Report of the RBRC Scientific Review Committee

Brookhaven National Laboratory

April 5 - 8, 2016

I. Introduction

The RBRC Scientific Review Committee met last on October 30 – November 1, 2013. This report discusses the important developments since that time.

The Scientific Review Committee consists of Sinya Aoki, Albert De Roeck, Xiangdong Ji, Richard Milner (Chair), Alfred Mueller, and Julia Velkovska. The Committee membership is listed in an appendix to this report, with members' addresses and affiliations.

The meeting opened with Dr. Hideto En'yo, Director of the RIKEN Nishina Center for Accelerator-Based Science, giving an overview of the RIKEN review system and schedule, terms of reference, and outlook. The present RBRC MOU runs through JFY2017 and the Committee was asked to consider the MOU for the next period JFY2018 through JFY2023. Within this next MOU period, it is expected that the scientific mission of RHIC will be completed and preparations will be advanced for the Electron-Ion Collider (EIC).

In this report we review the current program and recent achievements.

II. Director's Overview of the Current Program

Dr. Sam Aronson, the RBRC Director, presented an overview of RBRC personnel as well as recent achievements in the scientific program and the performance of the RHIC accelerator.

At the beginning of his presentation, Dr. Aronson discussed the management of RBRC and the role RBRC plays in the career development of scientists and scientific leadership. There has been significant renewal in the scientific staff since the last meeting and there are expressions of interest from several universities in Fellow Positions. He reported that Dr. Y. Akiba remains Experimental group leader with Dr. A. Deshpande, his deputy, and Dr. D. Kharzeev has replaced Dr. L. McLerran as Theory group leader, with R. Pisarski, his deputy. Dr. T. Izubuchi continues in the position of Computing Group Leader. Dr. Akiba has recently been elected Spokesman by the PHENIX collaboration.

Dr. Aronson reported that during 2011-2016 a large quantity of spin data has been acquired. In particular, PHENIX has accumulated about 150 pb^{-1} of polarized p-p collisions at $\sqrt{s} \geq 500$ GeV with proton polarization typically $\geq 50\%$. The most important new result to emerge recently is that the gluon does contribute significantly to the spin of the proton. In this period, heavy ion capabilities at RHIC have also improved significantly in terms of collision luminosity, beam lifetime, energy range and accelerated particle species. The next PHENIX detector capabilities such as VTX led by RIKEN and RBRC have allowed new measurements, e.g. higher-order particle flow, collision geometry effects, *c*- and *b*-quark yields, suppression of heavy quarks and photons, and searches for BSM effects. The 2016 run will conclude the data taking by the PHENIX detector.

During the next MOU period (2017-2023), Dr. Aronson described two main thrusts to the RBRC experimental effort. Firstly, the PHENIX collaboration (led by Y. Akiba) will analyze and publish the high statistics p-p, p-A, d-Au, and A-A datasets. Secondly, RBRC plans to participate in the construction of sPHENIX, a state-of-the-art jet detector. sPHENIX will be used to study both proton spin structure as well as the QGP and is expected to begin data taking in the early 2020s.

Dr. Aronson described an exciting new theory initiative on chiral matter. This involves collaboration with condensed matter scientists and requires high performance computing as well as development of new materials.

The lattice gauge QCD research has had a very productive period with recognition by prestigious prizes and worldwide usage of techniques developed by RBRC.

Dr. Aronson described RBRC contributions to the LSST project in cosmology. The focus has been on understanding manufacturing defects in CCD devices.

Dr. Aronson reported on the continued decline of the RBRC budget. Over the last 2-3 years, the budget has decreased to about 10% below the historic average.

III. Scientific Progress

A. Experimental Program

RBRC Experimental Group leader Yasuyuki Akiba described the three main activities of the group: spin physics, heavy ion physics, detector upgrades for PHENIX and R&D for the future sPHENIX experiment. RBRC members maintain a strong and visible role in the PHENIX data analyses and publications, playing a leading role in about 1/3 of all PHENIX publications. The overall PHENIX publications and citations continue to grow, and although the experiment will stop taking data after the completion of the 2016 RHIC run, this trend is projected to continue for at least five years. PHENIX has collected a diverse set of high-quality data spanning different collision systems and center-of-mass energies; many new high-quality results are still expected. Yasuyuki Akiba was elected PHENIX spokesperson starting in 2016. He is committed to continuing the PHENIX productivity. He highlighted several high-impact results. The first measurement of nuclear modification factors of electrons from charm and bottom hadron decays separated using displaced vertices identified with the VTX detector was achieved. This detector was built and operated by RBRC/RIKEN and the effort has come to fruition. The group also specializes in photon measurements. The nuclear modification factors of direct photons were measured in d-Au collisions and no significant modifications were found as expected. On the other hand, some intriguing results were found in Au-Au collisions, where surprisingly large elliptic and triangular anisotropies in the azimuthal distributions of direct photons were observed. In addition to the measurements related to the study of the quark gluon plasma, a search for a dark photon was performed using a large sample of Dalitz decays and the possibility that a dark photon can explain the muon g-2 anomaly was excluded at 2σ. Details of the spin physics program were given by the deputy group leader Abhay Deshpande in a separate presentation. Overall, the group's research activity comprises an impressive portfolio. The group is also involved in R&D studies for the tracking system in sPHENIX. A Si-based tracker is pursued. The status of this effort was discussed by Gaku Mitsuka, and the physics of sPHENIX for spin and heavy ion physics was presented by RIKEN/RBRC scientist Itaru Nakagawa and university fellow Megan Connors.

Takashi Hachiya (post-doc) presented details on the measurement of the nuclear modification factors of *charm* and *bottom* via their decay electrons using Run 11 data. This is a challenging measurement and first of its kind at RHIC. The results that were just published, find that at high p_T *bottom* is suppressed at the same level as *charm*, while it is less suppressed at $p_T < 4$ GeV/c, although the statistical and systematic uncertainties remain large and prevent strong conclusions. These surprising results can be further improved using a factor of approximately 10 more statistics of Au-Au collisions at 200 GeV recorded by PHENIX during Run 14 and Run 16.

Yorito Yamaguchi (post-doc) described his ongoing efforts to measure thermal dielectrons in Au-Au collisions. In a particular mass window, $1<m_{ee}<3$ GeV, thermal dielectrons dominate the spectrum and can be used to infer the thermal photon yield. The challenge is to suppress the large background from open charm decays, and this is where the use of the VTX detector comes into play. This measurement is a key element for understanding the thermal properties of the quark gluon plasma, especially in view of the puzzling direct photon flow results. Yamaguchi presented a viable plan of completing the measurement once the full statistics from Run 14 is available for analysis.

Megan Connors (university fellow) presented her prior work on jet-related analyses in PHENIX and her plans for future analyses with PHENIX and sPHENIX. She has just started a tenure-track faculty position in Georgia State University in Fall 2015 and has already developed an excellent research plan and taken a number of responsibilities for sPHENIX. She is working on simulations and development of a data analysis framework. At the same time, she is deeply involved in the HCAL effort, serving as an HCAL prototype manager. These activities are important for the success of sPHENIX, both in R&D and construction, and eventually – for extracting the exciting physics results for which it would be built.

Gaku Mitsuka (post-doc) presented work ongoing on tracker R&D for the sPHENIX detector. The R&D studies conducted in the RBRC experimental group are focused on the silicon tracker upgrade option, which is one of the two options considered by sPHENIX. One of the strong physics cases for sPHENIX is the study of heavy quarks via quarkonia and open *charm* and *b*-production, as a tool to understand the QGP. An all silicon tracker will be an excellent asset for such studies. Special emphasis was given on the reduction the material budget of the tracker and the choice or readout chip. For the latter a three-bit ADC is considered to be sufficient for track fitting and reconstruction, but it means no dE/dx information will be available. Dark current studies have been made and air-cooling tests will be conducted shortly.

Prototype R&D is ongoing and first full test will soon start at BNL. Suitable simulation code is being developed and the initial results on the resolution studies are encouraging.

Abhay Deshpande (Stony Brook University & RBRC Deputy experimental group leader) gave an overview of the spin physics program at PHENIX. He emphasized that RHIC is the first polarized high-energy collider, and much of the program became possible thanks to the RBRC funding and support. A major focus of the program has been the measurement of the polarized gluon distribution ΔG, by employing longitudinally polarized proton-proton collisions at various center-of-mass energies: 62, 200, and recently 510 GeV. Neutral and charged πs, direct photons and heavy quark production were used as experimental probes. The ΔG integral for $x > 0.01$ has now convincingly shown to be non-zero by the PHENIX and STAR experiments. Further, the anti-quark polarization was measured in $W^{+/-}$ production using final states with electrons or muons. Finally, a report was given on the program of the systematic studies of the transverse spin, which includes a transversely polarized proton beam on unpolarized proton or nuclear target. The transverse spin results continue to surprise, and no generally accepted explanation has yet been given for the strong A-dependence. Several interesting analyses are still in the pipeline. It was also pointed out that sPHENIX would be an excellent detector for spin physics, e.g. allowing to use the photon channel for a precise measurement of ΔG. sPHENIX is also thought of as a possible detector for the EIC with extensions for the electron part).

Xiaorong Wang (University Fellow NMSU) gave an overview of spin measurements using heavy flavor production, with the PHENIX detector. New Mexico State University has several physicists working on the longitudinal and transverse spin program in PHENIX. J/psi production has been studied to extract the polarized gluon distribution and this channel has the potential to be sensitive to lower-*x* values of ΔG compared to other processes. Another area of interest is the study of the gluon Sivers function in transverse single spin asymmetries. This function was also studied, as well as the twist-3 tri-gluon correlation function, using open heavy quark production processes.

Itaru Nakagawa (RIKEN/RBRC) presented the potential for the spin physics program with sPHENIX. Some recent achievements from PHENIX spin analyses were recalled, in particular the gluon polarization results from Run13 and the large forward neutron asymmetry in transverse polarized p-Al and p-Au scattering. Data using the beam-beam counters (BBC) for tagging and vetoing was discussed for the neutron measurements, in order to assess the effect of ultra-peripheral collisions in this asymmetry. The hadron structure program in sPHENIX can revisit these interesting measurements and conduct them with increased precision. Spin measurements at sPHENIX will continue to be of high of interest due to the improved tracker and full calorimeter coverage for the central region in this new detector, in particular for measurements using photons and π^0s as analyzers. Interesting projections for the reachable precision of sPHENIX have been shown. A possible study of the $\sqrt{s}$ dependence of the transverse single spin asymmetry in p-Au collisions using an internal fixed target to access lower $\sqrt{s}$ during sPHENIX running was discussed. The effect on the transverse p-A asymmetry using an internal new gold fixed target was shown. A detector extension in the forward region (fsPHENIX) would be beneficial for the spin program.

The Committee found that the RBRC experimental program is very visible both in spin physics and in the heavy ion program of RHIC. RBRC scientists are active in the PHENIX experiment, make important contributions and are principal authors on many publications of the collaboration. They have also provided leadership in the construction and operation of major detector components of PHENIX and to the R&D studies for sPHENIX and the EIC. Large data sets with diverse beam configurations unique to RHIC have been collected in the past few years. Many analyses of data already collected need to be finalized and published in the next 3-5 years, and the RBRC should keep that as a priority in allocating its near term resources.

For the future, it is clear that the RBRC group wishes to participate in the new sPHENIX collaboration. The sPHENIX measurements of jets and quarkonia are essential for the completion of the physics mission of RHIC in the studies of the quark gluon plasma. Having made major contribution to the heavy ion program of PHENIX, the RBRC members are well positioned to positively impact sPHENIX as well. Polarized p-p and p-Au running is also envisioned in the sPHENIX program, and would produce additional high-quality data sets for the spin program well before the start of the EIC. RBRC has been the main driver of the spin program in PHENIX and could play a leading role on this front in sPHENIX. We advise that the estimates for the projected sPHENIX results should be put in the context of the achieved (or anticipated) results from the PHENIX and STAR experiments.

RBRC wishes to take part in the tracker project, and is concentrating on the silicon tracker. It is recommended to keep options open and to engage also if the decision would favor a different technology. In addition, other detector components beneficial for the spin program should be considered as options for their focus. Obtaining the necessary funding for sPHENIX detector components will require careful planning.

RBRC has at present no direct connection with the STAR experiment, that will benefit from an additional polarized p-p run and the beam energy scan when the PHENIX detector data taking will be terminated. We suggest that RBRC should be open to collaboration with STAR on these significant opportunities.

B. Theory Program

Members of the RBRC Theory Group, led by Dmitri Kharzeev, work closely with staff members and postdocs in the BNL Nuclear Theory Group. The BNL Nuclear Theory Group is one of the top nuclear theory groups in the country with active research efforts in heavy ion physics, hadronic and spin physics, non-equilibrium QCD and the dynamics of equilibration in QCD, the physics at a future Electron Ion Collider (EIC) and the chiral magnetic effect. Mentoring of RBRC fellows and postdocs continues to be very good with the postdocs and fellows being very productive in the research areas of the BNL nuclear theory group.

There is a lot of activity centered around the chiral magnetic effect, where an external magnetic field induces an electromagnetic current due to the chiral anomaly. BNL theorists, especially Dima Kharzeev who himself was an RBRC fellow, have led the effort in developing the ideas around this effect. Although the chiral magnetic effect has not been definitively seen in heavy ion collisions, where the idea first came up, it has been seen in condensed matter as described by Jim Misewich (Associate Lab Director for Energy Sciences).

RBRC fellows and postdocs have gone on to permanent positions around the world, but especially in Japan and the US. They now form a major and influential component of young and active hadronic theorists.

We note that Larry McLerran who was responsible for building the current BNL Nuclear Theory Group, and who for many years was head of the RBRC Theory Group, will be leaving BNL this summer to become director of the DOE Nuclear Theory Institute at the University of Washington.

RBRC Theory Fellows

Fedor Bezrukov recently left the University of Connecticut, and RBRC, to take a position at the University of Manchester leaving RBRC with only two theory fellows. Rob Pisarski gave a summary of Bezrukov's work as a RBRC Fellow. His recent focus has been on the Higgs potential. His conclusions are that, within the context of the SM model, current top quark mass measurements indicate that the Higgs potential is very close to the boundary between stability and metastability.

Jinfeng Liao (Indiana University) described recent work he has done on searching for effects due to the chiral anomaly that could be measured in high-energy heavy ion collisions. His focus has been to use hydrodynamics, including the chiral anomaly, to obtain quantitative predictions on the amount of charge separation that can be expected from initial axial charge fluctuations due to the anomaly. For example, predictions for identified hadron pair correlations due to the chiral magnetic effect have recently been given.

Ho-Ung Yee (University of Illinois at Chicago) described two recent calculations he has done involving chiral magnetic effects in the quark gluon plasma. The first calculation was that of the second order transport coefficient relating the current and the magnetic field that indicates that the chiral magnetic current is resistant to magnetic field changes. The second calculation evaluates a signal for the chiral magnetic effect, the spin polarization for photons emitted in a plasma.

Recent RBRC Post-docs

Rob Pisarski described recent work of Akihiko Monnai who has recently left RBRC to join the theory group at Saclay as a postdoc. Monnai has been involved in developing hydrodynamic descriptions of the various flow harmonics measured in high-energy ion collisions. Among other interesting results he, with Y. Hatta and B. Xiao, have found analytic solutions to Gubser hydrodynamics which give good fits to RHIC data for v_2 for the difference of π^+ and π^- yields.

R. Pisarski also described the work of Koichi Hattori, who has recently taken a postdoctoral position in Shanghai. Hattori has recently been studying the effect on the v_2 of heavy quarks due to magnetic fields giving an anisotropic diffusion constant.

Current RBRC Postdocs

Vladimir Skokov described recent work on dijet azimuthal anisotropy in high-energy deep inelastic electron scattering on nuclei. This work could be important for

detecting parton saturation effects at an EIC. Rather large asymmetries were found using a simple McLerran-Venugopalan model of the nucleus.
Daniel Pitonyak described his recent work analyzing and evaluating transverse single spin asymmetries in proton-proton and electron-proton collisions using a collinear twist-three factorization procedure. His conclusion is that there are competing effects and the underlying mechanism is still unclear. At an EIC, the estimated effects are on the order of 10 percent, which is a significant asymmetry.
Finally, Dima Kharzeev (head of the RBRC Theory Group) and Jim Misewich (Associate Laboratory Director for Energy Sciences) described the chiral magnetic effect in condensed matter where the effect has been clearly seen in ZrTe5 crystals by a BNL, Stony Brook, Princeton, Berkeley collaboration. Both Dima and Jim were very enthusiastic and excited by this emerging research area at the boundary of nuclear and condensed matter physics.

There is an impressive program of broad research in theory. There is a need to replenish the theory fellows after recent and anticipated departures, particularly in areas associated with the core RBRC program.

The Committee was impressed by the activity in theory and experiment centered around chiral matter. D. Kharzeev and RBRC theorists have developed ideas in the context of heavy-ion collisions which have found realization in low temperature materials measured by BNL condensed matter experimentalists.

C. Lattice QCD Computing Program

Overview

Taku Izubuchi, as the group leader of the computing group, reviewed the organization of the group and RBRC computing facilities as well as the physics highlights in the last few years. In addition to himself, the RBRC computing group now consists of one fulltime fellow, three university fellows, three postdoctoral fellows, seven visiting scientists and five students from Columbia University. The group has been engaged in a close collaboration with physicists at Columbia University, University of Connecticut, and BNL (high energy theory and computational science center) since 1998 as the RBC collaboration, and with the UKQCD Collaboration in Great Britain since 2005. It has also started a somewhat loose collaboration with the JLQCD collaboration in Japan on measurement methods since 2012. In addition, participation in the LHP collaboration on nucleon structure has been underway since 2013. Recently, some of the RBRC members have started a new collaboration with physicists at the University of Tsukuba and AICS, a RIKEN branch at Kobe, on the calculation of the muon g—2 and nucleon matrix elements since 2014. The RBC/UKQCD collaborations have worked well in fostering young talent, producing 35 PhD theses since 2005, and currently having 12 PhD students. Some fellows and postdocs also have worked with other collaborations, NPLQCD collaboration (Brain Tiburzi), LSD collaboration (Ethan Neil and Sergey Syritsyn), and LatKMI (Hiroshi Ohki). The computing resources of the group consist of the QCDCQ at RBRC, ANL Mira (BlueGene/Q) at Argonne National Laboratory, BlueGene/Qs operated at Edinburgh and KEK through the collaborations, PC/GPU clusters at FNAL and Jefferson lab through the USQCD collaboration, and HOKUSAI FX-100 at RIKEN, Wako, Japan. The scientific activities of the group continue to attract worldwide attention as evidenced by 11 plenary talks and 11 publications in Physical Review Letters (including 3 Editor's suggestions) by the group members in 2014-2015. In addition, the members have been recognized by three awards, namely 2013 APS Fellowship, 2014 APS Fellowship and 2015 Kenneth G. Wilson Award. They have also played active roles in the lattice QCD community, serving on various committees and organizing workshops and meetings including the Lattice 2014 meeting at Columbia University, the most prestigious annual symposium in the community.

Highlights of recent physics results were presented by Izubuchi, and were followed by individual presentations providing more detail. Izubuchi emphasized that a new generation of lattice QCD simulations now produces several important results: (i) lattice QCD simulations at physical pion mass of 135 MeV using chiral lattice quarks have been performed at 2 lattice cutoffs (1/a=1.7 and 2.4 GeV) on large volume of $(5.5\ \mathrm{fm})^3$, (ii) sub-percent accuracy is achieved for many fundamental/basic quantities such as hadron masses and decay constants, (iii) the signal of the muon g—2 light-by-light scattering contribution is much improved as compared to the first signal reported in the last review, (iv) the kaon decay to two pions is investigated for both I=0 and 2 channels, establishing the $\Delta I=1/2$ rule, (v) the first signal for the direct CP-violating matrix element of the kaon decay to two pions is obtained, (v) B baryons as well as B mesons are investigated, leading to the new determination of the CKM matrix by LHCb, (vi) many other varieties of physical observables are examined, including (a) the inclusive tau decay, (b) electromagnetic properties and the form factors of nucleons, (c) neutron electric dipole moment, (d) parton distribution functions, (e) BSM physics, and (vii) those developments are made possible through new and existing computing resources as well as new computational algorithms such as the Mobius domain-wall fermion and the efficient code generator. In particular, All Mode Averaging (AMA) developed at RBC, achieves 10 -100 times speedup for physics measurements, and is now widely used in the community as the “de facto standard”.

Individual presentations

Brian Tiburzi described his work using lattice methods to explore electromagnetic properties of nucleons and nuclei. Working with the NPLQCD collaboration, he calculated the magnetic moments of light nuclei, from proton and neutron to ^{3}He and ^{3}H, in lattice QCD at heavier pion mass. He found the simple shell-model pairing structure in the magnetic moment of light nuclei, as similar to Nature. With the NPLQCD collaboration, he also investigated a nuclear reaction for the first time in lattice QCD. He calculated the magnetic dipole transition between *np* and the deuteron and obtained the effective coupling for this process. He recently investigated the effect of extreme magnetic field to light nuclei and obtained their magnetic polarizabilities in lattice QCD with NPLQCD collaboration.

Tom Blum reported his work on nucleon structure from lattice QCD with the RBC collaboration using configurations generated at the physical pion mass. He calculated the electromagnetic form factors of the nucleon, from which the proton radius can be obtained in principle, as well as the axial form factors including the axial charge g_A . He also calculated moments of the generalized parton distribution functions of the nucleon. Using lattice QCD, he also evaluated the neutron electric dipole moment (nEDM) induced by the θ-term coupled to the global topological charge in QCD. He proposed a new technique to enhance the signal, where he re-weighted the nEDM with the local topological charge instead of the global one. This method seems promising. He recently started considering other contributions to the nEDM from the higher dimensional operators such as the chromo-EDM, which might be generated by the physics beyond the SM above the electroweak scale.

Stefan Meinel presented his work on flavor physics with Λ_b baryon. He first reported on the electroweak transition form factors from Λ_b to proton or Λ_c in lattice QCD, in collaboration with Detmold and Lehner, using gauge configurations generated by RBC/UKQCD collaborations at three pion masses heavier than the physical one and two lattice spacing, a=0.112 and 0.085 fm. Combining his lattice QCD result with the LHCb measurement of the decay ratio gives $|V_{ub}|$=3.27(15)(16)(6), which is consistent with the other determination based on B meson decay to pion, where the first, second and third errors come from the experiment, lattice and V_{cb} , respectively. It is worth mentioning that, because of this contribution, Meinel received the 2015 Kenneth G. Wilson Award for Excellence in Lattice Field Theory "*for his substantial and timely contributions in a new research direction in physics of the bottom quark using lattice QCD*". He also reported on his recent work with Detmold on form factors, differential branching fraction and angular observables of the Λ_b decay to Λ + 2 leptons in lattice QCD.

Christopher Kelly presented his ambitious project, the direct lattice calculation of the I=0 two pion decay amplitude of the kaon, which is important to explain the $\Delta I=1/2$ rule and the direct CP-violation in the SM. To overcome technical difficulties in the direct calculation of the decay amplitudes, RBC/UKQCD collaborations introduced a special boundary condition, called G-parity boundary condition. After an exploratory study at heavier pion mass reported in the last review, he calculated the decay amplitudes at 1/a=1.7 GeV on a 32^3 x 64 lattice with almost physical pion mass. Although statistical errors are still large due to the cancellation between different weak operators, he obtained Re A_0 = $4.66(1.00)_{stat}(1.21)_{sys}$ x10^{-7} GeV, which should be compared with Re A_0 = 3.3201(18) x10^{-7} GeV in experiment, while he obtained Im A_0 = $-1.90(1.23)_{stat}(1.04)_{sys}$ x10^{-11} GeV . Combining these results with the previous RBC/UKQCD results on I=2 decay amplitude A_2, he finally obtained Re $(\varepsilon'/\varepsilon)$ = $1.38\,(5.15)_{stat}(4.43)_{sys}$ x10^{-4} . Although this value is 2.1σ smaller than the experimental value, 16.6(2.3) x10^{-4}, the fact that ε'/ε is evaluated by the first principles approach, lattice QCD, for the first time, is highly appreciated.

Hiroshi Ohki presented his recent study on the inclusive tau decay analysis with lattice QCD hadronic vacuum polarizations, in collaboration with RBRC members and others. He proposed a new method to determine $|V_{us}|$ from the inclusive tau decay using lattice QCD data, in order to elucidate a possible origin of the so-called $|V_{us}|$ puzzle. To test this idea, he calculated hadronic vacuum polarizations, employing 2+1 flavor domain-wall fermion gauge ensemble generated by RBC/UKQCD collaborations at almost physical pion mass and 1/a=1.7 and 2.4 GeV in (5 fm)^3 box. His preliminary results indicate that his method works well and gives a new estimate of $|V_{us}|$ from the tau decay, which is roughly consistent with the one determined from the Kaon decay within a large error. By reducing both statistic and systematic errors in future calculations, the method may provide a solution to the $|V_{us}|$ puzzle.

Ethan T. Neil reported on his work on lattice calculations for strong dynamics beyond the SM, working with the Lattice Strong Dynamics (LSD) collaboration. He first considered the case that the composite dark matter coupled to the Higgs particle. His lattice result shows that the composite dark matter cannot have mass generation purely from the Higgs mechanism in SU(4) gauge theory, without violating current experimental bounds. He also argued that this constraint may be very general and independent of the gauge group. Secondly, he investigated photon effective coupling to the composite dark matter. Explicitly, he calculated the polarizability of the dark matter in SU(4) gauge theory, which gives the bound of the composite dark matter mass. Finally, he explored the technicolor theory as a candidate of the composite Higgs model. He calculated the mass of the composite Higgs particle in SU(3) color gauge theories with $N_f = 8$ fermion flavors. Interestingly and surprisingly, he showed that the Higgs boson is as light as the pion, the pseudo-Nambu-Goldstone boson in this theory.

Future perspective of the computing group at RBRC

Taku Izubuchi, as a group leader of the computing group, presented the future perspective of the computing group. He stated that the computing group at RBRC will continue to attract top-level lattice physicists from all over the world, as excellent members and collaborators, and that the computing group at RBRC will provide excellent innovations, breakthroughs and opportunities in various areas in lattice QCD, which includes kaon decay to two pions, muon g—2, eRHIC physics, and many others. He also stressed that local, high-performance computers, which define the computer group at RBRC, have been essential to pioneer and test new physics topics and algorithms, and also have been essential to RBRC national and international scientific leadership. He recognized that high-performance computing has become increasingly important to progress in particle physics. In particular, progress in lattice QCD can be achieved by increasing statistics. Thus, he would like to have an upgrade in capability of local, high-performance computing in 2016/17 supported by BNL, DOE and RBRC, to maintain and enhance the competitiveness of the research activities. A suitable choice would be the 1.5 PfFlops Intel Knight Landing (KNL) cluster, with an approximate total cost of $4 million.

Christoph Lehner presented the vision of the future physics program of the computing group. He listed four main scientific problems in lattice QCD for the computing group in near future: (1) **kaon physics**, where one of the main goals is to evaluate long-distance contributions to kaon mixing and its applications, such as the neutral kaon mass difference, B_K, and rare K decays. while the second priority is to complete the RBC longstanding program for the direct CP-violation of kaon decay to two pions, by keeping all systematic errors under control. (2) ***b* quark physics**, where the precise determination of V_{ub} will be planed at physical pion mass. (3) **calculation of the muon g-2**, where both the hadronic vacuum polarization contribution and the hadronic light-by-light contribution will be evaluated more precisely than before with controlled statistical as well as systematic errors. (4) to investigate the **charged pion decay to lepton and neutrino** in QCD + QED simulations.

Tomomi Ishikawa talked about the future project on lattice QCD calculation of parton distribution functions (PDFs) for electron-ion collider (EIC) experiments, which will be pursued in collaboration with Ma, Qiu and Yoshida at BNL. He implemented a new approach to PDFs using lattice QCD, which has been recently proposed. In this approach, the PDFs are reconstructed using a global QCD analysis with the quasi-PDFs, which can be calculated in lattice QCD in principle. One of the crucial parts in this approach is the matching between the lattice quasi-PDFs and the continuum quasi-PDFs, which requires the subtraction of the power divergence as well as the renormalization of quark bilinear operators. He presented preliminary results and will improve the matching calculation in the future plan. If he can successfully complete the calculation using this approach, the PDFs obtained in lattice QCD will strongly support the physics analysis in future EIC experiment.

Norman Christ presented a report on RBRC lattice QCD, which includes physics as well as computing. He first summarized achievement of the computing group at RBRC such as kaon decay to two pions, K_L –K_S mass difference, the long distance part of ε_K, rare kaon decays and the muon anomalous magnetic moment. He then discussed opportunities, where one can reduce uncertainties in the calculation of the above-mentioned quantities by increasing statistics, taking the continuum and infinite volume limits, introducing the dynamical *charm* quark in lattice QCD simulation and including isospin-breaking effects due to both QED and the *up-down* quark mass difference. After briefly summarizing the status of present RBC computing resources and their importance to RBRC physics programs, he then discussed the future computing for the RBC collaboration. He is considering use of Intel many-core processors, which have higher sustained performance per peak as well as greater software flexibility than GPUs, and he has already started Intel/Columbia/Edinburgh Deep Co-design project from April 1st, 2016. As for the software, Peter Boyle, a member of the RBC collaboration, has achieved more than 50% efficiency for the core application on Intel Ivy Bridge and Broadwell CPUs, which are currently available in the market. His near term project of 2016-2017 is to procure a 144-node Intel KNL machine (cost approx. $1 million), whose peak performance is 0.864 Pflops and 0.288 Pflops sustained for the gauge configuration generation with domain-wall quarks. He emphasized that having local high-performance computing is crucial not only for algorithm/code development but also for the test of new ideas and medium-size physics. He closed his talk by describing the future proposal in 2018-2020 to obtain the 256-node KNH or KHP machine (approx. cost $2 million), which has 2 Pflops sustained performance. This machine will be used to prepare for the era of large Xeon Phi-based DOE pre-Exascale (Aurora) and Exascale machines.

Assessment of the RBRC computing group

Recent achievements by the RBRC computing group are excellent and widely ranging from very precise evaluations of fundamental quantities with controlled errors to new and challenging calculations, which include muon g—2, Kaon decay to two pions, the $K_L - K_S$ mass difference, Λ_b decay, and inclusive tau decay, at physical pion mass in some cases. The variety and scope of the research carried out by the RBRC computing group is truly impressive, and establishes it as one of the leading research groups in lattice QCD worldwide. For example, All Mode Averaging (AMA), developed mainly at the RBRC, brings great computational benefits not only internally to the RBC collaboration but also to worldwide lattice QCD research groups, so that it now has become the standard method in the community. In addition, several, new projects at RBRC, e.g. in nucleon structure and properties and in physics beyond the SM, add to the impressive research portfolio of this group.

Basically, the RBRC group should follow the current research projects and styles, in order to continue producing excellent results. The Committee, however, would like to suggest that the RBRC computing group could expand in research areas relevant to the RHIC experiments, such as finite-temperature and high-density QCD, in collaboration not only with the theory group at RBRC but also the lattice group at BNL. Calculation of parton distribution functions in lattice QCD is timely and strongly encouraged, as they will be important for interpretation of future EIC experiments. We believe that this expansion would make the RBRC computing group a unique and irreplaceable group in the world.

The Committee understands that local, high-performance computers have played an important and essential role in the excellent scientific achievements of the computing group at RBRC thus far. As argued effectively in Taku Izubuchi's presentation, maintaining competitive local, high-performance computers will be crucial for the future successes of the group. Thus, we recommend that RBRC should make hardware investments, leveraged with similar investments from BNL and DOE, which can provide this necessary local, high-performance computing for its scientific staff.

D. Astrophysics

About a decade ago, Drs. Aronson and May initiated an effort in cosmology at BNL. Since the last RBRC review, RIKEN has joined as a partner in this effort led by Dr. Morgan as BNL Cosmology Group Leader. Thus far, in this exploratory phase of the RBRC cosmology initiative, funding for present and possible new post-docs is coming from support by the RIKEN Astrophysics Group and not RBRC operating funds. This effort will require new funding if it is adopted as part of the research portfolio.

Dr. Morgan May presented an overview of BNL's role in the Large Synoptic Survey Telescope (LSST). BNL has a lead role in designing and delivering the Science Raft system of LSST. The RBRC group is envisaged as a PI with four post-docs and students focused on data analysis.

Yuki Okura (post-doc) described research directed at understanding bias in the cosmological parameters resulting from LSST CCD sensor features. A number of effects were described.

The Committee finds the physics motivation for the proposed broadening of scope of the RBRC mission to be compelling. The proposed initiative leverages the RBRC relationship. The Committee advises that care should be taken in initiating this new effort that the existing hadronic physics program, the essential basis of RBRC, is not negatively affected in any way.

IV. Future Perspective

Dr. Jianwei Qiu presented a high-level, theoretical perspective that EIC will be the ultimate QCD machine. Its unique capabilities will allow an exploration with

precision of the quark and gluon structure and properties of hadrons and nuclei. EIC will be a tomographic machine to explore strongly interacting matter with a spatial resolution better than 0.1 fm.
Prof. Abhay Deshpande gave an overview of the EIC accelerator and detector. EIC is identified by the US nuclear physics community as the highest priority for new facility construction after the completion of FRIB. He described significant work on the EIC detector design across the community. EIC users around the world are organizing into a structured users group. A National Academy of Science Review of EIC is getting underway in summer 2016. A positive outcome would trigger the formal CD process.

Dr. Yuji Goto described interest in Japan in EIC physics. Along with colleagues from China, India, and Korea, they have submitted a letter of interest from Asian countries to participate in the US EIC. He described a scenario where sPHENIX could be adapted to be an initial detector for EIC. At present, Japanese nuclear physicists are engaged in a long-range planning exercise where this will be discussed.

Dr. Wolfram Fischer presented an overview of the eRHIC accelerator design and R&D. There are currently three EIC accelerator designs: JLEIC at Jefferson Lab based on the existing CEBAF machine; an eRHIC linac-ring design based on the existing RHIC complex; and an eRHIC ring-ring design also based on RHIC. There is a significant R&D effort required to converge to an optimized, realistic design. This includes: high CW current polarized electron gun, cooling of the hadron beam, and SRF crab cavities.

Brookhaven ALD Berndt Mueller reported on the future plan for RHIC and eRHIC.
He highlighted the high level recommendation of EIC as the highest priority for new facility construction. He also pointed out that the LRP budget scenario that allowed EIC construction to ramp up assumed a sharp decrease in national facility operations. CD-0 for EIC could come as early as 2018.
He described the BNL plan to complete the RHIC scientific mission. This involved running in 2016-2018 at high luminosity with Au-Au; a d-Au beam energy scan; a high luminosity 510 GeV transverse polarized p-p run; and a Ru-Zr run at 200 GeV directed at searching for a signature of the chiral magnetic effect. He discussed sPHENIX, a proposed large-acceptance detector designed to make precision measurements of hard probes of the QGP at strongest coupling. Polarized p-p running is also envisaged with sPHENIX. sPHENIX would start data taking in the early 2020s, run for a period of time constrained by the EIC ramp-up, and serve as a basis for an initial detector for EIC.

V. Overall Evaluation of the Program and Recommendations

- RBRC continues to be a unique, highly successful model for international scientific collaboration. The growing, worldwide network of RBRC faculty at research universities and laboratories is very impressive.
- The young people are a dynamic, enthusiastic, and effective group. The RBRC fellows and postdocs are of high quality.
- RBRC workshops continue to play a major role in the evolution of the RHIC scientific community. They bring together theorists and experimentalists and facilitate progress in the field as a whole.
- In discussion with RBRC scientific staff, we formed the clear impression that full-time RBRC experimental fellows now are faced with some challenges in obtaining funding for R&D activities. In view of the importance of full-time resident fellows to both RBRC and BNL, and mindful of the fellows' future careers, we recommend that RBRC and BNL should seek to find a way to supply them with start-up like support for their research activities.
- We commend RBRC leadership for maintaining staffing levels in a challenging fiscal climate.
- We identify three outstanding scientific achievements which originate from RBRC:
  - The determination of a significant contribution by the gluons to the spin of the proton by both the PHENIX and STAR experiments is a major scientific result from RHIC-spin, made possible only by the substantial financial investments from RIKEN and the sustained scientific contributions from RBRC over two decades.
  - Chiral matter, originated in heavy ion theory, is now an exciting experimental activity at the interface of condensed matter and nuclear physics.
  - The All-Mode Averaging technique is now the standard used worldwide in the lattice community.
- The recommendation in the 2015 US nuclear physics long range plan that construction of an electron-ion collider (EIC) is the highest priority for new facility construction is a major milestone. The Laboratory has developed a sound plan for the future based on the electron-ion collider eRHIC starting operation in about a decade. eRHIC would leverage the considerable investments made by RIKEN in RHIC-spin. eRHIC would provide dramatic

new capabilities to explore proton spin and nuclei in the region dominated by gluons and sea quarks.

- The proposed extension of RBRC for the years 2018-23 offers a plan to complete the RHIC-era scientific program and to seize new opportunities. It would allow the analysis of a significant quantity of data already taken; allow RBRC participation in the construction and operation of the new detector sPHENIX; and position RBRC to be in on the ground floor of EIC just as they were for RHIC; and develop a new cross-disciplinary initiative on Chiral matter.
- We strongly endorse the proposed extension of RBRC in the years 2018-23. This will maintain the Center's outstanding scientific productivity in the areas of experiment, theory, and lattice at the RHIC facility.
- Our consideration of RBRC, according to President Matsumoto's terms of reference, yields a very positive evaluation.

Appendix

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