Abstract
Through a combination of experimental, theoretical, and engineering expertise from LANL's P, T, AOT, and CCS Divisions, we have successfully carried out a joint R&D to develop a new major scientific program for the next generation DOE flagship heavy ion physics experiment, the sPHENIX at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL). The sPHENIX 3rd science pillar of the new open heavy quark physics program is enabled through the state of the art Monolithic-Active-Pixel-Sensor based Vertex Detector (MVTX) upgrade. We have built up a new MVTX detector upgrade collaboration of 22 institutions from US and aboard to develop a new open heavy quark physics program for the sPHENIX experiment at RHIC. The final full proposal was submitted to BNL and DOE in 2018, and approved and funded by DOE through BNL in 2019. LANL is leading the MVTX upgrade effort. We carried out key R&D for the MVTX detector high-speed readout system and mechanical system integration, and designed a new cutting-edge, low mass, high efficiency pixel-based inner tracking detector and developed new b-jet identification algorithms to improve the significance of the proposed measurements in sPHENIX. Two prototype telescopes were built to demonstrate the new detector's key performances with test beams at the Fermilab in 2018 and 2019; On the theory side, we developed new theoretical framework needed to produce the first comprehensive set of predictions for sPHENIX b-jet measurements with MVTX upgrade, resulted in many publications in leading journals.

The success of this LDRD project has helped us to establish LANL's leadership role in the next generation DOE flagship heavy ion program in the US, and secured a new long-term DOE Office of Science Nuclear Physics support to LANL, as well as bring in new technical capabilities and talents for both experimental and theoretical programs.

Background and Research Objectives
A few microseconds after the Big Bang, while still at a temperature of several trillion degrees, the entire universe was permeated with quark-gluon plasma (QGP). Measurements at RHIC, where LANL plays a major role, and the Large Hadron Collider (LHC) at CERN have verified the existence of the QGP. However, none of the current experiments have revealed its microscopic structure, thus motivating a new experiment named sPHENIX, the next generation heavy ion physics program in the US, designed to collect a suite of unique jet and heavy quark observables with high statistics. sPHENIX experiment is an international collaboration of 77 institutions from the world, the detectors are under construction right now at BNL, and will be ready for physics run in early 2023, and will continue taking data for many years to come.

When the fundamental constituents of matter, quarks and gluons, traverse the QGP they scatter and lose a large amount of energy before escaping, a phenomenon that is extremely useful for probing properties of the QGP. The interactions of those particles with the plasma can be used to directly infer its microscopic quasiparticle structure. The final state observable is a jet, the collimated spray of particles created by fragmentation of the scattered high-energy quark or gluon. Bottom quarks, which are ~1,000 times heavier than the light quarks, produce unique energy loss signatures due to their large mass (4.2 GeV/c^2).

To identify b-jets, sPHENIX requires a precision inner tracking detector placed close to the beam line. This inner tracker has to provide very high position resolution and efficiency, while operating in a daunting high-occupancy, high-radiation environment. Only the most advanced pixel detector technology is up to this task, see Figure 1. At the beginning of this project, we set the following goals:

1) The primary experimental goal of this LDRD/DR project is to design, develop and validate a pixel-based inner tracker for sPHENIX, and also develop a full physics and detector upgrade proposal. We will select the best available semiconductor-based pixel technology, build a small prototype detector, and determine its performance using the test beam at Fermilab. This data, combined with GEANT-based detector and physics simulations, will ensure that sPHENIX is capable of optimal b-jet identification.
2) The primary theoretical objective is to develop the most accurate and comprehensive description of b-jet observables in heavy ion collisions and thereby pave the way for using b-jets as precision diagnostics of the QGP. Theoretical developments in several key areas of nuclear physics, high energy physics, and plasma physics are needed for a first-principles understanding of b-jet interactions with the QGP. We will pioneer applications of Soft Collinear Effective Theory to b-jet physics and use Molecular Dynamics (MD) simulations to determine the stopping power of strongly-coupled plasmas. This unique synergy between several branches of physics will result in a breakthrough in our understanding of heavy quark jet production and propagation in the QGP and allow the experiments to fully use the tomographic potential of b-jets as precision probes of this phase of matter.

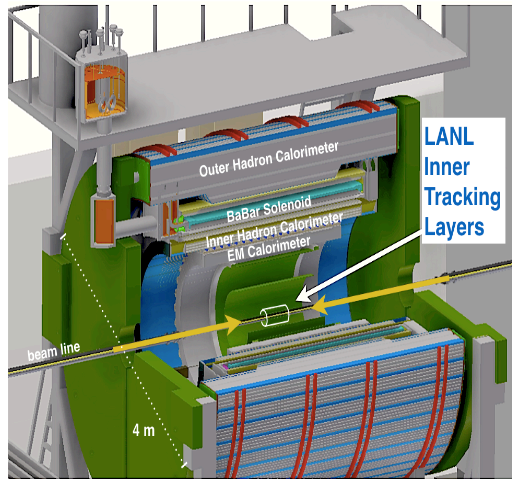

Figure 1. LANL proposed precision tracking detector for the sPHENIX experiment, capable of doing b-jet measurements at high multiplicity and high collision rate environment at RHIC. It is now known as the sPHENIX MVTX detector.

Scientific Approach and Results
Here we summarize major achievements from this LDRD.

Experimental highlights

At the beginning of this LDRD project, we carried out extensive physics and detector simulations to specify the minimal requirements of the tracking sensors for b-jet tagging in the sPHENIX detector configuration, including the detector sensor spatial resolution, response speed, efficiency, radiation hardness etc., and surveyed the current silicon sensor detector technologies being used or explored in the latest high energy nuclear and particle experiments in the world. Soon, we identified an ideal candidate for the sPHENIX upgrade – the state of the art Monolithic-Active-Pixel-Sensor (MAPS), called ALPIDE, just developed in time for the ALICE experiment Inner-Tracking-System upgrade (ITS) for Run-II at LHC. We quickly established a detector R&D collaboration with the ALICE ITS upgrade group to carry out key R&D for the sPHENIX MVTX upgrade proposal development. In the meantime, we also convinced other leading institutes to join our effort, including MIT and LBNL, and started building up a new collaboration for the MVTX detector upgrade to enable a new heavy quark physics program for the sPHENIX experiment. In less than a year, we established a collaboration of 22 institutes from US and abroad to work on the MVTX upgrade effort, form physics simulations to detector R&D.

Through this LDRD project, we have successfully carried out key R&D to demonstrate the feasibility to perform the proposed heavy quark physics measurements with the MVTX detector at RHIC. Also, we have organized many detector and physics workshops to further strengthen the MVTX proposal. A MVTX upgrade preproposal was first developed and submitted to BNL and DOE for initial discussion in 2017, followed by a full proposal in early 2018 [1,2]. After many (10+) technical and cost & schedule reviews conducted by BNL Director and DOE NP Office, the MVTX proposal was approved and funded by DOE through BNL in early 2019, with LANL as the leading institute.

Figure 2 shows the simulated single hadron DCA resolution (LH) based on the APLIDE sensors and the projected physics sensitivity of b-jet R_{AA} in sPHENIX (RH). The expected MVTX tracking performance was demonstrated with two prototype telescopes using test beams at Fermilab in 2018 and 2019.

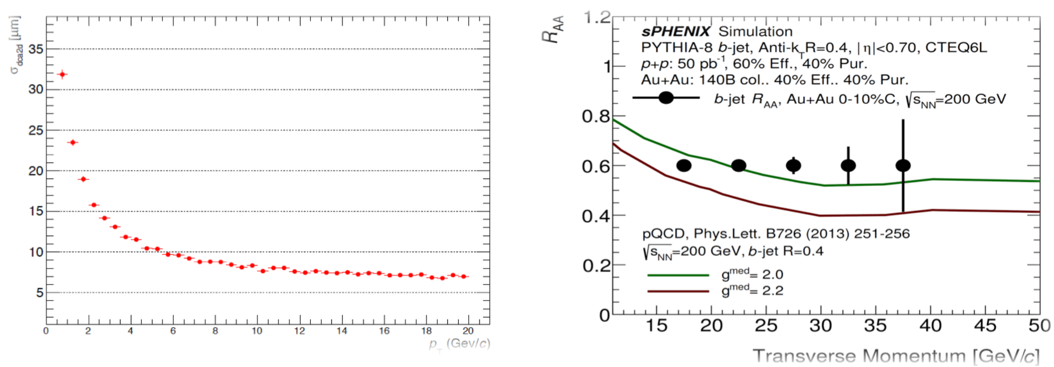

Figure 2. LH: Single hadron DCA resolution vs transverse momentum pT from MVTX simulation; RH: projected b-jet nuclear modification factor R_{AA} using the MVTX detector in sPHENIX, theory curves are from this LDRD work. These plots are used in the MVTX full proposal to BNL and DOE.

MVTX readout system integration

After the sensor technology selection, the next major task was to integrate the sensors into the sPHENIX readout Data Acquisition System (DAQ). In 2017, ALICE experiment was still in the early stage of developing readout electronics for the ALPIDE sensors. After taking into account of pros and cons of various readout options, including developing our own readout electronics as a Plan-B, we decided to use the (early prototype) ALICE front-end Readout Unit (RU) for sPHENIX MVTX front-end readout interface board, and use the generic high performance Front-End Link eXchange (FELIX) system designed for the ATLAS experiment Run-II upgrade as the interface between the RU and the sPHENIX DAQ, detector control and TCC (Timing, Trigger and Control) systems, see Figure 3.

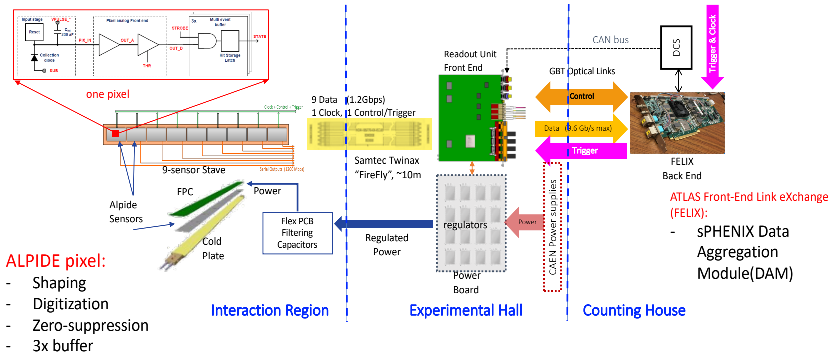

Figure 3. Proposed sPHENIX MVTX readout and control systems. The full electrical chain has been demonstrated successfully through R&D at LANL.

After more than a year's R&D effort, successfully developed custom firmware and software to integrate ALPIDE sensors, RU and FELIX into the sPHENIX DAQ, and demonstrated the sensor's key performances through two MVX prototype telescopes, using test beams at the Fermilab in 2018 and 2019.

<u>MVTX prototype telescope development and Fermilab test beam results</u>

To verify that the MVTX detector will perform as expected within the RHIC environment, it is necessary to expose the equipment to beam conditions similar to those produced at RHIC. This was be achieved by using the Fermilab Test Beam Facility (FBTF) at Fermi National Accelerator Laboratory (FNAL or Fermilab). The FBTF is capable of producing 4s long packets of high-enrgy single particles. The user can specify the rate of particles and their composition. The rate can approach 300 kHz which is significantly higher than the sPHENIX DAQ trigger rate of 15 kHz while the user can choose between different particle species. The LANL group used both 200 GeV protons ($\gamma \sim 200$) and 5 GeV electrons ($\gamma \sim 10{,}000$).

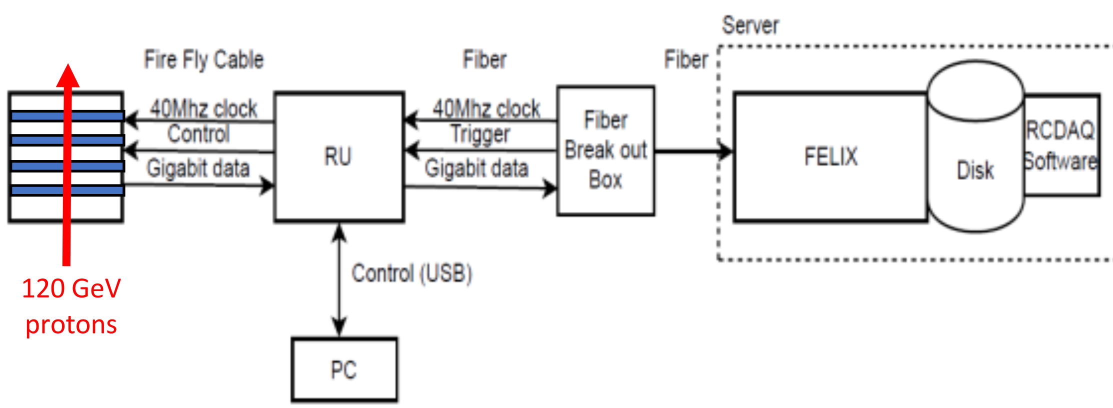

Figure 4. The test setups used at the FBTF in 2018 and 2019. A 4-MAPS sensor telescope(2018) and 4-production-stave telescope (2019) were used at Fermilab to study the performance of the ALPIDE sensors and the readout electronics chain in the sPHENIX DAQ.

Two MVTX telescope setups constructed at LANL were taken to Fermilab for testing; one setup consisting of four single ALPIDE chips in 2018 and another setup consisting of four full 9-chip staves in 2019. The sensors were used with progressively more advanced readout electronics, with the latter test beam using a system that was electrical identical to the final system, although minor layout changes are to be made for the final detector.

The data were extracted from the sensors via high speed links produced by SamTec where they were combined and packaged within Readout Units (RU). The first test beam used RU v1.0 while the second test beam used RU v1.1 which is electrically identical to the final RU. The data was then converted from electrical to optical signals using a VTRx and transmitted to the FELIX unit using the GBT protocol. The optical transmission was handled over a significant length designed to emulate the distance between the experimental hall and the counting house within sPHENIX. The 2018 test beam used FELIX v1.5 (designed for ATLAS at LHC) while the 2019 test beam used FELIX v2.0 (designed for sPHENIX) which is the production version. The data was packaged into runs using the RCDAQ system that will be used in sPHENIX. The trigger signals from the FBTF were sent to the FELIX unit using a GTM which also produced the clock signals. The GTMs used are equivalent to the production versions that will be used in the final experiment. Finally, power was supplied to the staves using a pre-production version of the Power Unit which is electrically identical to the production version. The layout of the test setups can be seen in Figure 4.

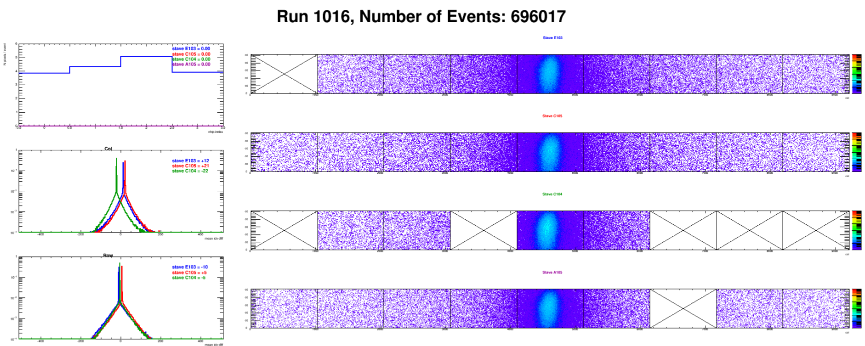

Figure 5. A typical event monitor from the test beam.

Figure 5 shows a typical event monitor from the test beam. The top left plot is the number of hits per event. The middle left plot is the difference in hit column between the first stave and the subsequent staves. The bottom left plot is the difference in hit row between the first stave and the subsequent staves. The right plots show the cumulative hit positions in the four staves. The chips are separated by black lines and chips that were excluded from the test beam are represented by crosses.

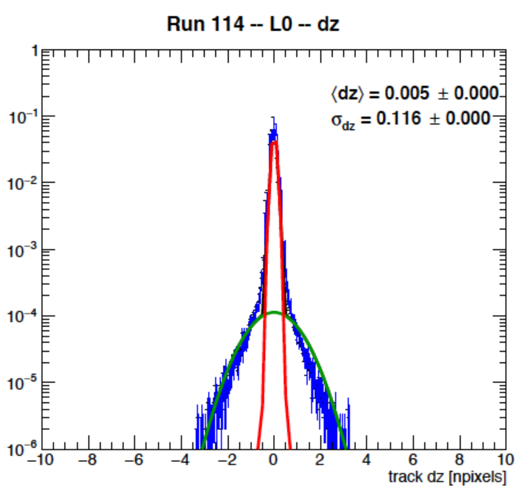

Figure 6. A fit to the cumulative track positions in the ALPIDE chip. The Gaussian resolution is quoted in units of pixels.

The purpose of the initial test beam in 2018 was to characterize the performance of the ALPIDE chips. As previously described, the currents and voltages of the digital and analogue electronics can be altered by the user however, the optimal settings for sPHENIX were not known a priori. Studies from the test beam show that the chip is capable of a hit resolution of approximately 6 µm which is far below the upper resolution limit of 50 µm, see Figure 6.

The tests in 2019 with the staves were used to further characterize the ALPIDE settings, study the material budget of the staves and create data samples that can be used to optimize the tracking algorithms that will be used for the MVTX.

The analogue electronics of the ALPIDE have a pulse shaping time on the order of a few microseconds (the exact value is configurable). While the pulse is above threshold, the chip is capable of producing a digital signal. This digital signal creates a logical AND with a strobe pulse which produced at every input of a trigger signal (which is produced by the GTM). Thus, if the AND condition is true then the data from that pixel is read out of the system. This requires the analogue signal to be above threshold for enough time for the trigger signal to propagate through the readout system, which for sPHENIX is approximately 5 μs.

To determine the maximum trigger latency for sPHENIX under various operation conditions, we altered the threshold and bias currents of the sensor then introduced a delay to the trigger signal. By measuring the number of pixels fired per-event as a function of trigger delay, the maximum trigger delay can be determined for various pixels settings while keeping a minimal hit efficiency of 90%. The results of the test were able to yield a configuration of the pixel that meets the requirements of the sPHENIX trigger latency, see Figure 7.

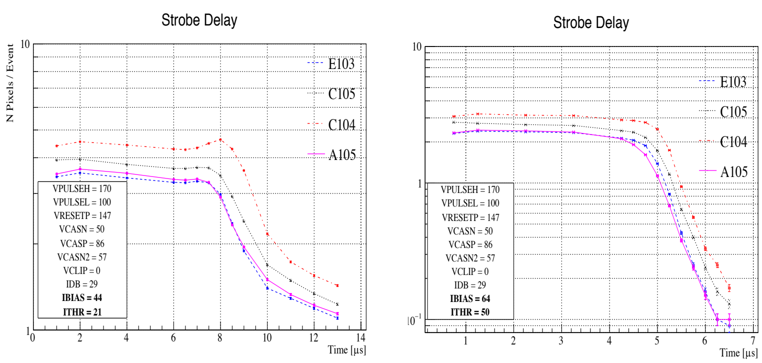

Figure 7. The number of pixels hit per event as a function of trigger delay. The configuration parameters used can be seen in each plot. LH: settings for very large trigger latency up to 8uS; RH: Default setting allows maximum trigger latency of 4.5uS, the optimal operation point is at 2uS.

The test was extended to allow for the single pixel efficiencies to be calculated rather than the global chip efficiency. This was achieved by introducing the trigger delay in a single readout unit rather than at the GTM. This way, the trigger is able to reach three of the staves while being delayed in the fourth stave, allowing three of the staves to be used as a telescope to precisely pinpoint the pixel that should be hit in the fourth stave. This can only be achieved due to the excellent hit resolution of 6 μm compared to the much larger pixel size. This can be used to remove any biases in the configuration determination introduced by noisy or broken pixels in the rest of the chip.

The FBTF provides single particles in 4s bunches per minute with a variable rate. Each single particle is capable of producing a trigger signal, thus, by increasing the number of particles it is possible to study the effect of trigger rate on the data flow. Beyond a certain rate, the readout FIFOs will fill faster than the information can leave thereby creating a bottleneck effect and incurring data loss. The maximum trigger rate for sPHENIX is 15 kHz while the FBTF is capable of producing a rate of up to 300 kHz. The particle rate was increased steadily, with no loss of data up to 100 kHz. At 100 kHz, the data loss was 10^{-4} % while at the maximum particle rate, the loss was measured to be 0.1%. The loss rate was not affected by decreasing the trigger delay from 2 μs to 100 ns.

Electrical signal quality is known to degrade over distances due to several effects such as cross-talk and differential impedance. The length travelled by the electrical signals from the stave to the RU where the optical conversion takes place is significant in sPHENIX, at least 10m. To study whether the signal would degrade to a point that the information becomes unreadable, a set of custom long cables were used with an overall length of 11.4m. There was no noticeable degradation in the data quality using these long cables.

A major advantage of MAPS technology is the thinness of the chip compared to a conventional chip+sensor detector, with the thickness of the ALPIDE being only 50 µm, only about 12% of the total material budget, including cooling and support carbon structure. The average effective thickness of the full stave is only about 0.3% radiation length, far less than a typical silicon detector of 1%. To investigate the how the materials affect the resolution of the tracking, a 5 GeV electron beam was used to increase the multiple scattering of particles as they traverse the telescope sensors. The difference in hit position between consecutive staves was found to increase in accordance with multiple-scattering law as the beam was changed from high-energy 120GeV protons to low-energy 5GeV electrons as can been seen in Figure 8. The data collected from this run will be used to calculate the true material budget of the detector and will improve the simulations of sPHENIX detectors.

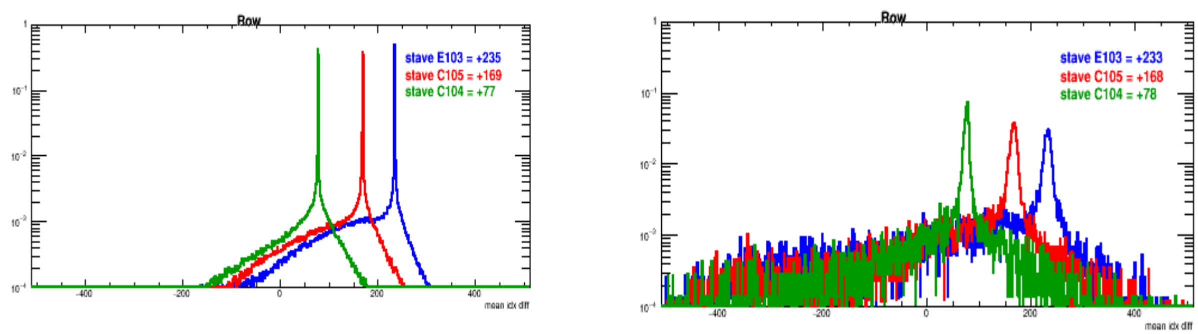

Figure 8. The difference in hit position between the first stave and subsequent staves for tracks at η = 1 for 120 GeV protons (LH) and 5 GeV electrons (RH)

The single particles provided by the FBTF are useful to characterize components however, they do not exactly emulate the harsh environment experienced in a high energy collision where several particles can be produced in each collision. This results in several hits across the detector and can provide more of a challenge to readout electronics. To more accurately produce a high energy environment, an 8-inch lead block was placed 10 feet upstream of the telescope. When protons strike this lead block, they can produce numerous tracks at various angles and varying species, see Figure 9. The telescope showed no bottleneck effect and inspection of the data revealed several tracks traversing single chips showing that the MVTX should encounter little difficulty with the challenging environment at RHIC. This data is currently being analyzed by the sPHENIX

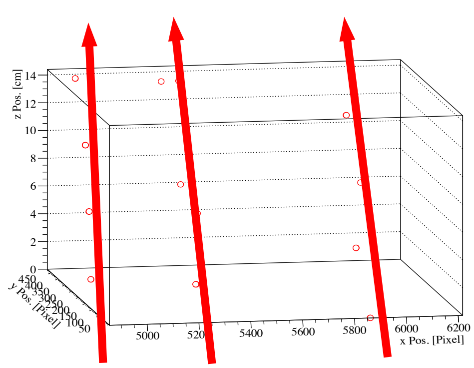

Figure 9. Tracks produced from a proton-lead collision. The x-y plane covers the area of a single chip.

collaboration to improve the track reconstruction algorithms for the final detector.

Detailed offline analysis of the data revealed that the mean cluster of an event for perpendicular tracks was 2.4 pixels with a standard deviation of 1.7 pixels. This is in line with the expectation of a pixel detector with typical cluster sizes of ~3 pixels. As the angle of the tracks was increased to a pseudorapidity of 1, the mean cluster size increased to 3.0 pixels with a standard deviation of 1.9 pixels which is to be expected due the increase of the hypotenuse of the track with respect to the chip, see Figure 10.

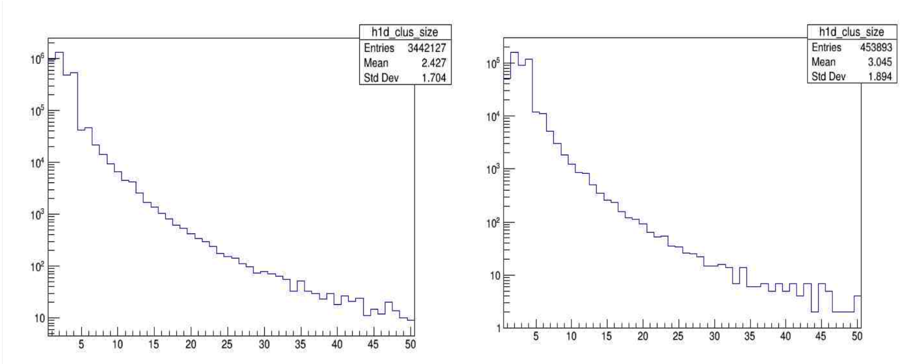

Figure 10. The distribution of cluster sizes per-event using the four-stave telescope for perpendicular tracks (left) and tracks with eta = 1 (right).

Overall the test beams using the two MVTX protypes were highly successful with a large data set that is currently being used by the collaboration to improve and tune parameters to enable day one physics. The sensor pixel operating parameters have been tuned to enable the detector to collect data in a RHIC scenario with no bottleneck effects occurring with the operating region of the MVTX.

<u>MVTX Detector Mechanics design R&D</u>

We have successfully designed a preliminary mechanical support to integrate the ALPIDE staves into the sPHENIX environment, see Fig. 11. The CAD model for this design has taken into account mechanical constraints that have been added from other elements of the sPHENIX tracking system. The current CAD model also includes a detailed design for the “service barrel” that acts as an extension to the MVTX detector, bringing out all the services to a single patch panel that will be located just outside of the sPHENIX HCAL detector. The design for the service barrel allows the installation fixtures to be incorporated in the current overall sPHENIX detector design. Laboratory demonstrations in the Fermilab test beam have confirmed that having 40.0 cm power extension “pig-tails” at the ends of the staves work fine and have been integrated into the current overall CAD model. Confirmation of having a signal cable run of at least 11 meters was also demonstrated at the Fermilab test beam in 2019. Interconnection for the signal cables have been finalized and also incorporated in the current CAD model.

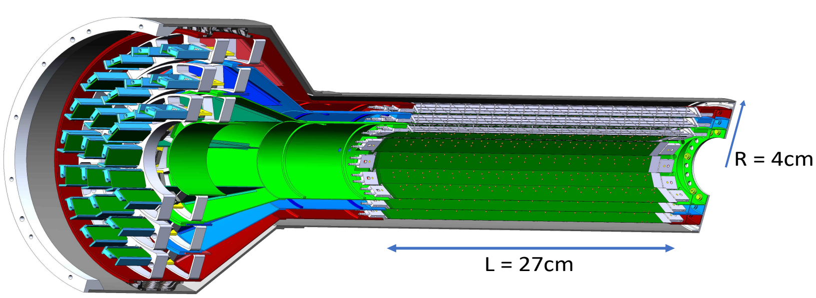

Figure 11. CAD design of the MVTX detector for sPHENIX, showing 3-layer of 27cm long MAPS sensor staves, radius R = 2.5 – 4.0cm.

The status of the current MVTX mechanical design is now at a state where request for quotations on various components is being explored based on detail drawings.

Theoretical achievements highlights

In developing jet theory in heavy ion collisions, we have taken a comprehensive approach building upon expertise from proton-proton collisions and light quark jets. We started by introducing a new kind of jet function: the semi-inclusive jet function which describes how a parton (quark or gluon) is transformed into a jet with a jet radius [3]. Within the framework of Soft Collinear Effective Theory (SCET) we calculated those jet functions to high accuracy (next-to-leading order or NLO) for popular jet reconstruction algorithms. We derived the renormalization group (RG) equations that govern the energy dependence of jet production and can be used to perform the ln R resummation for inclusive jet cross sections with a small jet radius R. It is quite interesting that the applications of the new semi-inclusive jet functions to inclusive jet production of jets is very similar from $e^{+}+e^{-}$ to p+p collisions. We demonstrated that single inclusive jet production in these collisions shares the same short-distance hard functions as single inclusive hadron production, the only difference being the substitution of the fragmentation function *D* with the semi-inclusive jet function *J.* Application of the new theoretical formalism noticeably improved the description of the jet cross sections at the LHC. As a next step, we extended the new theory to describe the production of hadrons inside reconstructed jets [4]. This observable, called jet fragmentation function, is part of a new class of observables, known as jet substructure observables, that have recently been proposed to test the dynamics of the strong force. Our framework allows the jet fragmentation function can then be expressed as a semi-inclusive observable, in the spirit of actual experimental measurements, rather than as an exclusive one. We demonstrate the consistency of the effective field theory treatment and standard perturbative quantum chromodynamics (QCD) calculations of this observable at next-to-leading order. Numerical results for p+p → (jet h)+X in the new framework, and find excellent agreement with existing LHC experimental data.

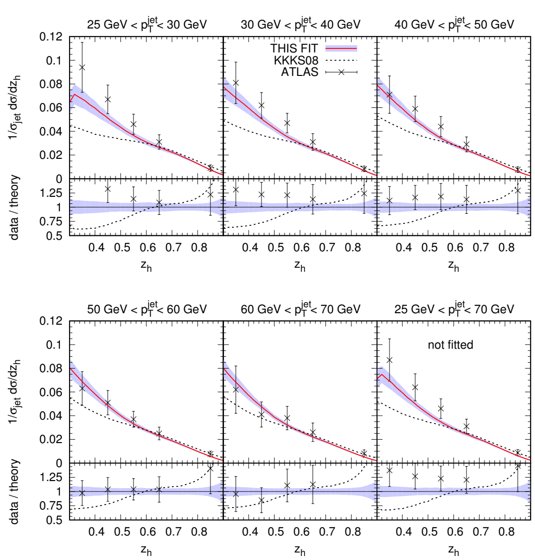

Figure 12. Data on in-jet-fragmentation into D mesons measured at C.M. energy of 7 TeV as a function of the momentum fraction zh in five bins of pT. In each panel, NLO results obtained with our best fit (solid lines) and early extraction (dashed lines) FFs are*

Despite the excellent description of light hadron production, tensions with the description of heavy mesons, such as the *D* and the *B,* were discovered. The inability to describe heavy flavor production inside jets was common to high energy event generators like PYTHIA and the perturbative approach. This necessitated using hadron-in-jet data in a global analysis of heavy flavor fragmentation. Whenever an observable involves detected hadrons in the final state, the theoretical calculation requires non-perturbative parton-to-hadron fragmentation functions (FFs). Our novel global QCD analysis of charged *D**-meson fragmentation functions at next-to-leading order accuracy [5] was achieved by making use of the available data for single-inclusive *D**-meson production in electron-positron annihilation, hadron-hadron collisions, and, for the first time, in-jet fragmentation in proton-proton scattering. The presented technical framework is generic and can be straightforwardly applied to future analyses of fragmentation functions for other hadron species, as soon as more in-jet fragmentation data become available. The obtained optimum set of parton-to-D^* fragmentation functions is accompanied by Hessian uncertainty sets which allow one to propagate hadronization uncertainties to other processes of interest. Our results are exemplified in Figure 12, together with the main result – gluon contribution to heavy flavor production is significant.

Having made improvements in the non-perturbative fragmentation functions, we turned to the essential component of the calculation – the propagation of partons inside the quark-gluon plasma (QGP). Our goal was to go beyond the traditional energy loss phenomenology and bridge the gap between high energy and nuclear physics. To do that, we developed a version of Soft Collinear Effective Theory (SCET) which includes finite quark masses, as well as Glauber gluons that describe the interaction of collinear partons with the QGP [6]. In the framework of this new effective field theory, labeled $\mathrm{SCET}_{\mathrm{M,G}}$, we derived the massive splitting functions in the vacuum and the QCD medium for all relevant binary branching parton processes. The numerical effects due to finite quark masses are sizable. In addition, we presented a new framework for including the medium-induced full splitting functions consistent with next-to-leading order calculations in QCD for inclusive hadron production. Our numerical results for the suppression of D and B-mesons in heavy ion collisions are a clear improvement over earlier descriptions. An example of comparison between theory and experiment is shown in Figure 13.

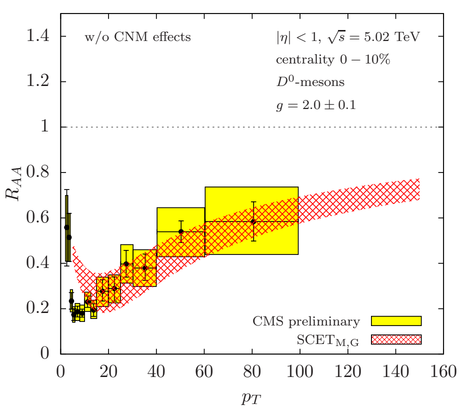

Figure 13. Nuclear modification factor denoted R_{AA} for D0 mesons in comparison to preliminary the CMS data of CMS. We have C.M. energy 5.02 TeV, and 0-10% centrality.

Even though our work led to significant improvement in the description of heavy flavor mesons we went a step further and extended the heavy quark radiation theory. Our formalism relied on the universal features that the branching processes of partons exhibit when they are expressed as solutions to iterative equations that build correlations between multiple scattering centers in the QGP [7,8]. The differences between the various splitting channels are conveniently captured by the light-front wavefunctions and coefficients that depend on the quantum numbers of the partons that interact with the medium. We showed second order in opacity corrections explicitly. Our general approach allows to obtain even higher order in the opacity of nuclear matter if desired.

<u>*Theory of jet production in heavy ion collisions*</u>

We developed a new formalism to describe the inclusive production of small radius jets in heavy-ion collisions, which is consistent with jet calculations in the simpler proton–proton system. Only at next-to-leading order (NLO) and beyond, the jet radius parameter R and the jet algorithm dependence of the jet cross section can be studied and a meaningful comparison to experimental measurements is possible.

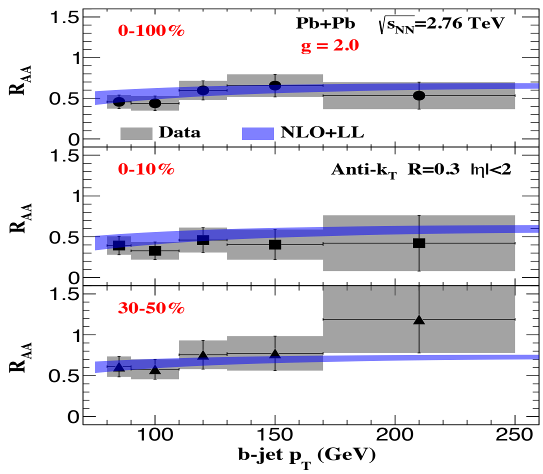

Figure 14. The b-jet cross-section nuclear modification factor R_{AA} for different centrality classes (0-100%, 0-10% and 30-50%), as indicated in the legend. All theoretical predictions are present as the blue bands and are compared to the data from CMS measurements.

We were able to consistently achieve NLO accuracy by making use of the recently developed semi-inclusive jet functions within Soft Collinear Effective Theory [9]. Our initial work only covered light jets, but we extended the theoretical formalism to heavy jet production in [10]. Our approach relies on hard-collinear factorization, where the cross section is expressed as the convolution of the PDFs, the hard kernel, and jet functions. This is the first calculation of heavy flavor jets in heavy ion collisions using the heavy flavor semi-inclusive jet functions technique. We compared the theoretical cross section results for inclusive c-jet and b-jet production to the experimental data from p+p and Pb+Pb collisions and found very good agreement between data from the Large Hadron Collider and theory, see Figure 14. For the more complex heavy ion collisions, we did include the CNM effects and, for the first time, collisional energy losses in the jet fragmentation function formalism. These were shown to play an important role in the overall suppression of the heavy flavor jet cross sections.

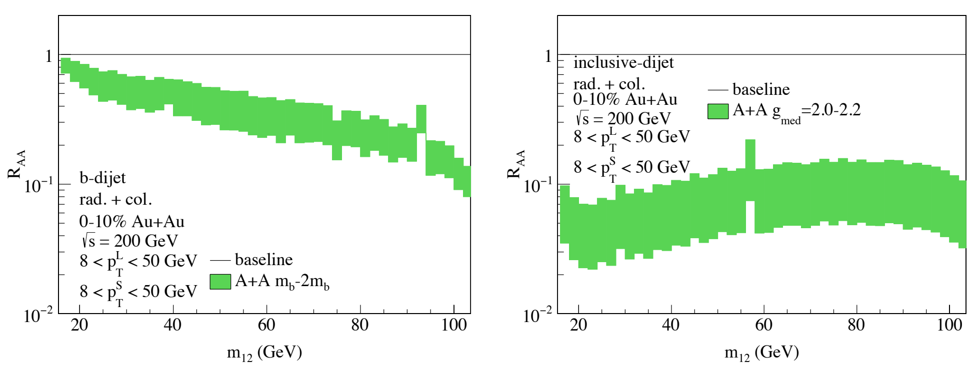

Figure 15. Nuclear modification factor R_{AA} plotted as a function of di-jet invariant mass m_{12} for inclusive (right) and b-tagged (left) dijet production in Au+Au collisions at C.M. energy 200 GeV for sPHENIX.

From inclusive jets we moved on to evaluate light and heavy flavor di-jet production and di-jet mass modification in heavy ion collisions [11]. This project is also the first research project of Jared Reiten – a graduate student that we co-advise. He received the first UC-National Laboratory Graduate Student Reinvestment Fellowship in particle and nuclear physics do co his PhD work on sPHENIX b-jet theory. Back-to-back light and heavy flavor di-jet measurements are promising experimental channels to accurately study the physics of jet production and propagation in the QGP. They can provide new insights into the path length, color charge, and mass dependence of quark and gluon energy loss in the quark-gluon plasma produced in reactions of ultra-relativistic nuclei. To this end, we proposed the modification of di-jet invariant mass distributions in such reactions as a novel observable that shows enhanced sensitivity to the quark-gluon plasma transport properties and heavy quark mass effects on in-medium parton showers. This observable is particularly powerful at sPHENIX - we found that jet quenching effects on the di-jet mass distribution can be significantly amplified in the kinematic range accessible by the future sPHENIX experiment, because of steeply falling spectra. In the mass region m_{12} = 20 – 100 GeV, the QGP-induced suppression is a factor of 10 or larger for inclusive dijet production. On the other hand, the suppression for b-tagged di-jets shows a different behavior, as shown in Figure 15.

b-jet substructure study
C. Lee and postdoc V. Vaidya set out to develop new strategies and observables to predict and probe the substructure of b-quark initiated jets to high precision and explore strategies to use these results to probe mass effects and distinguish heavy quark and light parton jets. The DR supported the summer visit of P. Shrivastava from Carnegie Mellon who collaborated with us on this project. We explored a class of observables known as energy correlators, which had been shown to have excellent performance in distinguishing light quark and gluon jets, in addition to being predictable to high precision analytically. We showed in Monte Carlo simulations using Pythia that their performance in distinguishing heavy quark from light parton jets was also very good, as long as we applied a procedure known as jet grooming to eliminate wide-angle, soft contamination from the jets. We then developed a new effective field theory (EFT) framework that would be able to predict accurately the properties of groomed heavy quark jets. EFTs for groomed light jets (SCET_+) and top-quark jets (boosted Heavy Quark Effective Theory or bHQET) existed in the literature, but we constructed the first theoretical framework combining these two theories. We demonstrated that the combined SCET_+/bHQET theory was applicable to groomed b jets, used it to factorize and resum two-point energy correlators (e_2^\alpha) for b jets to NLL accuracy in resummed perturbation theory, and matched the resummed predictions to fixed-order QCD to first order in the strong coupling \alpha_s by performing a new numerical computation. These are the first such predictions for groomed heavy quark jet energy correlators. Our work also demonstrated that bHQET could actually be applied to b jets, whereas previously it was believed only to be applicable to top jets. We showed that jet grooming provides a way around this restriction. We demonstrated that these energy correlators could be predicted accurately from first principles in QCD, especially their modification from massless parton to heavy quark-initiated jets. Our work was published in JHEP [13]. Some more work is still required to develop energy correlators as a method to actually tag b jets in collider event samples, namely, computing the effect of B hadron decays on the energy correlator spectrum, and also to compute their modification in a dense medium. Our work lays the groundwork for both of these future directions which tie into our DOE-funded efforts in Nuclear Theory, as well as already providing the baseline prediction for jets in vacuum. C. Lee gave an invited lecture on this topic at the 2019 CFNS Summer School at Stony Brook, and V. Vaidya gave 4 invited talks at several international workshops.

Postdoc V. Vaidya along with fellow T-2 postdoc Y. Makris advanced technologies for improved phenomenology of transverse-momentum distributions of hadrons in jets that are groomed. In JHEP [14], they used the combined theories of SCET_+ and bHQET (which we had developed for the b-jet energy correlators) to make predictions for the spectrum of hadron p_T inside a groomed b jet. These predictions were only to LL accuracy matched to fixed-order predictions at first order in \alpha_s, but already show good agreement with Pythia simulations and demonstrate the predicted independence of the groomed spectrum on the hard scale Q. The scaling of the leading nonperturbative corrections can also be predicted. This work shows the promise of these observables for measuring heavy quark TMD fragmentation functions and heavy quark jet substructure. In a related paper [15], with collaborators at Madrid and Amsterdam, they presented NNLL resummed predictions for hadron transverse momentum distributions of groomed light parton jets. They showed the great reduction in nonperturbative effects as well as non-global logs thanks to grooming, and the relation between the remaining corrections appearing in e^+e^- dijet events and in semi-inclusive deep inelastic scattering (SIDIS). This makes it possible to extract TMDPDFs in SIDIS more accurately while controlling the hadronization effects.

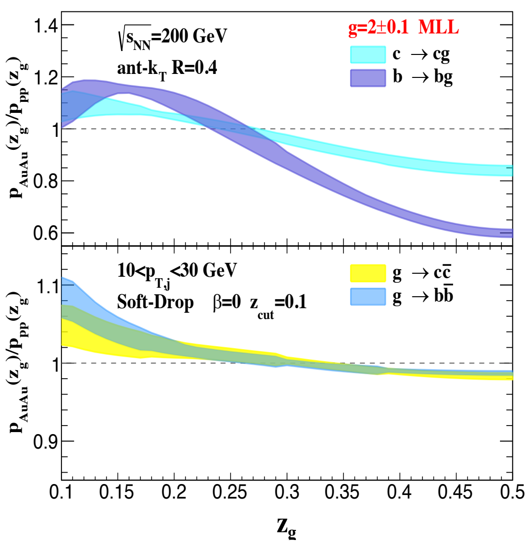

Figure 16. The modifications of the splitting functions for heavy flavor tagged jet in C.M. energy 200 GeV Au+Au collisions. Note the strong quenching effects for prompt b-jets contrasted by the lack of any significant QGP-induced modification for the gluon splitting.

Finally, we carried out the first study of the substructure of heavy flavor jets. This led to the proposal of a new experimental measurement in relativistic heavy ion collisions, based on a two-prong subjet structure inside a reconstructed heavy flavor jet, which can place stringent constraints on the mass dependence of in-medium splitting functions. We identified the region of jet transverse momenta where parton mass effects are leading and predict a unique reversal of the mass hierarchy of jet quenching effects in heavy ion relative to proton collisions. Namely, the momentum sharing distribution of prompt b-tagged jets is more strongly modified in comparison to the one for light jets, as can be seen in Figure 16.

<u>*Numerical implementation of jet and QGP interactions*</u>

Essential building blocks for the numerical calculation of the medium-induced branching process are (1) simulation of the QGP medium, (2) program code for the splitting function calculation on the QGP medium, and (3) theoretical/numerical descriptions for the high-orders in opacity.

<u>*Simulation of the QGP medium*</u>

One of the most up-to-date approach producing the required QGP medium for the heavy-ion collision simulations is the hydrodynamic simulation. After comparing a few available hydrodynamic simulation codes available on the market, we chose the iEBE-VISHNU package, which provides the state-of-the-art hydrodynamics including the viscosity and density fluctuation. On the package, we implemented the equation of state (EOS) calculated by the

HotQCD collaboration and produced the QGP medium needed for the splitting function calculation.

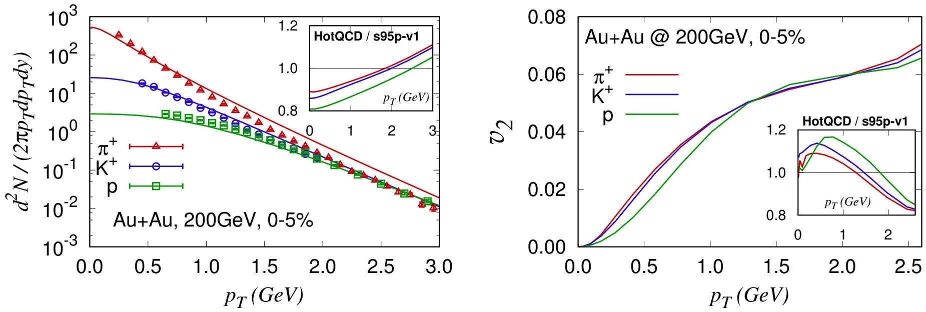

Figure 14. Spectra and v2 flow coefficient calculated from the hydrodynamic simulations with HotQCD EOS. Up to 20% difference is found in those for the old s95p-v1 EOS and the new HotQCD EOS

Code development for the parton splitting function calculation

A program code is developed for the calculation of the splitting functions. The code reads the QGP medium produced from the hydrodynamic simualtion and numerically calculates the parton splitting functions at various values of the kinematic parameters. In the calculation, most of the computational cost is spent for the evalulation of the multi-dimensional integration. After comparing various numerical algorithms and their implementations, we found that the Vegas algorithm implemented in the Cuba library gives the best peformance for our problems. The code is written in C++ and shows almost ideal thread scalcing on a single node with memory shared system. We carried out dedicated code optimization and obtained 400 times faster program code than the initial implementation. The results are applied for the light and heavy flavor di-jet production and dijet mass modification in heavy-ion collision [11].

Parton splitting functions at second order in opacity

In hot or cold nuclear matter, the parton splitting functions are modified by the medium-induced bremsstrahlung processes and radiative parton energy loss. These effects can be calculated order by order in powers of the opacity, the average number of scattering centers, but the effect of multiple scatterings has been ignored in literature because of the complexity of the calculation. Sievert and Vitev developed a formalism for the evaluation of the splitting functions at arbitrary order in opacity [7], and we evaluated their numerical values up to second order in opacity in the QGP medium and found that the second order in opacity corrections can change the energy dependence of the in-medium shower intensity [8].

Our theoretical work is useful in guiding experimental efforts at the Large Hadron Collider and especially the Relativistic Heavy Ion Collider in the near future. It has played a critical role in the DOE approval of the MVTX project.

Anticipated Impact on Mission

Modern high-energy nuclear physics experiments are expensive endeavors that take time to develop, but deliver important physics for decades, as our previous PHENIX has done, and we expect the same for sPHENIX. They bring new, stable, long-term DOE funding to LANL, in line with the national priorities, and add new capabilities and talents to the laboratory.

This LDRD project has extended LANL's position as an international leader in the next generation study of heavy ion collisions into the new kinematic regime opened up by jet measurements. The state-of-the-art P-25/AOT electrical (high speed digital communication) and P-25 mechanical (carbon composite support structure) engineering capabilities developed during the course of this project will benefit a variety of new high-tech mission needs at LANL. An LDRD investment made now will bring in new MVTX detector construction funds (~$6.5M) and DOE support for a strong physics program at LANL for many years to come (~$3M/yr). This DR project is aligned with the Laboratory's mission to enhance the nation's scientific capabilities, as laid out in detail in the recent 2015 DOE NSAC Long Range Plan. The first recommendation of the 2015 plan is to "capitalize on the investments made in nuclear science" [17], which includes the RHIC heavy ion program. This project is a promising portal for LANL into the physics behind the next new major facility for nuclear physics, the EIC, for which the sPHENIX detector will likely be reused.

Conclusion

We have successfully carried out key R&D work and achieved all milestones and transitioned into a new DOE supported long term NP physics program.

Through joint experimental and theoretical effort, we have established the 3rd science pillar, open heavy quark physics program, for the sPHENIX experiment at RHIC. We have developed a theoretical framework and produced the first comprehensive set of predictions for sPHENIX b-jet measurements that will be tested with the state of the art MVTX detector. The LANL-led MVTX detector that is under construction now will be ready for the day-1 sPHENIX physics in 2023.

This project has established LANL's leadership role in the next generation DOE flagship heavy ion program, the sPHENIX experiment in the US, and brought a new long-term DOE Office of Science Nuclear Physics support to LANL, as well as new technical capabilities and talents for both experimental and theoretical programs

***** END OF (15) PAGE-LIMITED SECTION *****

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Pages used to list references will not be included in the report page count. List all references you may have used throughout the body of your report and number them accurately so that they match the in-text reference numbering. You may use End Note or a similar tool.

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