broader discussion in the theory community on the connection between the single spin asymmetries and the saturation scale is needed to put interpretation of these measurements on firmer ground.

### 2.2.3 2-week p+Si run

Additional p+Si running in Run 15 would provide further opportunities for exploration of the nuclear geometry effects and for saturation physics if, indeed, the $A_N$ measurements prove to be sensitive to the saturation scale. Together with the $^3$He+Au data from Run 14 and the p+Au data from Run 15, the measurements in the soft particle sector are expected to provide better understanding of the origin of the correlation phenomena observed in d+Au collisions at RHIC and p+Pb collisions at the LHC. The PAC recommends two weeks of p+Si running as a second priority during Run 15 to extend the system-size dependent studies at RHIC.

## 2.3 Discussion of Run 16 priorities

### 2.3.1 Introduction

For Run 16, STAR requested 10 weeks of Au+Au collisions at 200 GeV, followed by 7 weeks of transversely polarized p+p collisions at 510 GeV. The PHENIX collaboration requested longitudinally polarized p+p and Au+Au runs, both at 62 GeV, for 6.5 weeks and 9 weeks, respectively. PHENIX also requested p+p at 510 GeV for 1 week, motivated by the RHICf proposal (see Section 2.4).

The PAC commends both collaborations for their efforts to maximize the physics potential from the RHIC 2016 run before the start of the planned Beam Energy Scan

Phase II program. The PAC's recommendation for the Run 16 plan is based on the following considerations.

## 2.3.2 10 week 200 GeV Au+Au run

The STAR HFT upgrade is a DOE MIE project. Its heavy flavor physics program was based on a multi-year RHIC commitment for two substantial Au+Au runs at 200 GeV and a major p+p run at 200 GeV for comparison. In Run 16 a new set of PXL layers (inner layers of the HFT) with Al cables will replace the current PXL layers with Cu cables, significantly reducing multiple scattering for low transverse momentum particles. An effective online vertex selection will also be used in 2016 to improve the HFT fiducial coverage for acquired events. For low $p_T$ $D^0$ mesons, an effective figure-of-merit improvement of about 6 is expected in comparison to the Au+Au data from Run 14. Such an improvement is important to establish charm quark collectivity through flow and correlation studies in several collision centrality bins. The Run 16 data set is also expected to enable the first heavy-ion measurement of the charmed baryon $\Lambda_c$, which has a short lifetime, $c\tau$□ of approximately 60 μm. The combined measurements of charmed mesons and baryons would provide access to the quark evolution dynamics and properties of the QGP created in these collisions.

The quarkonia program using the STAR MTD upgrade will also benefit from a 10-week Au+Au run at 200 GeV in 2016. Combination of J/Ψ measurements from the MTD and from its displaced vertex from the HFT reconstruction will allow measurement of bottom decays at RHIC from the expected data.

PHENIX could benefit from possible improvements in the run conditions in 2016 and may be able to acquire a slightly larger data sample than that recorded in Run 2014. This factor of two increase in statistics could be a benefit both for interpretation of interesting results from, and the understanding of systematic uncertainties in the 2014 data set.

The PAC recommends the 10-week Au+Au 200 GeV the highest priority for the run 2016 plan.

## 2.3.3 7 week 510 GeV transversely polarized p+p run

STAR also requested a 7-week transversely polarized p+p run at 510 GeV. The physics program is driven by the measurement of $A_N$ for W bosons, direct photons and possibly Drell-Yan pairs. The PAC recognizes the fundamental importance of the measurement with theoretical prediction rooted in the gauge invariance of QCD. This is also the subject of the DOE HP13 performance milestone (2015). Among the possible observables, the W boson asymmetry $A_N$ is deemed to be the cleanest probe theoretically. STAR has demonstrated the feasibility of such measurement from run 2011 transversely polarized p+p 510 GeV data, limited by statistics of 25 $pb^{-1}$ luminosity. The projected sensitivity for W $A_N$ with 900 $pb^{-1}$ luminosity shows considerable statistical uncertainty. A definitive measurement of the famous 'sign change' due to the time-reversed contributions of the quark Sivers function in these processes may be out of reach in Run

16 if the current theoretical predictions are close to being correct. We note that a RHIC measurement from Run 16 will, in any case, have a significant impact on the understanding of TMD evolution.

The PHENIX collaboration has also considered high and low mass Drell-Yan measurement and the feasibility studies are still in initial stages.

The PAC would like to request both collaborations to further investigate physics capabilities for a 7-week transversely polarized p+p run at 510 GeV. We encourage more interaction between the theory community and experimental collaborations to investigate the TMD evolution—critical to evaluation of experimental sensitivity for Run16. Next year, the PAC would like to see the best possible case for these measurements as they relate to the DOE HP13 milestone.

### 2.3.4 62 GeV Au+Au and p+p run

The PHENIX collaboration also requested a 9 week Au+Au run at 62 GeV and a 6.5 week p+p run at 62 GeV to produce a comprehensive data set at that energy. Recent results from PHENIX indicate that the nuclear modification factor $R_{AA}$ for non-photonic electrons (NPE) from Au+Au collisions at 62 GeV is above 1 for electron $p_T$ between 1.0 and 3.5 GeV/c. The Au+Au data were from run 2010. Systematic errors due to the normalization uncertainty in the reference p+p data from ISR dominate the experimental uncertainties. This observation may be an important indication that charm quarks undergo significant collective motion in a QGP, leading to a large change in the nuclear modification factor due to more steeply falling charm $p_T$ spectra at 62 GeV. Systematic comparisons between 62 and 200 GeV data may also shed light on the temperature dependence of properties of the QGP drops formed in collisions at these energies. In addition, measurements of thermal photons and $v_2$ for heavy quarks will be very interesting for Au+Au collisions at 62 GeV.

In view of the higher priority for a 10-week Au+Au at 200 GeV, the PAC asked PHENIX whether a viable 62 GeV run plan could be formulated for a 7-week period. PHENIX presented a possible plan, with a 5-week Au+Au run and a short 2-week p+p run. The p+p data would be used to set the normalization scale for the $p_T$ spectra from the ISR experiments.

The PAC asks both collaborations to present estimates of the expected statistics of the data sets and the achievable accuracy of the proposed observables for 7 weeks of 62 GeV running. A strong physics case including how the proposed measurements would impact quantitatively our understanding of the QGP properties and/or collision dynamics will be needed to justify such a run.

## 2.4 RHICf Proposal: *Precise Measurements of Very Forward Particle Production at RHIC*

This proposal has two objectives: first, measurements of 510 GeV proton-proton collisions helps to improve the existing hadronic interaction models used in simulations of cosmic-ray air showers and, secondly, measurement of the spin asymmetries in forward neutron production.

The group has performed a similar experiment at CERN (LHCf) and plans to install that detector at RHIC, close to the PHENIX detector, for the 2016 run. The PHENIX collaboration is willing to host this experiment which has only very limited demands with respect to resources and beam time. The experiment is meant to run parasitically with STAR in a possible 510 GeV p+p run in 2016.

The RHICf collaboration made an excellent case for the necessity of high quality data from both the LHC and RHIC to test cosmic ray models. However, the PAC has the impression that the impact of RHICf on cosmic shower modeling will be somewhat limited because of the relatively large projected systematic errors. With respect to the neutron spin asymmetries, the measurement will provide interesting complementary data to test theoretical models. The PAC feels that the ratio of scientific impact to required resources is high, but not high enough to significantly influence the decision on 510 GeV p+p running in 2016. Furthermore, the PAC is not in favor of a one week dedicated 510 GeV p+p run.

Because the PAC feels that the differing requests of PHENIX and STAR for 2016 require further input and discussion, it unfortunately came to the conclusion that a decision on the 510 GeV p+p running, and therefore the RHICf proposal should be postponed until the 2016 schedule can be fixed. If there are of order 7 weeks of 510 GeV p+p running in 2016, the PAC recommends that the RHICf proposal be approved.

# 3. The RHIC Beam Energy Scan

A major effort to use heavy ion collisions at RHIC to survey the phase diagram of QCD is now underway. Experimental data show that QGP with low baryon chemical potential ($\mu_B$) 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, the QCD transition is a rapid but continuous crossover. Much less is known about the phase diagram of strongly interacting matter with larger $\mu_B$. 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 $\mu_B$ 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 $\mu_B$ 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 $\boldsymbol{\mu}_B$, 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 Beam Energy Scan program and indeed of the overall RHIC program. Questions that can be addressed in this regime 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.

By dialing its collision energy downward (to date, running at the energies $\sqrt{s_{NN}}$=200, 62.4, 39, 27, 19.6, 14.5, 11.5 and 7.7 GeV) RHIC can study collisions that freeze out at points on the phase diagram with $\mu_B$ ranging from 20 to 400 MeV. We commend the C-AD and the collaborations for an outstanding first phase of this program, with measurements of all the important observables targeted in the planning of this campaign now having been made in collisions with energies varying by a factor of 25, allowing for a first look at a large region of the phase diagram of QCD. Although we await with interest the results from the most recent run in this program at $\sqrt{s_{NN}}$=14.5, where data were taken only a few months ago, and although, as the collaborations have stressed, there are many observables where the measurements at and below $\sqrt{s_{NN}}$=19.6 GeV are limited by statistics, it is already possible to see trends and features in the data that provide compelling motivation for a strong and concerted theoretical response and for the much higher statistics data at these lower energies (i.e. at these larger values of $\mu_B$) that the second phase of the Beam Energy Scan program (BES-II) will provide in 2018 and 2019.

The early goals in the survey of the phase diagram of QCD should relate to obtaining a quantitative understanding of the crossover region of the phase diagram as a function of increasing $\mu_B$. Data now in hand from the first phase of the Beam Energy Scan provide key inputs and impetus toward this goal. We give four examples here, intended to be illustrative, of areas where a coherent experimental and theoretical effort would be beneficial now, in each case noting the substantial impact that the further measurements anticipated at BES-II would provide:

- The directed flow observable $dv_1/dy$ features a dip as a function of collision energy, with a minimum at energies somewhere between $\sqrt{s_{NN}}$=11.5 and 19.6 GeV. This has long been predicted in qualitative terms as a consequence of the softening of the equation of state in the transition region of the phase diagram. We now need hydrodynamic calculations with nonzero baryon density, with all the sophistication that has recently been developed for higher energy collisions including initial fluctuations and a hadronic afterburner, applied to these lower energy collisions. These hydrodynamic+hadronic calculations should be used to compare the $dv_1/dy$ data to lattice calculations (done via Taylor expansion in $\mu_B/T$) of the equation of state in the crossover region of the phase diagram. This is a program where a quantitative comparison will be of great interest whether it is successful or unsuccessful, since the latter could signal the presence of a first order phase transition. The precision of a comparison like this will be improved in future when BES-II data allow $dv_1/dy$ to be measured with tightly specified centrality.
- A second goal of the hydrodynamic calculations referred to above should be to use identified particle BES $v_2$ data to map, in quantitative terms, where and how hydrodynamics starts to break down at lower collision energies, and where, to a larger and larger extent, $v_2$ must develop during the hadron gas phase when viscosities are not small and where the contribution of the partonic phase to observed measures of collectivity must decrease in importance. A key experimental input to this program is $v_2$ of the $\phi$ meson, which needs to be measured with substantially greater statistical significance in the BES-II program. The first measurements of $v_2$ of $\Omega$ baryons at these collision energies, also anticipated in BES-II, will represent a further, substantial advance. Seeing $\phi$ mesons flowing like lighter mesons and $\Omega$ baryons flowing like lighter baryons in collisions at a given energy would indicate that the dominant contribution to the collective flow in those collisions was generated during the partonic phase.
- STAR has now measured the first four moments (mean, variance, skewness and kurtosis) of the event-by-event distribution of net proton number and net charge. At the lowest collision energies, although the statistics are at present clearly rather limiting, there are interesting trends, including, for example, the drop in the kurtosis of the net-proton distribution at $\sqrt{s_{NN}}$=27 and 19.6 GeV. While this drop

may be simply due to baryon number conservation, and URQMD does reproduce the trend qualitatively, a subsequent rise of the Kurtosis at lower $\sqrt{s_{NN}}$ would be difficult to understand in conventional terms and thus would be suggestive of a contribution from the fluctuations near a critical point. Determining whether this is so will require the higher statistics that BES-II can provide. Present data should already be very useful, however, as they can be compared to lattice calculations of the baryon number and charge susceptibilities. First versions of this comparison were reported at the recent Quark Matter conference. In the longer term, the data at lower collision energies motivate a theoretical response that incorporates the sophisticated hydrodynamic calculations referred to above coupled with a fluctuating chiral order parameter.

- Heavy ion collisions at top RHIC energies and at the LHC have now seen several experimental phenomena that may be related to the chiral magnetic effect (CME). In each case, alternative explanations are also being considered. One of the intriguing BES results from STAR is that the three-particle correlations that are related to charge separation across the reaction plane, possibly induced by the CME, are robustly observable over most of the BES range but then seem to turn off at $\sqrt{s_{NN}}$=7.7 GeV, where the elliptic flow $v_2$ is finite. This is an indication that $v_2$-induced backgrounds alone do not explain the observed correlations. The observation that these three-particle correlations disappear at the lowest energy could prove crucial to understanding their origin and how they are related to the formation of QGP. On the theoretical side, hydrodynamic calculations incorporating magnetic fields and chiral effects are needed, and are being pursued by several groups. On the experimental side, higher statistics BES-II data will make it possible to determine with much greater precision the $\sqrt{s_{NN}}$ at which this effect turns off and will also make it possible to measure the (related but theoretically more robust) chiral magnetic wave phenomenon, which has also been seen at top RHIC energy and at the LHC, and which should turn off at the same $\sqrt{s_{NN}}$ if these interpretations are correct.

BES-II will also open the door to measurements that were not yet accessible in the first phase of the BES program. Here we give only one example:

- Dileptons are unique penetrating probes with which to study the chiral properties of hot and dense matter. The dielectron invariant-mass distributions measured in the BES-I (in data taken at $\sqrt{s_{NN}}$=200, 62.4, 39 and 19.6 GeV) have shown that there is a significant enhancement of low mass dileptons below 1 GeV relative to a hadronic cocktail. The data so far are qualitatively consistent with a model in which hadron properties are modified in the medium and there is a partonic contribution as well. However, data at lower energies with higher statistics are crucial in order to test the predicted strong dependence of dilepton yields on baryon density and draw firm conclusions. The dilepton measurements at and below $\sqrt{s_{NN}}$=19.6 GeV that BES-II can provide will yield qualitatively new understanding of the chiral properties of QCD matter with significant baryon density. There are two interesting dilepton mass windows to be studied at BES-II: the low mass window (300 MeV-700 MeV) and the high mass window (800 MeV – 1.5 GeV). The former would provide indirect information on chiral symmetry restoration via the interaction of vector mesons with (excited) baryons, while the latter would provide direct information on chiral restoration via the mixing between the vector and axial-vector mesons in the hot/dense environment.

Each of the examples we have sketched makes it clear that in order to maximize the physics outcome from BES-I and BES-II, it is essential to organize a coherent effort between experimentalists and theorists working on QCD at nonzero $T$. Indeed, there has been considerable progress in lattice QCD recently on the calculation of various QCD susceptibilities and the QCD equation of state in the regime where $\mu_B$ is nonzero but sufficiently small compared to $3T_C$. These lattice calculations provide the necessary inputs for the kind of sophisticated hydrodynamic calculations (including initial fluctuations and a late stage hadron cascade) that have been developed over the past few years to be extended to include nonzero $\mu_B$. For some purposes, these calculations will need to be coupled to a fluctuating chiral order parameter. In concert, such tools will be critical to relating BES-I and BES-II data to quantitative questions about the phases, the crossover, and perhaps a critical point and first order transition, on the QCD phase diagram.

Each of the examples that we have sketched makes the point that BES data, at present and in future from BES-II, together with the concerted theoretical response that present data motivates, will yield quantitative understanding of the properties of strongly coupled matter in the crossover region where QGP turns into hadrons, with quantitative connection between measured quantities and QCD. This, in and of itself, is an outstanding scientific goal.

If Nature puts a critical point in the region of the phase diagram with $\mu_B < 400$ MeV, with a first order phase transition starting at the critical point, BES-II data on fluctuation and flow observables at $\sqrt{s_{NN}}$=19.6 GeV and below together with the theoretical tools developed in response to BES-I data should yield evidence for both the critical point and the first order phase transition. This cannot be counted on, but if achieved it would constitute a landmark for the field as well as on the phase diagram.

We strongly support BNL and its C-AD in their plan to provide the electron cooling needed for the BES-II program, to run in 2018 and 2019.

STAR detector capabilities, including those that will be provided by the modest upgrades that STAR plans (the iTPC and EPD upgrades) are very well matched to the scientific goals of the BES-II program; we encourage the collaboration and the laboratory to pursue the upgrades vigorously. STAR is also considering the installation of a gold target into the vacuum pipe, to allow collisions between gold nuclei in the halo of the beam and in the fixed target. These collisions have lower $\sqrt{s_{NN}}$, and reach higher $\mu_B$, than could otherwise be reached at RHIC. STAR ran a first test of this capability in 2014, installing such a target during the $\sqrt{s_{NN}}$=14.5 GeV run. This test showed that such collisions can be accomplished without disrupting the main program. We look forward to seeing analyses of the data taken during this test in order to get some sense of the detector capabilities and physics reach that such a parasitic fixed-target program would provide if pursued during the BES-II era.

During the BES-II runs in 2018 and 2019, the PHENIX collaboration will have removed much of the present PHENIX detector and will be part way through installing the new sPHENIX detector. It is clear that PHENIX would substantially benefit from using data taken in 2019 during the BES II run to commission as much of their new detector as they can have in place; this should lead to a faster ramp-up for physics and more efficient use of beam time in subsequent years. The PAC also sees value in having two collaborations cross-checking at least some of the important BES-II measurements, meaning that we hope that PHENIX will have as much of its silicon tracking and calorimetry in place as is possible.

# 4. Prospects for p+p and p+A runs in FY 2021 and 2022

With the advent of eRHIC, BNL would lose the possibility for (polarized and unpolarized) p+p and p+A runs. Therefore, PHENIX and STAR were asked by the directorate to outline the physics opportunities motivating a possible high intensity p+p and/or p+A program in FY 2021 and FY2022 with the then enhanced capabilities of the sPHENIX and STAR detectors.

Both PHENIX and STAR require detector upgrades in the forward direction and aim at similar physics capabilities such that the physics discussion can be summarized in general terms. As the measurements proposed for FY 2014 and FY 2015 by STAR take into account the presently known spectrum of opportunities, any physics program for FY 2021 and FY2022 was discussed primarily as a continuation of the former, which is characterized by a multitude of observables of which the following are only a selection.

## 4.1 p+p with longitudinal polarization

RHIC is presently the only Laboratory capable of determining directly the longitudinally polarized gluon and sea quark distribution functions $\Delta g(x,Q^2)$ (DOE performance milestone HP12) and bar $q(x,Q^2)$ (or more precisely provide input for global fits with especially large weight) via jet, direct photon and W/Z production and will still be so in 2021/22. With the planned forward detector upgrades STAR and PHENIX can better access the lower and higher x regions of the polarized parton structure functions. That will be an important step before the start of the EIC physics program and will further strengthen the unique position of RHIC in the field. In view of the fundamental importance of these distribution functions for hadron physics, an increase in precision for these measurements would be most valuable.

## 4.2 p+p with transverse polarization

RHIC can also constrain the third twist-2 distribution function of the proton, transversity, by analyzing the Collins contribution to transverse single spin asymmetries and by analyzing two hadron correlations related to interference fragmentation functions. As the nucleon has three twist-2 parton distributions the determination of transversity finalizes our understanding of nucleon structure at that level. Also in this case RHIC can provide a unique contribution which will help determine these quantities which in the year 2021 will still be only partially known.

Transverse polarization provides a window into some of the most debated physics of Transverse Momentum Dependent distribution functions (TMDs) which are the next logical step when deepening our understanding of hadron structure beyond the twist-2 level. Not to get lost in the huge number of TMDs, this discussion has focused on the Sivers function because it should show a most characteristic sign change between SIDIS and DY single spin asymmetries. This property is related to the fundamental nature of local gauge theories, leading to path-dependent phase factors. Its confirmation was therefore selected as a DOE performance milestone HP13. And again RHIC is in a unique position to provide results for this QCD prediction. In the last two years these measurements have gained additional importance due to the theoretical prediction of strong evolution effects for TMDs, which can be tested, e.g. by comparing RHIC and CERN fixed target (COMPASS-II) measurements. In their original paper (0903.3629) Kang and Qiu predicted very large Sivers asymmetries for W production based on fits for the Sivers function to lower energy data. During the last year two groups have studied numerically a higher order effect, namely the evolution of the input functions to the scale of the W mass. This reduced the expected asymmetry dramatically, down to just a few percent. However, these predictions still have a large systematic uncertainty and further study is needed to judge reliably the prospects of the proposed experiment at $\sqrt{s_{NN}}$= 510 GeV. Within the next year the theoretical situation can be expected to clarify. If possible, BNL should support the needed efforts, e.g., by hosting a workshop on TMD evolution. However, as the theory of TMDs requires a substantial extension of our understanding of gauge theories, there are many puzzles and unsolved theoretical problems. Without any doubt, this field will change markedly between now and 2021, and it is presently essentially impossible to predict how our understanding will improve, and, consequently, which measurements will then be judged most crucial. It is certain, however, that many of them will require data on transversely polarized p+p reactions which are only possible while RHIC is still operational.

## 4.3 Unpolarized p+A

RHIC provides unique contributions both for the heavy ion and spin physics community. Presently one of the hottest topics is the observed similarity between the behavior of many observables for p, d+A and A+A which poses the fundamental question how small a system can exhibit thermalized QCD behavior. This physics promises to deepen our understanding of, for example, which requirements have to be fulfilled for hydrodynamics to be applicable. As these questions are of fundamental nature and difficult to answer, they will certainly still be of great interest in 2021/22 while the detailed questions asked will certainly evolve. RHIC will then be in a perfect position to continuously contribute important data on p+A and d+A. Some other examples illustrating the importance of p+A running are the investigation of energy loss in cold nuclear matter, the ridge phenomenon, and the Cronin effect. In all cases, RHIC p,d+A experiments provide important data, which are necessary to correctly interpret the corresponding phenomena in A+A collisions. Other channels like dilepton production allow a test of saturation, which is one of the fundamental elements of our present understanding of the structure of fast moving nuclei.

In addition to the QGP-oriented research discussed so far, the ions can also be used as sources of Weizsäcker-Williams photons. Processes like exclusive J/psi production from photon gluon fusion should, for example, provide information on the presently basically unknown generalized parton distribution function *E* for gluons.

## 4.4 Transversely polarized p + A

As the characteristic gauge link structure associated with, for example, the Sivers function can be thought of as generated by re-summed gluons, the associated single spin asymmetries should be especially sensitive to gluon saturation effects in nuclei. Recently, a number of proposals indicate that this observation can provide a very sensitive probe of saturation phenomena. However, the theory is still too preliminary to permit a clear prediction for what the situation will be in 2021, except for the general conclusion that there most likely will be a high demand for precise experimental data.

While the discussion surrounding transverse spin phenomena clearly shows that there exists a whole new level of gauge theory phenomena to be explored, in particular by EIC, it also demonstrates that the demands for theory support increase dramatically with the increasing complexity of the phenomena investigated. Additional theoretical support in this field should be encouraged.

## 4.5 Summary

The PAC thanks both collaborations for their stimulating input and congratulates them on their outstanding work which in many respects is unique and has extremely strong impact on many aspects of hadron physics. Based on this assessment the PAC has no doubt that the collaborations would make good use of a high intensity p+p and p+A physics program in FY 2021 and 2022. Nevertheless, the collaborations are strongly encouraged to identify and give priority to those aspects of the p+p and p+A program that would be complementary to an envisioned EIC program. However, in view of the unsettled state of many aspects of the ongoing theoretical discussion the PAC presently cannot give a clear assessment of the impact such a program would have at the time.

# 5. New opportunities

A wide array of new results from LHC and RHIC shown at the most recent Quark Matter conference have confirmed and extended the striking similarity seen in particle correlations in small systems (high multiplicity p+p, d+A, p+A) and the radial/elliptic hydrodynamic flow signals analyzed in nucleus-nucleus collisions. They include observations considered key signals of the strongly interacting QGP, such as particle mass dependence, higher order harmonics and higher order cumulants. This exciting and very surprising discovery is leading to a paradigm shift, where the smaller and more 'elementary' collisions systems (p+p, p+A) are no longer seen merely as baseline and comparison data, but are of prime interest in their own right in the study of dense and strongly interacting matter. Establishing the existence of a large, essentially macroscopic, thermal system with almost perfect collectivity was a crucial milestone reached in collisions of the largest nuclei at RHIC; now small but dense systems provide a new and unique opportunity to study the onset of collectivity and other QGP signatures not only as a function of beam energy, the current prime aim of the RHIC BES, but also as function of system size and system lifetime.

These new results raise a new set of important questions, including:

- What is the smallest (in terms of size and energy content) droplet of QGP to which a fluid dynamical description can be applied?
- Are there mechanisms other than hydrodynamics that can generate and quantitatively reproduce the observed collective features in these collisions?
- How do collectivity and other signatures (jet quenching, quarkonia suppression, ..) emerge as a function of system size and energy density? What are the relevant scales (time, energy, size) which control the onset and strength of these signals?
- Are different signals controlled by different scales, as seems to be indicated by the apparent absence of high $p_T$ suppression and dijet asymmetries in p+Pb collisions which otherwise exhibit flow-like signatures?

The flexibility of RHIC both in terms of energy and beam combinations is uniquely suited to address these new opportunities. Some of the data of interest are already available (or will be available soon) and need to be analyzed, including high multiplicity p+p collisions at 200 and 510 GeV and the 'size scan' using p, d, and $^3$He projectiles colliding with Au and, possibly, Si.

While it is too early to judge if additional beam combinations (like C+C or C+Au) are warranted in the near or medium term, both results from the existing data, as well as the new and lively theoretical interest in small dense collision systems could provide the basis for an informed decision in the near future.