PROJECT SUMMARY

Overview

Jet quenching, the suppression of high-momentum final-state particles resulting from energy lost by a parton interacting with a color-charged medium, was first observed at the Relativistic Heavy Ion Collider (RHIC) as a signature of Quark Gluon Plasma (QGP) formation in high energy heavy ion collisions. The understanding of energy loss in the QGP has evolved with the ability to precisely measure higher energy jets via full jet reconstruction at the LHC. However, to probe the QGP on shorter and shorter length scales, the need for an upgraded experiment designed to measure jets and Υs at RHIC, known as sPHENIX was highlighted in the recommendations of the 2015 Long Range Plan for Nuclear Science and has since been approved by the Department of Energy to start construction. Electromagnetic and hadronic calorimeters are necessary for accurately measuring the energy of the jets. The approved sPHENIX design includes an electromagnetic calorimeter supported by an aluminum frame inside a solenoid magnet with hadronic calorimetery outside the magnet. Hadronic showers will begin in the aluminum frame. We propose to instrument to the aluminum frame to create an inner hadronic calorimeter by inserting scintillator tiles between the aluminum plates creating a second longitudinal layer of hadronic calorimetry.

Intellectual Merit

High energy partons are expected to lose energy in traversing both cold and hot nuclear matter. It is critical to measure this lost energy as a function of the parton energy, and particularly at the highest energies. The highest energy partons are dominated by light quarks and are the most sensitive to energy loss because they originate from the scattering of rare high-x quarks. The inner hadronic calorimeter enables precision measurements of these highest energy quark jets, and at the same time significantly improves the jet measurements across all energy scales, which will impact all jet measurements from sPHENIX.

Broader Impact

The development of this calorimeter will provide opportunities for the diverse population of graduate and undergraduate students at the collaborating institutions to gain experience in research and hardware. The University of North Carolina Greensboro is a Title IV minority serving institution (MSI). Augustana University is classified as a primarily undergraduate institution (PUI). The PI, an early career scientist, has been active in supporting Women in Physics and continues to serve as advisor of the GSU Women in Physics student organization. The PI and co-PIs have a proven record of attracting women and minorities into their groups.

Project Description

a. Information about the Proposal

a1. Instrument Location and Type

Instrument Location: 1008 experimental hall at Brookhaven National Laboratory in Upton, NY.

The inner HCal will be fully integrated into sPHENIX [1], a major detector upgrade that has been approved by the Department of Energy to start construction (passed CD-1/3A review in 2018). The frame for the inner HCal is an integral part of the mechanical structure, supporting the weight of the EMCal, and in turn being supported by the outer HCal. The EMCal and outer HCal are major parts of the ongoing sPHENIX upgrade. This proposal will instrument the frame to form a hadronic calorimeter.

The inner HCal is a sampling hadronic calorimeter with a depth of $0.25\lambda_I$, which is modest relative to the overall calorimeter system depth of $4.9\lambda_I$ but provides critical information about the location of the hadronic shower development, enabling new physics measurements as well as improving overall performance. Along with the sPHENIX outer HCal, the inner HCal is the first hadronic calorimeter to utilize the tilted plate design.

a2. Justification for submission as a Development proposal

The inner HCal will be an integral part of the sPHENIX detector system. Once the sPHENIX detector system is completed, it will run for at least three years and will be shared by an international collaboration of scientists to achieve the intended physics goals mentioned below. The results of this research will be disseminated publicly through journal publications and conference presentations.

The inner HCal is a one of a kind instrument and cannot be purchased from a vendor. Not readily available in literature, it will be the first hadronic calorimeter to utilize the tilted plate design. By having the hadronic calorimeter consisting of two separate compartments (inner and outer HCals), information about the longitudinal (radially outward from the interaction point) development of the hadronic showers is preserved and comparable to more conventional shashlyk designs, while the hermeticity of the acceptance as well as the simplicity of the mechanical construction are greatly improved over the conventional shashlyk design. This design is unique and complicated which neccesiated an extensive prototyping and beam testing over the past few years [2].

The collaborating institutions on this MRI proposal played a major role on the R&D efforts and contributed to the various stages of the beam tests. From these R&D studies, a final design and read out electronics has been reached. The collaborating institutions, therefore, developed the necessary experience and have the man power to oversee building the inner HCal and carry out testing and assembly. The critical component of the inner HCal is the scintillating tiles. These will be produced by the same commercial vendor that is manufacturing the scintillating tiles for the outer HCAL, and has been working with the sPHENIX collaboration throughout the prototyping process. The collaborating institutions have developed a quality assurance process that will allow to remotely monitor the tiles' production and ensure their performance quality as they are being produced. The tiles will be delivered to the collaborating institutions for final testing and calibration with the sPHENIX electronics and will then be assembled into the aluminum frames as discussed below. The sPHENIX detector system including the inner HCal must be ready for the first RHIC-sPHENIX run in 2023. The tile test stands will be designed to test the light yield and accommodate the unique dimensions of the various produced tiles and they require help from local machine shops at the involved institutions to build those stands.

The main risk in this project is in the scintillating tiles production and the risk mitigation plan is developing dedicated testing stands that allow testing the tiles at the factory right after production where each tile must satisfy a well defined set of specifications. In addition, the tiles will be tested before and after the assembly at the local institutions and again at BNL.

b. Research Activities to be Enabled

b1. Introduction

The sPHENIX detector represents a major upgrade to the PHENIX detector region at the Relativistic Heavy Ion Collider (RHIC) [1]. The overall scientific mission is to study the quark-gluon plasma (QGP) at different length scales to understand the coupling and evolution of the plasma. This mission will be accomplished by focusing on hard scattering processes like jets, jet correlations, heavy flavor jets and Υ states. The sPHENIX detector schematic is shown in Fig. 1. The detector is designed around the BaBar magnet that produces a 1.5 T solenoidal field. The tracking system consists of a time projection chamber (TPC), intermediate tracker of four silicon strip layers (INTT), and the silicon pixel detector closest to the beampipe (MAPS). sPHENIX also includes calorimeters to measure the energy of the produced particles. A hadronic calorimeter (outer HCal) is located outside of the magnet and serves as the flux return for the magnet. The electromagnetic calorimeter (EMCAL) is supported by an aluminum frame within the magnet. This proposal is to instrument that frame to form an inner hadronic calorimeter (inner HCal).

Results from RHIC and the Large Hadron Collider (LHC) heavy ion experiments have provided a wealth of data for understanding the physics of the QGP. One very surprising result discovered at RHIC was the fluid-like flow of the QGP [3–6], in stark contrast to some expectations that the QGP would behave as a weakly coupled gas of quarks and gluons [7]. It was originally thought that even at temperatures as low as 2-5 times the critical temperature, the quark-gluon plasma could be described with a weakly coupled perturbative approach despite being quite far from energy scales typically associated with asymptotic freedom. Motivated in part by the new information provided by LHC jet results and the comparison of RHIC and LHC single and di-hadron results, the theoretical community is actively working to understand the detailed jet-medium interaction. The challenge is to understand not only the energy loss of the leading parton, but how the parton shower evolves in medium and how much of the lost energy is re-distributed in the QGP. Theoretical calculations attempting to describe the wealth of this new data from RHIC and LHC have not yet reconciled some of the basic features. Some models include large energy transfer to the medium as heat,

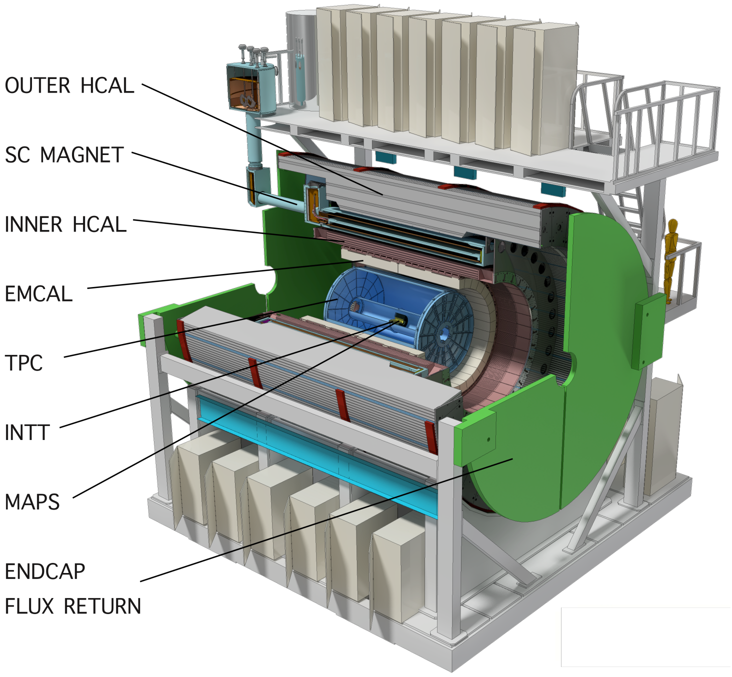

FIG. 1. Schematic of the sPHENIX detector with its components.

for example Ref. [8]. Others describe the interaction with mostly radiative energy loss, for example Ref. [9, 10]. None of the current calculations available has been confronted with the full set of jet probe observables from RHIC and LHC.

The measurement of jet structure and its modification in terms of energy flow promises a much closer connection to the underlying theory. Measurements of jet substructure observables, along with their flavor dependence, are sensitive to the details of medium interactions; therefore, these measurements should be ideal for extracting precise medium properties [11]. The sPHENIX upgrade will enable measurements of jet observables at RHIC that are sensitive to the underlying physics. These new measurements of jets at RHIC energies with jets over a different kinematic range will allow for specific tests of these various theoretical descriptions.

Jets provide a very rich spectrum of physics observables, ranging from single jet observables such as R_{AA}, to correlations of jets with single particles, to correlations of trigger jets with other jets in the event.

b2. Inner HCAL and Jet Performance

The key aspects of jet performance are the ability to find jets with high efficiency and purity, and to measure the kinematic properties of jet observables with good resolution. It is also necessary to discriminate between jets from parton fragmentation and fake jets caused by fluctuations in the soft underlying event. For the sPHENIX physics program, there are four crucial observables that are simulated in detail to demonstrate the jet performance: single inclusive jet yields, dijet correlations, γ+jet correlations, and modified fragmentation functions. An important focus is to demonstrate the capabilities of sPHENIX for central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, where the complications of the underlying event are the most severe.

Since it is not practical to simulate with GEANT4 a sample of events equivalent to a full year of RHIC running, different levels of simulations described in detail below are performed. The most sophisticated and computationally intensive are full GEANT4 simulations with PYTHIA [12] or HIJING [13] events where all particles are traced through the magnetic field, energy deposits in the calorimeters recorded, clustering applied, and jets are reconstructed via the FASTJET package [14, 15]. This method is utilized to determine the jet resolution in p+p and Au+Au collisions from the combined electromagnetic and inner and other hadronic calorimeter information. We have also performed a full GEANT4 study of the reconstruction of PYTHIA jets embedded in central Au+Au HIJING events to gauge the effect of the underlying event on jet observables. In order to gain a more intuitive understanding of the various effects, we use the parametrized performance of the energy resolution from the GEANT4 studies under various jet reconstruction conditions to demonstrate the improved performance with the inner HCAL.

Figure 2 shows the result of full GEANT4 simulations of the performance of the sPHENIX calorimetry system for Pythia8 dijet events with and without the inner HCAL. The design of the outer HCAL is such that the sampling fraction changes with depth in the calorimeter towers. As such, fluctuations in the depth of the hadronic shower result in significant variations of the measured energy. With the addition of the inner HCAL (inside the magnet cryostat, between the electromagnetic calorimeter and the outer HCAL) a second measure of the hadronic energy in the shower as a function of depth allows for a correction to the total hadronic energy, resulting in significantly improved energy resolution for the calibrated jet energy.

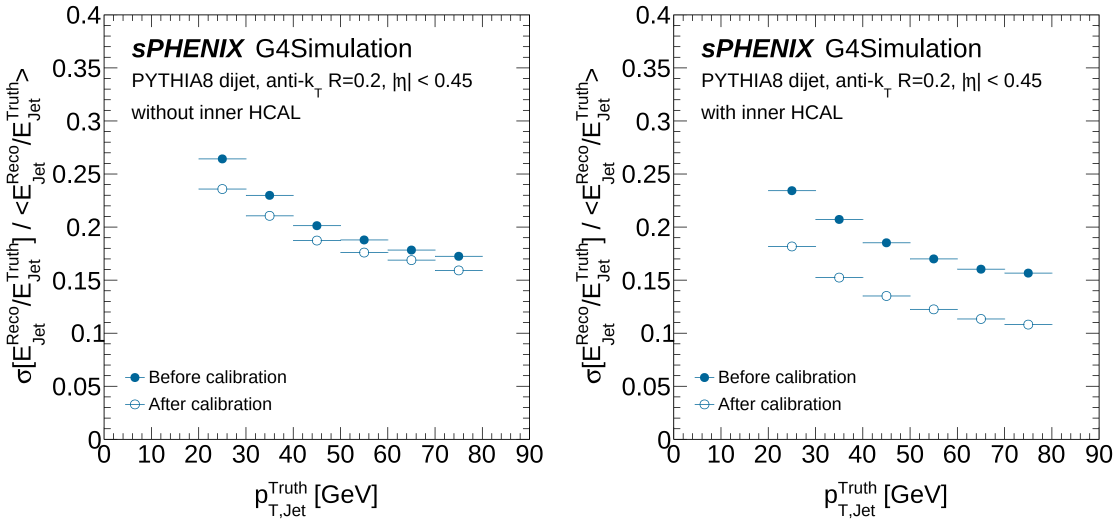

FIG. 2. The energy resolution of the sPHENIX calorimetry system for R=0.2 jets before calibration (filled symbols) and after calibration of the jet energy scale (open symbols). The lefthand plot shows the resolutions without the inner HCAL, while the righthand plot shows the improved resolution obtained with the additional information provided by the inner HCAL.

To further investigate the improvement the inner HCAL can provide to the physics performance in heavy ion events, PYTHIA8 jets were embedded in 0-20% central Au+Au HIJING events, fully simulated in a GEANT4 model of the detector, and reconstructed with an algorithm that subtracts the energy contribution to the jet from the underlying event. Because the subtraction of the underlying event factorizes with calibration of the energy scale in each calorimetry segment, we can apply the same jet energy calibration as used in Figure 2. Fluctuations in the underlying event will add in quadrature with the intrinsic calorimeter resolution, which will reduce the difference between the jet p_T resolution with and without the inner HCAL. However, as shown in Figure 3, for anti-k_T R=0.2 jets the difference in p_T resolution is still clearly visible for high p_T jets. The p_T resolution improvement in R=0.2 jets at high p_T in Heavy Ions is equivalent to removing a constant term added in quadrature of about 13%. For R=0.4 jets this is reduced to 8.5% due to the increased influence of the underlying event. In both cases this is a significant improvement in the jet p_T resolution. Finally, note that with the inner HCAL the p_T resolution function shows only a low-side non-Gaussian tail, presumably due to energy leakage out the back of the outer HCAL, while both a high and low-side tail are visible without the inner HCAL. This high-side tail arises due to the inability to correct for fluctuations in the depth of the hadronic shower without the inner HCAL.

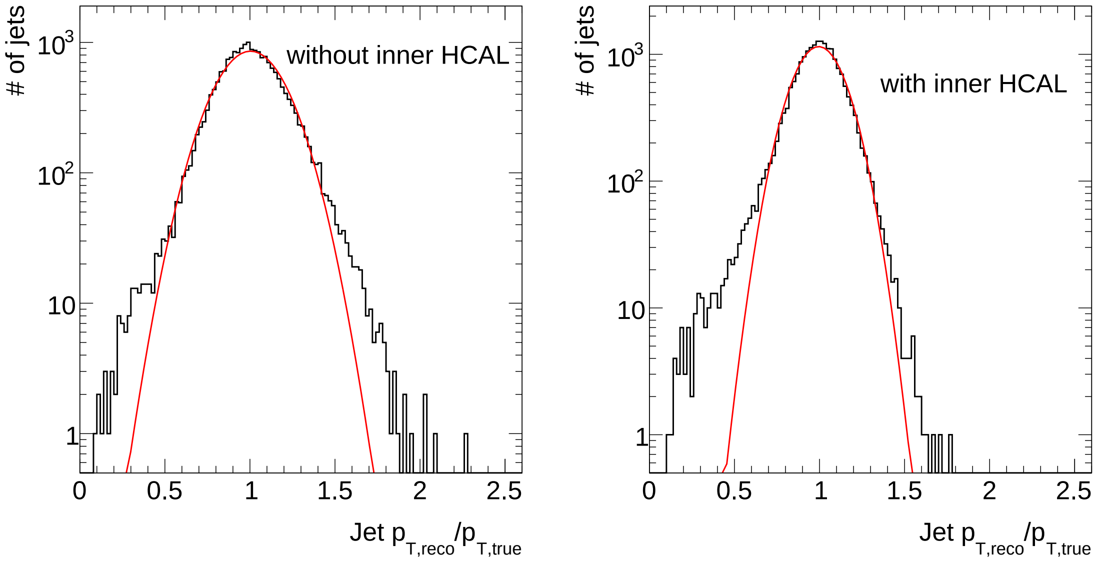

FIG. 3. Resolution functions for calibrated 50 GeV jets embedded in 0-20% central Au+Au HIJING events. The improved energy resolution with the inner HCAL is still clearly visible even after subtraction of the underlying event in the Heavy Ion jet reconstruction. While both resolution functions (with and without the inner HCAL) exhibit non-Gaussian tails in the resolution function, the high-side tail is more significant without the inner HCAL.

The improved jet p_T resolution with the inner HCAL will result in a reduced smearing of the measured jet p_T spectrum that will require correction by an unfolding procedure. To demonstrate this, we used the embedded jet simulations described above to extract the jet p_T resolution function in 2.5 GeV bins from 20-80 GeV in p_T. These p_T resolution function were sampled to smear an NLO pQCD calculation of the jet cross section, scaled to the number of jets anticipated in 0-20% Au+Au central collisions with 100B minimum bias

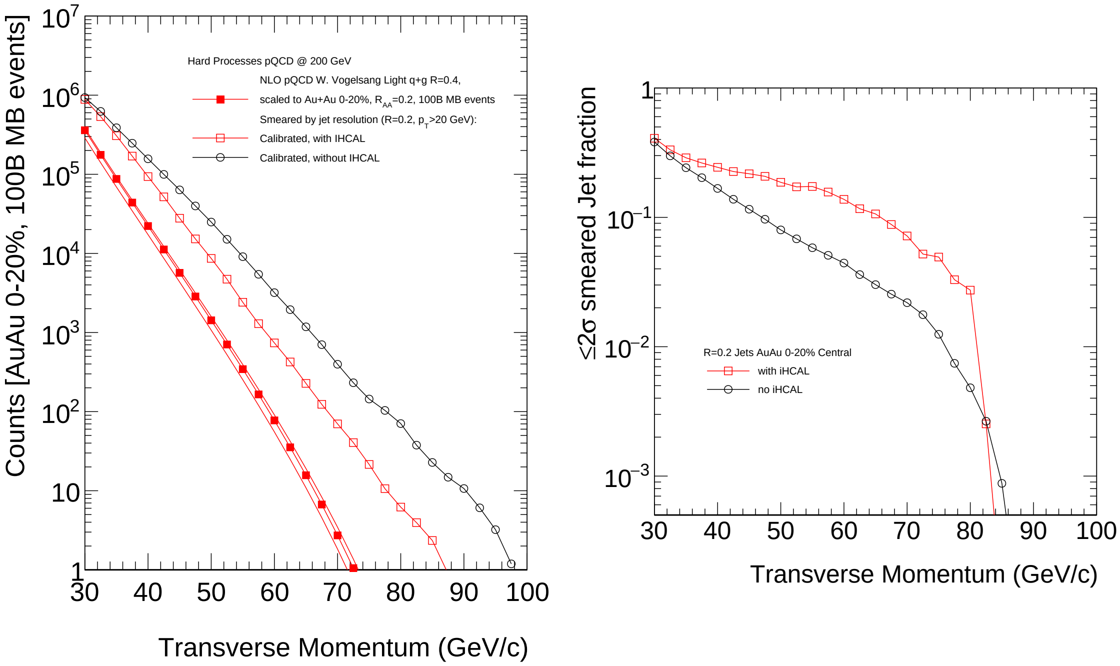

FIG. 4. The result of applying the simulated resolution jet energy resolution in 0-20% central Au+Au events with (red curves) and without the inner HCAL (black curves). The lefthand panel shows the result of smearing the NLO cross section for jets $p_T > 20$ GeV, while the righthand panel shows the fraction of events at a given reconstructed jet energy that sample the Gaussian portion within $\pm 2\sigma$ of the jet energy resolution function.

events sampled by sPHENIX. The results are shown in Figure 4, which shows clearly the additional smearing imposed by the decreased performance without the inner HCAL. In order to quantify this smearing, we measure the fraction of jets in these simulations that result, at a given reconstructed p_T, from sampling the p_T resolution within the Gaussian portion of the response, which we characterize as $\leq 2\sigma$. The righthand panel of Figure 4 shows that with the inner HCAL at the highest p_T there is an improvement of roughly a factor of five in the fraction of events that come from sampling the Gaussian portion of the p_T resolution function. This will directly result in reduced systematic errors when unfolding the reconstructed jet cross section, most importantly at high p_T.

It should be noted that in these simulations the non-Gaussian response in the p_T resolution functions are known exactly. In doing the actual experiment, it is often quite difficult to characterize tails in the true p_T resolution function, and this uncertainty implies an additional contribution to the systematic errors in the unfolded jet distributions, in particular at high p_T. The addition of the inner HCAL, by reducing the relative contribution of the tails overall, will improve the quality of jet measurements at high p_T by limiting the influence of these systematic errors. This is particularly important given that statistics become more limited at high p_T. By improving the jet p_T resolution at high p_T, the inner HCAL will enable high precision measurement for the energy loss of high-x quarks in Heavy Ion collisions, as well as for corresponding measurements in p+A collisions.

b3. Results from Prior NSF Support

The research activities of the co-PIs supported by NSF Grants are Connors by Grant #1714802, Grau by Grant #1719601 and Salur by Grant #1352081.

Results from Grant #1714802: Dr. Megan Connors and her graduate students are currently supported through the NSF Grant, titled "Probing Energy Loss in the Quark Gluon Plasma with Direct Photon Correlations." The award period is August 2017-July 2020 and totals $165,000. The status of the work achieved under this Award after the first 15 months of support is reported here.

INTELLECTUAL MERIT: Direct photon-tagged jets are considered a golden channel for measuring energy loss in the QGP. While jet reconstruction is challenging in the PHENIX detector, the PHENIX electromagnetic calorimeter is well designed to make measurements of the direct photons. Therefore the goal of this NSF award is measuring direct photon hadron correlations using the Run 16 Au+Au data to constrain energy loss models. Graduate student Hodges created the centrality recalibrator which is necessary for any analysis using centrality cuts in the 2016 Au+Au dataset. This recalibator was documented and made accessible to all members of the PHENIX collaboration. Additional calibrations for this data set are ongoing. Therefore, Hodges in collaboration with fellow GSU graduate student, C. Wong has started analyzing neutral pion-hadron correlations in the 2010 and 2011 datasets. Neutral pions are a major background to the direct photon measurement but can also be used to directly extract the energy loss parameter $\hat{q}L$ as well as probe the path length and jet flavor dependence on the energy loss by comparing to the direct photon-hadron correlations which are predominately quark jets. The group also developed a tile tester for testing the sPHENIX hadronic calorimeter tiles during production.

BROADER IMPACTS: This project included mentoring graduate and undergraduate students in hardware, coding, and analysis. The students involved in this project represent the diverse student body at GSU. Graduate students Hodges and Wong attended and presented their work at the National Nuclear Physics Summer School. In addition, Dr. Connors continued her outreach activities with Adopt-A-Physicist, Science Olympiad, visits to a local elementary school, and presented at a meeting of Atlanta Metro Physics Teachers. She also continued her role as advisor to the GSU Women in Physics group and drove several GSU undergraduate women to the local APS Conference for Undergraduate Women in Physics in 2018.

DISSEMINATION OF RESULTS: In addition to being a member of PHENIX and ALICE collaborations which published several articles in this period, Connors was a primary author of the review article on jets [11] and the paper on the test beam results for the sPHENIX calorimeter prototypes [2]. In addition, the PI has organized two workshops on jets at BNL and given several invited talks at conferences including Hot Quarks, APS-JSP Joint Meeting, the RHIC-AGS Users Meeting. Preliminary results were presented at the Hard Probes confernce in 2018.

Results from Grant #1719601: Dr. Nathan Grau has been supported as the principal investigator for Research at Undergraduate Institutions (RUI) since 2013 and is in the beginning of the second year of the current 3-year grant titled "RUI: Studying the Strong Nuclear Force at Augustana University." The award period is August 2017 - July 2020 and totals $120,000. The grant supports the basic science research in high energy nuclear physics.

The RUI has provided summer salary for Grau and several undergraduates to perform data analysis and detector development tasks. The awards have also provided funding to travel to disseminate information from the work.

INTELLECTUAL MERIT: The MPC-EX sub-detector[16] of the PHENIX experiment is a silicon-tungsten pre-shower located directly in front of a lead tungstate ($PbWO_4$) electromagnetic calorimeter. The calorimeter and preshower are located at $3.1 < |\eta| < 4.8$. The preshower improves the position resolution of the calorimeter to resolve photons from π^0 decays up to π^0 energy of 80 GeV. The previous RUI from 2013 - 2017 provided funding for Grau and undergraduates to participate in the development of a Fermilab test beam test, the development of the readout testing, and for the beginning analysis of the data. During the previous summer two undergraduate students D. Li and S. Li began an analysis of the 2016 dataset looking at jet-like two-particle correlations using π^0 triggers at midrapidity and forward rapidity. That analysis is ongoing and will continue during the next summer. The goal is to study the interplay between cold nuclear matter energy loss and saturation physics using two-particle jet-like correlations.

Grau and his undergraduate students have developed a laboratory to test Hamamatsu MultiPiexel Photon Counters (MPPCs) also known as Silicon PhotMultipliers (SiPMs) for the sPHENIX collaboration. The SiPMs will be the light collection devices coupled to the electromagnetic and hadronic calorimeters. The full order of approximately 100,000 SiPMs was submitted in the fall of 2018 and first shipments will arrive for testing in February of 2019.

BROADER IMPACTS: The impact of the work beyond the science is related to undergraduate student learning and achievement post-graduation. In particular the mix of hardware and software tasks has been successful in recruiting students into physics, aiding in retention, and broadening career opportunities. All but one student in Grau's group has gone on to graduate school. The others are employed in areas ranging from software development to defense contracting. Having both data analysis and hardware work gives students with diverse interests opportunities for research. During the summer of 2018 two students who were interested in physics and software worked on the MPC-EX analysis. One student whose interest was in mechanical and electrical engineering worked on the SiPM test stand.

DISSEMINATION OF RESULTS: During the current grant, Grau has participated in several conferences and workshops including giving the PHENIX overview talk at the RHIC-AGS User's Meeting, Jet tutorial and MPC-EX tutorial at the annual PHENIX summer school, a parallel talk at the joint APS-JPS DNP meeting, and a talk at the Winter Workshop in Nuclear Dynamics. All of the talks centered on jets and the work done on the MPC-EX. In the last four years Grau has had four different undergraduate student participate in the Conference Experience for Undergraduates (CEU) at the APS DNP meetings. One student, J. White, participated three different times. Grau, as a member of good standing, has been a co-author on all PHENIX publications since 2001. Grau has played an important role in the writing and/or analyzing results on unlike-sign electron-muon azimuthal correlations in d+Au collisions, which is sensitive to the gluon content of the nucleus [17], and two-particle di-hadron correlations in Au+Au using an improved underlying-event subtraction technique [18].

Results from Grant #1352081: Dr. Sevil Salur and her group has been supported by NSF since 2011. Her latest award is titled "CAREER: Probing the Quark Gluon Plasma with Jet Tomography", for the period May 1 2014 - April 30 2019, PI: Salur. Since 2014, this grant support has contributed to 142 heavy ion physics publications, and members of Salur's research groups served as lead or principal authors on 20 of these.

INTELLECTUAL MERIT: Salur's group performed studies with CMS detector at LHC. These studies show jet quenching to be attributed to final state effects, have a strong correlation to the event centrality, a weak inverse correlation to the jet transverse momenta, and no apparent dependence on the jet radii in the kinematic range studied. The landmark study of small radii inclusive jets that are measured in reference pp collisions was essential to have a better control on theoretical calculations, as they showed the necessity of next-to-next-leading order (NNLO) corrections. Radii dependent corrections were assumed to be small at NLO, but they turn out to be quite large at NNLO. A novel data driven technique, based on control regions in data, was introduced to derive the spectrum of jets that are not from a hard scattering. They also demonstrate that jet quenching does not have a strong dependence on parton mass and flavor, at least in the measured jet transverse momentum range.

DISSEMINATION OF RESULTS: Dr. Salur and her group members gave invited presentations reporting the research results at various meetings including the BJPJ Symposia in 2018, APS Division of Nuclear Physics meeting in 2017, Conference for Undergraduate Women in Physical Sciences (U Nebraska) 2017, 19th Particles and Nuclei International Conference, Winter Workshops for Nuclear Dynamics that were held during 2017 and 2016, Santa Fe Jets and Heavy Flavor Workshop in 2016, the Eleventh Conference on the Intersections of Particle and Nuclear Physics, International High PT Workshops, Hard Probes 2018, ICFA Symposium in Ottawa in 2017, Collaboration and Analysis Meetings, Quark Matter, Hot Quarks, Hard Probes, Definition of Jets in a Large Background Workshop, FCCP, Topical Groups in Hadronic Physics, LPC, 4th Heavy Ion Jet Workshop, and DNP Meetings of APS, Symposia of Undergraduate Research of Aresty Research Center and Douglass REU, and CEU experience of DNP of APS and various seminars and colloquia.

BROADER IMPACTS: Salur organized various meetings and workshops. These are the Definitions of Jets in a Large Background workshop in 2018, Hot Quarks 2014, 2016 and 2018, which is a workshop for young scientists on the physics of ultra-relativistic nucleus-nucleus collisions, Inaugural sPHENIX Collaboration Meeting at Rutgers (2015), APS Conference for Undergraduate Women in Physics (CUWiP) at Rutgers in January 2015 and at Princeton in January 2017. To encourage them to study STEM fields, Salur served as a mentor and gave lectures about nuclear physics and radioactivity in the Target Program during summer of 2015 to 28 6th grade girls who were invited to Rutgers for a week of activities and to high school students in the QuarkNet program during the 2016 and 2018 summers. Salur worked with undergraduate students, 6 of whom are women or members of underrepresented minority groups. These students received NSF fellowships and Goldwater Scholarships. Most of these researchers, after completion of their undergraduate studies, are pursuing their Ph.D. studies in physics.

c. Description of the Research Instrument and Needs

Design concept

The inner HCal is a hadronic calorimeter and is part of the sPHENIX calorimetry system. Along with the sPHENIX outer HCal, it will be the first hadronic calorimeter to utilize the tilted plate design. This design greatly improves the hermeticity of the acceptance as well as the simplicity of the mechanical construction over the conventional shashlyk design. A single compartment with the tilted plate design has appreciably less information about the longitudinal shower development than a shashlyk design, but this information is largely restored by the addition of a second compartment.

Technical description

The inner HCal is a tilted plate sampling calorimeter designed to have four crossings (sampling frequency of 4) for particles with a straight trajectory. The absorber material is hardened aluminum alloy (Al 6061). The active material are scintillating plastic tiles, which are made from a mixture of 98.49% polystyrene doped with 1.5% PTP and 0.01% POPOP.

An individual segment of the calorimeter is called a tower. Each tower includes 4 tiles grouped along the azimuthal direction which are read out by a single pre-amplifier board. The complete detector has 64 towers in azimuth covering 2π and 24 towers longitudinally covering $|\eta| < 1.1$ for a total of 1536 towers and 6144 tiles. The mechanical structure of the inner HCal comprises 32 sectors to be assembled azimuthally, so that each sector has 2 towers in azimuth and 24 towers in longitude. Each sector has 8 gaps (4 gaps per tower) into which the scintillating tiles are placed, 7 full-thickness absorber plates, and two half-thickness plates on either side azimuthally. The absorber plates are bolted to endcap plates on either side longitudinally as well as four structural support combs evenly spaced in the middle. The support combs increase structural rigidity and ensure that the gap thickness is consistent so that the tiles fit properly at all locations along the sector. Figure 5 shows a schematic of an inner HCal sector.

The inner HCal resides inside of the sPHENIX solenoid magnet, which has a highly uniform field of 1.5 T, is essential for the tracking system. For that reason, the inner HCal must be made of non-magnetic material. The inner HCal provides mechanical support for the sPHENIX EMCal, therefore it must have sufficient strength and rigidity. Hardened aluminum alloy (Al 6061) is both non-magnetic and has sufficient strength to fulfill these two roles. Acquisition and machining cost makes hardened aluminum alloy preferable to other possible candidate materials, such as non-magnetic stainless steel (e.g. SS310).

Each tile has an embedded wavelength shifting fiber, with both ends in the same location at the back of the tile serving as a single fiber exit. A plastic light blocker is placed over the fiber exit to block cladding light. A silicon photomultiplier (SiPM) is mounted to the light blocker and serves as the optical device for the readout. The output from the 4 SiPMs in each tower is passively summed on a single preamp board.

The preamp passively sums the output, amplifies it, shapes it, and differentially drives the the signal to a digitizer board. Each digitizer board has a 14-bit ADC that operates at 60 MHz (six samples per RHIC clock tick). The digitizer boards are integrated into the sPHENIX trigger and data acquisition system. On each end of a sector are an interface and a

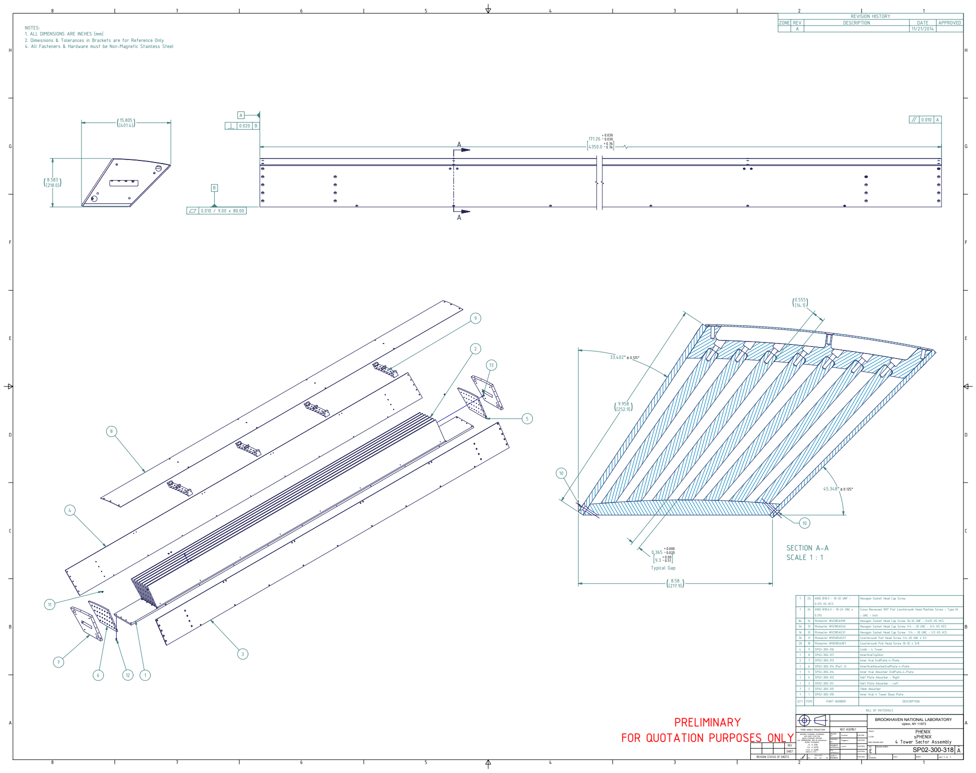

FIG. 5. Mechanic drawing of an inner HCal sector.

backplane board (two of each per sector, 64 of each total) to handle the voltage distribution to the SiPMs and preamps, monitoring and gain corrections for the SiPMs, and LED drivers for the monitoring and calibration light pulses.

Project execution

The key elements of the execution of this proposal are as follows: testing of the electronics, testing of the scintillating tiles, and assembly and testing of the sectors. Augustana University (AU) will perform all of the electronics testing. Georgia State University (GSU) will perform most of the scintillating tile testing. The University of North Carolina Greensboro (UNCG) assemble and test 20 of the 32 sectors. Rutgers University (RU) will assemble and test the remaining twelve sectors and will also test the scintillating tiles for same. The testing of the electronics will be supervised by co-PI Grau and performed by undergraduates. The testing of the scintillating tiles will be supervised by PI Connors and secondarily by co-PI Salur. The assembly and testing of sectors will be supervised by co-PI Belmont and secondarily by co-PI Salur.

The testing of the electronics requires modest laboratory space, which has already been provided by AU, and the purchase of testing equipment, which is included in the budget. The tested electronics will be shipped to UNCG and RU for assembly into the sectors. The testing of the scintillating tiles requires modest laboratory space and an SiPM readout unit; GSU already has the needed space and the SiPM readout unit, RU has the needed space and the SiPM readout unit is included in the budget. Tiles tested by GSU will be shipped to UNCG; tiles tested by RU be assembled into sectors there. The assembly and testing of sectors requires approximately 600 square feet of laboratory space and a replica of the sPHENIX electronics rack (including power supplies, digitizer boards, etc). UNCG and RU will provide the needed laboratory space, and the electronics racks will be loaned by BNL.

d. Broader Impacts

A large amount of the work to test and assemble the detector will be performed by undergraduates. The American Physical Society, American Institute of Physics, and the American Association of Physics Teachers have all endorsed substantive research opportunities as an integral part of the undergraduate physics education experience. Research allows students to learn and gain additional practice in technical skills, analytical skills, and communication skills. These skills benefit those students entering graduate school in physics and are skills 21st-century employers are expecting of college graduates. Since about 85% of physics undergraduates do not pursue post-secondary education[19], research experiences allow those students to learn or practice skills that make them readily employable after graduation. The research proposed here will involve several undergraduates who pursue degrees in physics and pre-engineering and will teach and reinforce those skills.

The four participating institutions are from diverse parts of the country and attract diverse students. AU is classified as a primarily undergraduate institution (PUI). Both GSU and Rutgers are state institutions that service a diverse student population. At GSU more than 65% of its students identify as a racial minority group and 59% are female. Minority students comprise 32% of the total student body at Rutgers. UNCG is a Title IV minority serving institution (MSI). The student body overall is about 66% women and 40% people of color. UNCG awards bachelor's degrees in physics only.

The PI and co-PI's all have experience mentoring undergraduate and graduate student work, especially with women and minorities. Connors, an early career scientist, is the advisor for Women in Physics student organization. The majority of the previous undergraduate advisees of Salur were women or from underrepresented groups. Just less than half the students mentored by Grau at Augustana have been women.

Specifically, particular women and minority students already at the participating institutions will likely be involved in the work proposed. Examples include graduate student Anthony Hodges and undergraduate Krista Eastman who designed the test stand and testing criteria for the HCal tiles at GSU. Early career Rutgers graduate students Ms. Shraddha Dogra and Ms. Wan Lin will participate in this project and this training will prepare them effectively to become prominent global scientists. Ms. Shannon Dancler has worked with Grau on setting up the SiPM test station at Augustana and the work proposed here would be in time for a senior thesis project.

Beyond the individual mentoring of undergraduate students, there are some specific activities that will be provided to undergraduates. The construction and testing of sectors will be taught as an undergraduate course at UNCG. While most of the course enrollees will be physics majors, there will be no prerequisites so anyone will be able to take the class. The students will learn a variety of highly valuable skills working on a cutting-edge detector using sophisticated testing equipment.

The Physics & Astronomy Department at UNCG has considerable experience with outreach. The department is the primary administrator and operator of the Three College

Observatory (TCO), which hosts a 0.8 m telescope. Though the TCO is a high-quality research facility, it is also used extensively for community outreach, including a variety of events for the general public. These include public nights that are open to all as well as organized visits for schools, scout troops, etc. Following this model, UNCG will host public visits the inner HCal facility. These visits will include a tour of the facility, an explanation of the assembly and testing equipment, and a short explanation on how we study the early universe using collisions of heavy nuclei.

e. Management Plan

The inner HCal will be integrated into the sPHENIX experiment which will be located at building 1008 along the RHIC ring. This building previously housed and supported the operation of the PHENIX experiment which collected data at RHIC from 2000 to 2016. The removal and refurbishing process has been underway since 2016 in preparation for sPHENIX. sPHENIX is an approved DOE project (CD-1). Once incorporated into the sPHENIX experiment, BNL will assume responsibility for maintenance and operation of the inner HCal. The inner HCal was designed as part of the original sPHENIX proposal. A prototype of the current inner HCal design was tested during the beam test of the sPHENIX calorimeter system. The detector performance was consistent with expectations from GEANT4 simulations.

The sPHENIX collaboration currently includes 244 registered members from 73 different institutions. David Morrison (BNL) and Gunther Roland (MIT) serve as co-spokespersons for the collaboration. Edward O'Brien (BNL) is the project manager and coordinates with the managers of the individual subsystems. John Lajoie (Iowa State) is the manager of the Hadronic calorimeter and Eric Mannel (BNL) is the manager for the calorimeter electronics. For the outer HCal Megan Connors (GSU) oversees the testing of the scintillator tiles, Christopher Poniteri (BNL) oversees the assembly of steel and Stefan Bathe (Baruch) oversees the final testing and assembly of the completed sectors. The calorimeter electronics will be tested at universities including AU. Nathan Grau will oversee the electronic testing planned at AU for the sPHENIX. For the inner HCal, we will utilize the expertise and infrastructure developed for the existing sPHENIX calorimeter system while providing additional opportunities to students away from BNL to gain experience with hardware for these large scale nuclear physics experiments. Nathan Grau (AU) will oversee the purchasing and testing of the electronics for the inner HCal. As part of a negotiated reduced cost with the vendor, BNL will purchase the SiPMs for the inner HCal. We will have two assembly sites for the inner HCal, Rutgers University and UNC-Greensboro. Megan Connors and Murad Sarsour will oversee the tile testing at GSU for 20 sectors and ship tiles to UNC for assembly. Ron Belmont who has analyzed prototype data and performed scans of the tiles while working at University of Colorado will oversee the assembly at UNCG. Rutgers has facilities to perform both tile testing and assembly and will produce the remaining 12 sectors of the inner HCal. Sevil Salur who has also been active in prototype testing will oversee these activities at Rutgers together with Ron Gilman who has substantial experience in building detectors with scintillators including the ones for the MUon proton Scattering Experiment (MUSE), which is commissioned at the Paul Scherrer Institute in Switzerland. The aluminum frames of the inner HCal are part of the existing sPHENIX design to support the EMCal. The frames will be shipped to the proposed assembly sites. Once assembly and

Year	Institution	Milestone
1	AU	Purchase electronics
1	AU	Assemble electronics
1	AU	Begin electronics testing
1	GSU	Purchase tiles and SiPMs
1	GSU	Begin tile testing
1	Rutgers	Purchase tiles and testing/assembly equipment
1	UNCG	Purchase Assembly equipment
2	GSU	Complete tile testing
2	AU	Complete electronics testing
2	UNCG	Complete and ship 20 assembled sectors
2	Rutgers	Complete and ship 12 assembled sectors
2		Sectors installed in sPHENIX

TABLE I. Timeline of Milestones. Year 1 refers to Oct 2019-Sept 2020 and Year 2 refers to Oct 2020-Sept 2021

testing is completed at Rutgers and UNCG, the sectors will be shipped to BNL for assembly into sPHENIX. To maintain the current sPHENIX construction schedule, installation of the inner HCal sectors starts in February 2021.

Risks for this project are minimized since we are building from established procedures set by the sPHENIX experiment for the outer HCal. In particular AU and GSU are already prepared to test the electronics and scintillator tiles respectively. The tile testing procedure will be established at Rutgers by sending an experienced GSU member of the project to train students at Rutgers. Likewise the testing procedure for assembled sectors has been established at BNL for the outer HCal and that knowledge will be transferred to the inner HCal assembly sites. The collaboration has biweekly HCal and calorimeter electronics meetings as well as general and project manager meetings where the status and any issues are discussed.

The sPHENIX experiment is scheduled to begin data collection in January 2023. The sPHENIX collaboration has prepared a five year running strategy which includes Au+Au, p+p and p+Au collisions at 200 GeV. The exact number of years is dependent on funding and potential EIC development but it is expected to collect data for at least three years. Each year consists of roughly 22 weeks of data collection useful for physics analyses. In addition, time is allocated each year for tuning the beams and calibrating the detectors. An extended commissioning time is also included in the first year's run plan which will allow all detector systems to fine tune critical parameters and calibrations for data collection.

All members of the sPHENIX collaboration, which continues to grow each year, will have access to the data collected by the inner HCal. It will be integrated into the reconstructed data files used for analyses. In particular the energy measured in the inner HCal will be used in reconstructing the jet energy and will allow for measurements to extend to higher momentum. The results will be published in refereed journals such as PRL and PRC.

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