Early Career Research Proposal:
Experimental Study of the Strongly-coupled Quark Gluon Plasma via Heavy Quark Production at RHIC

DOE National Laboratory:	Lawrence Berkeley National Lab
Street Address/City/State/Zip:	One Cyclotron Road, Berkeley, CA 94720
Principal Investigator (PI):	Xin Dong
Position Title of PI:	Staff Scientist
Business Mailing Address of PI:	MS70R0319, One Cyclotron Road, Berkeley, CA 94720
Telephone Number of PI:	510-486-4121
Email of PI:	XDong@lbl.gov
Program Announcement Number:	LAB 11-572
DOE/Office of Science Program Office:	NP
Topic Area:	Heavy Ion Nuclear Physics
Topic Area Technical Contact:	Gulshan Rai
Year Doctorate Awarded:	2005
Number of Times Previously Applied:	0
PECASE Eligible:	No

Budget Explanation

The requested budget, as detailed in the attached budget sheets, supports the PI (50% in the first two years and 80% in later years), one graduate student (in the first two years) and two postdoctoral fellows including travel, computing and support for other scientific activities. Table 1 shows an overview of the total cost and the personnel supported by this project.

	FY2012	FY2013	FY2014	FY2015	FY2016
Total Budget (K$)	501	504	548	562	575
FTE PI	0.5	0.5	0.8	0.8	0.8
FTE Postdocs	2.0	2.0	2.0	2.0	2.0
Graduate students	1.0	1.0	0.0	0.0	0.0

Table 1: Summary of FY2012-FY2016 budgets and personnels supported by this project.

The requested budget is based on the following considerations:

- **PI:** In the first two years, the PI will focus on Heavy Flavor Tracker (HFT) detector commissioning and calibration tasks as well as physics simulation and partial data analysis. The PI will devote 50% of his time into this project to coordinate the efforts for detector commissioning and calibration and lead the physics analysis. The other half of the PI's time will be occupied by existing commitments to the STAR Collaboration in these two years. In the later three years, the PI will be focusing more on extracting the physics results from the data collected with the HFT. The PI also anticipates a significant reduction of commitments to the STAR collaboration. 80% of the PI's salary covered by this project in this period is requested and necessary to ensure intensive focus on physics analysis.

- **Postdocs and graduate students:** Two full time postdoctoral fellows supported by this project are necessary to carry out and complete the proposed project in a timely way. They will concentrate on the important tasks such as the HFT commissioning and calibration in the first two years, and the physics data analysis, particularly the heavy quark correlation analysis. In view of the importance of detector commissioning and calibration, we ask for the support for one more graduate student to work on these tasks in the first two years of this project. Involving postdocs and graduate students into the project will not only guarantee timely completion of the project but will also train the next generation of scientists in this exciting area of advanced experimental nuclear physics research.

- **Travel:** We ask for an annual $20K support for domestic travels of project personnels to the Brookhaven National Lab for detector commissioning and calibration, and for travels to participate national conferences and workshops to present the latest results from our research. We also plan to organize regular workshops on heavy flavor production at LBNL. We ask for an annual $10K support for foreign travel to international conferences and workshops. This is estimated to cover the expenses of three travels every year to important international meetings, e.g. Quark Matter, Hard Probes etc.

- **Computers:** We ask for support of $10K/year for computing resource buying at NERSC facilities. In the first year, we request an additional $10K initial buying for laptops for the postdocs and students.

The detailed budgets for FY2012-FY2016 are attached.

Experimental Study of the Strongly-coupled Quark Gluon Plasma via Heavy Quark Production at RHIC

Xin Dong (Principal Investigator)
Nuclear Science Division, Lawrence Berkeley National Lab

Quantum ChromoDynamics (QCD) calculations predict that a new state of matter, the Quark Gluon Plasma (QGP), exists at extremely high temperature or high density. To discover and study the properties of such matter is the main physics goals of the Relativistic Heavy Ion Collider (RHIC). RHIC results over the past decade have taught us that hot, opaque, strongly interacting matter with partonic collectivity is formed in Au+Au collisions at a center-of-mass energy of 200 GeV per nucleon pair. The next important task of relativistic heavy ion collisions is to quantify the properties of this novel state of matter, the strongly-coupled quark gluon plasma (sQGP). Heavy quarks, because of their intrinsic large masses, are much more sensitive than light quarks and gluons to the interaction strength between them and the sQGP medium. They therefore serve as a clean and penetrating probe for studying the sQGP medium properties.

I propose to carry out an experimental study of the sQGP through precision measurements of heavy quark production and correlations at RHIC, utilizing the heavy flavor tracker (HFT) at the STAR experiment. The STAR HFT upgrade, based on advanced silicon pixel technology and mechanical systems to achieve unprecedented spatial resolution, is a DOE funded project, and is scheduled to be installed in STAR by fall of 2013. The thin and high-resolution silicon pixel design of the HFT system will cover large acceptance at mid-rapidity and full azimuth at STAR, enabling precision measurements of heavy quark hadrons via full typological reconstruction over a wide kinematic region. The large acceptance of STAR provides a great opportunity to measure heavy quark correlations to probe the sQGP medium properties. The heavy quark correlation measurements will be unique at RHIC because the leading order back-to-back production process for heavy quarks is dominant at RHIC, leading to a clean interpretation of correlations in heavy ion collisions.

The proposed project will include experimental support for HFT commissioning and calibration, mostly in the first two years, as well as physics data analysis of heavy quark production and correlations. The experimental analysis will start with measurements of charm hadron production yields and elliptic flow to address the parton energy loss mechanism and medium thermalization issues. We will focus more on systematic studies of the heavy quark correlations to further address the medium response to the heavy quark jet and its properties utilizing the clean kinematic features of heavy quark production at RHIC. The completion of these projects will significantly improve our understanding of the sQGP matter by quantifying its physical properties with controlled accuracy.

1 Introduction

Quantum ChromoDynamics (QCD) is the fundamental gauge theory that describes quarks, gluons and the interactions between them. QCD matter is observed as hadrons in nature, with quarks and gluons being confined inside hadrons. Lattice QCD calculations predict a phase transition to a new state of matter, the Quark Gluon Plasma (QGP), with sufficient temperature or density. In this new phase, quarks and gluons are liberated from hadrons, and propagate over large distances rather than being confined in hadrons. The number of degrees of freedom increase dramatically during such a phase transition. This state of matter is believed to have existed in the early universe, a few micro-seconds after the Big Bang. Relativistic heavy ion collisions allow us to create and study this type of matter in the laboratory, by depositing huge amounts of energy in a compact volume. The study of this state of matter is the primary mission of the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National laboratory.

RHIC started its operation in 2000, and has generated numerous discoveries in the past decade. These include [1]:

- High transverse momentum (p_T) particle production and correlations are significantly suppressed in central Au + Au collisions compared to reference measurements in $p+p$ collisions. This indicates that the medium produced in central Au + Au collisions is very dense and opaque to energetic partons. The energy loss per unit length inside the medium is about a factor of 50-100 larger than that in cold nuclear matter.

- Bulk particle production shows strong collective flow behavior, with inclusive p_T spectra and elliptic flow (v_2) well-described by hydrodynamic model calculations, indicating that the components of the medium strongly interact with each other.

- Particle production in the intermediate p_T region ($2< p_T <5$ GeV/c) shows a baryon/meson grouping. Particularly the elliptic flow of hadrons including the multi-strange hadrons show a Number-Of-Constituent Quark (NCQ) scaling, indicating that partonic collectivity has been developed in the system.

Summarizing these discoveries, we have learned that a hot, opaque, and strongly interacting medium exhibiting partonic collectivity, namely the strongly-coupled quark gluon plasma (sQGP), is formed in Au+Au collisions at a center-of-mass energy of 200 GeV per nucleon pair. The next important task of relativistic heavy ion collisions is to quantify the properties of this novel state of QCD matter. Heavy quarks are a unique probe for this purpose.

1.1 Why heavy quarks?

In elementary particle collisions, processes involving heavy quarks with mass much larger than the QCD scale Λ_{QCD} are, in principle, amenable to perturbative QCD (pQCD) calculations. Because of their large masses, heavy quarks are expected to be predominantly produced from the initial hard scatterings [2], and their masses are not easily modified by the QCD medium [3]. Therefore heavy quarks serve as a clean and penetrating probe to study the novel QCD medium created in heavy ion collisions at RHIC. In particular, heavy quark correlations, which have not been explored so far, will provide a novel and unique tool that can significantly enhance our detailed knowledge about the medium properties.

1.1.1 Heavy quark cross section

Studying heavy quark production to understand sQGP properties requires a systematic study of the heavy quark production in $p+p$, $p(d)+$ A, and A + A collisions. The total charm production cross section in $p+p$ collisions is the first crucial measurement to test the applicability of pQCD, as well as to provide a baseline for studying the medium properties in A + A collisions. Precise and systematic studies of the charm cross sections from $p+p$ to central A+A collisions are mandatory to understand both the open charm and charmonium production mechanisms in cold and hot nuclear matter. This requires the measurement to cover large momentum space and as many charm hadron states as possible, to minimize the systematic uncertainties.

1.1.2 Heavy quark energy loss

Energetic partons are expected to lose a significant amount of energy when traversing the sQGP medium. This has been most commonly attributed to gluon bremsstrahlung radiation via multiple scatterings in the medium. Heavy quarks are expected to lose much less energy via gluon radiation compared to light quarks, because the radiation at small angles is significantly suppressed due to their large masses, known as the "dead-cone" effect [4]. Other energy loss mechanisms such as elastic collisional energy loss have also been proposed [5, 6, 7], prompted by the observation that the nuclear modification factor (R_{AA}) of heavy flavor decay electrons show similar suppression as light hadrons [8, 9]. Until now, all results are from measurements of heavy flavor hadron decayed leptons. Precise measurements of charm and bottom production at high p_T will significantly improve our knowledge of the parton energy loss mechanisms in sQGP. In addition, an alternative description using the AdS/CFT correspondence has been developed to describe the suppression of the measured R_{AA}. It has been suggested that the measurement of the charm/bottom double yield ratios of the nuclear modification factors will help to disentangle the applicability of pQCD vs. AdS/CFT in the hot dense sQGP [10].

1.1.3 Heavy quark collectivity

The behavior of heavy quarks in the sQGP system can be seen in analogy to the Brownian motion in a thermal system. The interactions with the hot QCD medium provide unique and sensitive measurements of the medium properties. The interaction strength between heavy quarks and the medium will be sensitive to the medium transport properties, which can be revealed from the experimental observables. Theoretical calculations show that the charm quark R_{AA} together with the 2nd order azimuthal anisotropy parameter - elliptic flow (v_2) - is sensitive to the medium diffusion constant, thus can be directly related to the shear viscosity over entropy ratio (η/s) [11, 12]. The collective behavior of heavy quarks in the medium will also shed light on the mechanism of thermalization in such collisions, since heavy quark collectivity requires significantly more rescattering with other components of the medium. Testing the hydrodynamic behavior of heavy quarks in the medium will experimentally demonstrate the degree of thermalization of both, heavy quarks and light quarks, in the system.

1.1.4 Heavy quark correlations

Particle correlations have been widely used to study the medium response, and thus infer the medium properties, in heavy ion collisions. Studying the behavior of heavy flavor jets traversing the medium by triggering correlations with heavy flavor will help us to understand the properties of the medium from a new point of view. At RHIC energies, the dominant process for charm quark production is the leading order $2 \to 2$ process, thus one would expect a clear back-to-back $D\overline{D}$ correlation in $p+p$ collisions. In heavy ion collisions, the back-to-back $D\overline{D}$ correlation is expected to be suppressed and modified in different ways, depending on the strength of charm-medium interactions [13, 14]. Therefore heavy quark correlations in heavy ion collisions at RHIC provide a sensitive probe to quantify early thermalization of the medium. Such measurements will be unique at RHIC, since at LHC energies, calculations show that higher order processes (e.g. gluon splitting, flavor excitation etc.) will alter the charm quark azimuthal correlations considerably even in $p+p$ collisions [15], thereby complicating the interpretation of $D\overline{D}$ correlations in heavy ion collisions.

Measurements of heavy quark correlations will also aid the dilepton physics program. Charm quark correlations generate a sizable contribution to the dilepton mass spectrum in the intermediate mass region ($1.1 < M_{ll} < 3$ GeV/c^2) at RHIC. Theoretical calculations show that the QGP thermal radiation contribution may be significant in central heavy ion collisions in the same mass region [16, 17]. Measurements show that electron pairs from correlated charm quark pair production dominate in this mass region in $p+p$ collisions. Measurements in Au+Au collisions seem to indicate either a modification of the charm correlation or an additional source, presumably the QGP thermal radiation, is needed to explain the data [18, 19]. To clarify the question of QGP thermal radiation production, it is critical to understand the charm-charm correlations in heavy ion collisions at RHIC. Systematic studies of charm quark correlations in heavy ion collisions will significantly enhance the physics outcome of the dilepton program.

Measuring heavy flavor hadron production spectra and correlations is a DOE milestone in 2016.

1.2 RHIC results on heavy quark production

There have been many achievements in the first decade of RHIC in the area of heavy flavor production. These have deepened our knowledge of the novel QCD matter, and some of them have triggered significant follow-up questions which need further measurements to answer. Heavy flavor measurements have been carried out thus far mainly with heavy flavor decayed leptons, with some utilizing hadronic decay channels with limited kinetic coverages.

1.2.1 Charm production cross section

In $p+p$ collisions, measurements of the total charm production cross section provides a crucial test of pQCD calculations as well as a baseline for further measurements in heavy ion collisions. Both PHENIX and STAR collaborations have extensively studied this via heavy flavor decay (HD) electrons at mid-rapidity. The production cross section of HD electrons is found to be consistent with the upper bound of a Fixed-Order-Next-to-Leading-Logarithm (FONLL) pQCD calculation [20] for $p_T(e) > 1$ GeV/c [21, 22]. However, low p_T electrons suffer from significant systematic uncertainties due to the small signal-to-background ratio in the measurements, which results in a significant extrapolation uncertainty in obtaining the total cross section over the full p_T acceptance. STAR has also studied charm hadron production via hadronic decays without topological reconstruction on secondary decays. The recent results cover a p_T region of 0.6 up to 6 GeV/c, and the measured charm hadron (D^0, D^{*+}) cross sections are also found to be consistent with the upper bound of FONLL pQCD calculation [23].

At RHIC, both experiments have carried out similar analyses for Au + Au collisions. PHENIX's single electron measurements and STAR's D^0 meson measurements show that the total charm production cross section in heavy ion collisions approximately scales with the number of binary collisions, indicating that charm quarks are dominantly produced via initial hard scatterings in RHIC heavy ion collisions [9, 23].

STAR has also reported a measurement of the D^0 spectrum in Au+Au collision using the large data sample collected in Run10 [23]. The Au+Au spectrum seems to show some modifications compared to that in $p+p$ collisions. However, due to the currently large systematic error, no final conclusions can be drawn yet. The Au+Au D^0 spectrum is significantly different from the Blast-Wave model predication with the freeze-out parameters obtained by a fit to the light hadron spectra, indicating that D^0 mesons freeze-out earlier from the system compared to light hadrons.

1.2.2 R_{AA} and v_2 of electrons from heavy flavor decay

One of the most striking results of heavy flavor production is the measurement of HD electron R_{AA} in Au+Au collisions. The result shows that the suppression of HD electrons in central Au+Au collisions is at about the same level as that of light hadrons at $p_T > 5$ GeV/c [8, 9]. This contradicts the naive expectation from the heavy quark "dead-cone" effect for gluon radiation, which challenges our understanding of the parton energy loss mechanism in hot dense sQGP matter. The result has stimulated a lot of theoretical developments, including considering the importance of elastic collisional energy loss for heavy quarks and the dynamic expansion of the medium [5, 6, 7]. The HD electrons contain decay contributions from various charm and bottom hadrons, and the experimental uncertainties are still large. Therefore, precision measurements of R_{AA} for individual charm hadrons will provide a clearer picture and help us understand in detail the energy loss mechanism. Similarly, the heavy flavor elliptic flow has so far come from the heavy flavor decay electron v_2. Thus, the experimental uncertainties are large due to the ambiguity of mixing charm and bottom decays. The result is not conclusive [24].

1.2.3 Heavy flavor correlations

The individual charm and bottom contributions to the HD electrons have been studied via $e-h$, $e-K$ and $e-D$ correlation measurements in $p+p$ collisions by the STAR and PHENIX collaborations [25, 26]. The bottom contribution becomes dominant at $p_T > 5$ GeV/c. The relative contribution of charm and bottom to HD electrons is found to be consistent with the FONLL calculations, within large uncertainties. By combining the relative bottom contribution with the HD electron R_{AA}, one can infer that electrons from bottom decay at $p_T > 5$ GeV/c are also suppressed in central Au+Au collisions.

There has been an initial attempt to measure the azimuthal angular correlations between charm hadrons D^{*+} and fully reconstructed jets in $p+p$ collisions by STAR [27]. However, due to the trigger bias in the near side correlation, the charm hadrons observed are mostly from gluon jet fragmentation, indicating higher order processes for charm production. Combining the measured higher order gluon splitting rate with a pQCD calculation of the gluon jet cross section, one can infer that the gluon splitting process contribution to the total charm production is small at the RHIC energy of $\sqrt{s} = 200$ GeV.

Heavy flavor triggered correlation measurements in Au+Au to investigate the medium response via flavor dependent triggers have been started. Both STAR and PHENIX have reported heavy flavor triggered electron - hadron azimuthal angle correlation measurements in Cu+Cu and Au+Au collisions [28, 29]. The measurements, although limited by statistics, show a hint of away side modification compared to $p+p$ collisions.

1.3 Limitations of current measurements and future directions

The measurements of heavy flavor production so far have limitations, which prevent us from obtaining precise understanding of the properties of sQGP matter.

- Current instrumentation does not have the capability to reconstruct the secondary vertices of heavy flavor decay hadrons. Even with large statistics, we only have limited precision on the D^0 hadron spectrum measurement, over only limited p_T coverage. The measurement precision for charm hadron elliptic flow is marginal, and we don't yet have measurements for other charmed hadrons or bottom hadrons.

- High p_T electrons are triggerable, so that one can accumulate good statistics. However, the measured electrons are a mixture of decays of all charm and bottom hadrons. The separation of contributions has limited precision in $p + p$ collisions, and the separation is almost not feasible in Au+Au due to unknown medium modifications to the heavy flavor angular correlations. Separating the different charm and bottom hadron contributions is crucial to understand the exact charm and bottom production. Furthermore, the momenta carried by the daughter electrons are different from the momenta of the parent particles. In a given electron momentum range, the heavy flavor parent come from a very wide momentum region. This makes the interpretation of electron measurements complex.

These limitations can only be overcome by full topological reconstruction of secondary decay vertices of heavy flavor hadrons, which will lead to precision measurements of heavy flavor production. The decay topology must be measured via hadronic decay daughters to reconstruct the complete charm hadron kinematics. It is not sufficient for precise measurements to measure semileptonic daughters and extract the charm/bottom contributions via a statistical separation on the track impact parameter distribution. Because the decay impact parameter distributions for bottom hadrons and some charm hadrons (such as D^+) are similar, arising from their similar lifetimes, the separation will suffer from relative large systematic uncertainties due to the unknown charm hadron cross section. To understand the heavy quark production mechanism, as well as its interaction with the sQGP medium, we need systematic and precise measurements of various charm and bottom hadrons in $p+p$, $p(d)$+A, and A + A collisions. This therefore calls for a large acceptance, thin, silicon pixel detector placed very close to the primary interaction vertex to carry out precise measurements of heavy quark production.

2 Heavy Flavor Tracker for STAR

2.1 Detector design

In order to overcome the difficulties in the decay lepton measurements and reduce the systematic errors in heavy flavor measures for both charm and bottom hadrons, STAR experiment is building a Heavy Flavor Tracker (HFT). The HFT upgrade is a DOE funded project [30]. It has received the CD-2/3 approval recently. The key subsystem - the PIXEL detector will be ready for Run 2014.

The HFT covers the pseudorapidity region in $|\eta| < 1$ and the full azimuth. It consists of three subsystems:

- One layer of Silicon Strip Detector (SSD) at a radius of 22 cm to the beam pipe center. The SSD detector is an existing subsystem in STAR. The readout electronics is being upgraded to match the TPC read out speed.

- One layer of Intermediate Silicon Detector (IST) at a radius of 14 cm. The IST will be a newly built subsystem using the conventional silicon strip technology.

- Two layers of PIXEL detector (PIXEL) at radii of 8 cm and 2.5 cm respectively. The PIXEL detector provides the ultimate pointing resolution in the HFT system. It utilizes state-of-the-art CMOS active sensor technology with pixel size of 18.4 × 18.4 cm^2. To allow precision measurements of charm hadrons at low p_T, the whole detector thickness is minimized as much as possible.

The HFT detector is described in the HFT project proposal [30] and the Conceptual Design Report (CDR) [31]. The primary purpose of the SSD-IST-PIXEL detector is to provide graded resolution from the STAR Time Projection Chamber (TPC) into the interaction point and to provide excellent pointing resolution at the interaction point for resolving secondary particles and displaced decay vertices. Table 2 lists the key parameters for all three subsystems.

Table 2: Some key parameters of each subsystem of the HFT detector.

Detector	Radius (cm)	Hit Resolution $R-\phi/Z$ (μm)	Thickness
SSD	22	30/860	$1\%X_0^\dagger$
IST	14	170/1800	$1.3\%X_0$
PIXEL	8	8/8	$0.37\%X_0$
	2.5	8/8	$0.37\%X_0$

† X_0 - radiation length.

The two layers of thin, high resolution pixel detectors are the key part of the HFT system. The design is optimized for the charm and bottom studies. High resolution is necessary for direct topological reconstruction of charm and bottom decay vertices with high detecting efficiency and controllable combinatorial background in central heavy ion collisions. A thin detector with low material budget is needed to obtain precision measurements for low momentum charm hadrons that are significant in constraining the total charm yields and sensitive to medium thermalization.

2.2 Full detector response simulation and expected performance

We have carried out detailed simulation studies on the performance and physics capabilities with the HFT detector installed into STAR [31]. The full detector simulations were done in the GEANT environment and the tracking reconstruction was processed via the standard STAR offline tracking software. The simulation also considered the pileup hits in the PIXEL detector due to the finite integration time in the expected RHIC II environment.

Figure 1 shows the pion track pointing resolutions to the collision vertex in the $R-\phi$ and Z directions after requiring two layers of PIXEL hits from full GEANT simulations. The simulations are compared to two toy model calculations. The results show that with the HFT, the tracking resolution can be better than 30 μm at $p_T > 0.8$ GeV/c, which allows a clear separation of the charm hadron decay vertex from the collision primary vertex even for very low p_T charm mesons. Detailed physics projections on the D^0 meson spectra, R_{cp} as well as v_2 can be found in the HFT Proposal [30] and CDR [31].

2.3 The STAR detector in 2014

In the year 2014, the HFT as well as another major upgrade detector - Muon Telescope Detector (MTD) [32] will be installed in STAR. The STAR midrapidity detector subsystems will be (from most inner to most outer):

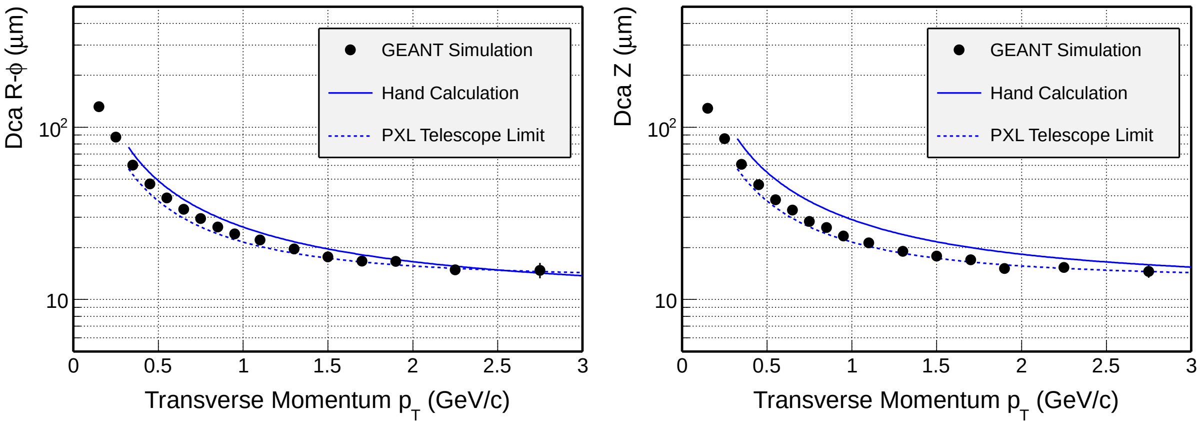

Figure 1: Pointing resolutions in $R-\phi$ (left) and Z (right) directions respectively from full GEANT simulations for STAR tracking with HFT compared with fast toy model calculations.

- Heavy Flavor Tracker (HFT): Precision tracking detector aiming for heavy flavor secondary decay measurements.
- Time Projection Chamber (TPC): STAR main tracking detector determining the momentum resolution and providing particle identification (PID) via ionization energy loss.
- Time Of Flight (TOF): Hadron PID detector extending the TPC hadron PID up to intermediate p_T, and improving the low p_T electron PID.
- ElectroMagnetic Calorimeter (EMC): Electron/Photon detector providing the electron PID, energy measurement and triggering at high p_T.
- Muon Telescope Detector (MTD): Muon detector providing muon PID after combining with TOF.

All the subsystems cover similar pseudorapidity region ($|\eta|$ <1) and full azimuthal angle except that MTD has limited coverage. The combination of these detectors will be well suited for precision measurements of identified hadrons, electrons, muons, weak decay strange hadrons, and charm/bottom hadrons. Large midrapidity acceptance and full azimuthal angle coverage will be unique and important for correlation measurements.

3 Research Proposal

The PI proposes to carry out a program of experimental study of the sQGP through precision measurements of heavy quark production and correlations at RHIC utilizing the heavy flavor tracker (HFT) at the STAR experiment. The proposed project will include experimental support for the HFT commissioning and calibration, mostly in the first two years, as well as physics data analysis on the heavy quark production and correlations at RHIC. The basic measurements that STAR will perform with the HFT are detailed in the HFT documents [30, 31]. We will play a leading role in that program and in addition propose a physics program with detailed heavy quark correlation studies. Taking advantage of the large acceptance and full azimuth coverage of the STAR detector, we will focus on systematic experimental studies of heavy quark correlations from $p + p$ to central Au+Au collisions to further address the medium response to the heavy quark jet utilizing the clean kinematic features of heavy quark production at RHIC. A variety of combinations of different detector subsystems further provides an opportunity to systematically study the correlation distributions triggered via different heavy flavor channels.

Details of the research proposal are described in the following sub-sections.

3.1 HFT commissioning and calibration

The timelines for the HFT project involve an engineering run with a prototype of PIXEL detector in RHIC run 2013 (year 2013), and to have the full PIXEL system installed for RHIC run 2014 (year 2014). In the first two years, we will play a leading role in the HFT system commissioning in the STAR run as well as necessary online/offline monitoring and calibrations. Here is the list of tasks we are going to carry out.

- Integration of the HFT readout into the STAR DAQ system. This includes time-in of the HFT readout signals, DAQ infrastructure to offline tape as well as the online monitoring pool, interface development with the high level trigger (HLT).
- Online monitoring. This includes the monitoring and QA of the HFT detector conditions, the DAQ readout, and the possible online reconstruction.
- Calibrations. We will be focusing on the alignment calibrations for the HFT system. This includes two tasks: the inner pixel position map on each sensor and the global alignment of the PIXEL detector with respect to the STAR coordinate. Measurements or surveys on the first one will be carried out in the lab before the detector is installed into STAR. The position map will be stored into the STAR data base for global calibration and tracking. The global alignment will be carried out in STAR with dedicated datasets, such as cosmic ray data, zero-field run data and/or regular beam-beam collision data. All these will give a systematic understanding of the alignment which is crucial for silicon detector tracking.
- Offline software infrastructure construction. This includes the construction of the offline DAQ reader to convert the DAQ data into the standard STAR offline DST data structure, the construction of the data base tables for various online/offline usages, the analysis software for standard offline heavy quark analysis, and the simulation/embedding software etc.

After the summer 2014, the HFT system will be in the operation mode. We will continue the support of the calibration and software development in the following RHIC runs. We will then focus on the physics analysis with the datasets collected in the STAR detector with the HFT. The proposed physics analysis topics will be discussed in the following sections.

3.2 Charm quark cross section in $p + p$ collisions

3.2.1 Charm total cross section in $p + p$

Heavy quark cross section in $p + p$ collisions is one of the first crucial measurements to validate the pQCD application for heavy quark production as well as to provide the baseline to understand the possible heavy quark modifications and medium properties in heavy ion collisions. The initially produced heavy quarks will be distributed into different heavy flavor hadrons in the final state. To minimize the extrapolation systematic uncertainties, precision measurements on the total heavy quark production cross section at mid-rapidity require a) a wide p_T coverage down to low p_T b) measurements of as many charm hadrons as possible. With the full STAR HFT+TPC+TOF system, we will carry on our current charm meson measurements, and perform precision measurements of not only D^0, D^{*+}, but also D^+, D_s^+, Λ_c^+. The low p_T limit can be close to zero in $p+p$ collisions with very small combinatorial background.

3.2.2 Charm hadron production at high p_T in $p+p$

Precision measurements on charm hadron cross section in $p+p$ collision up to high p_T is necessary for nuclear modification factor R_{AA} measurements in heavy ion collisions. The difficulty for high p_T particles with hadron decay daughters is that they are not easily triggerable with the BEMC detector to take advantage of the full RHIC II luminosity. Understanding the trigger on charm hadron decay daughters will be challenging as charm quark has a hard fragmentation function, and BEMC is much more sensitive to the neutral energies, thus the BEMC triggers usually favor the soft fragmentation processes and suppress the hard fragmentation contribution. There have been some developments in STAR to use the jet-patch triggers, which requires a minimum total electromagnetic energy in a 1x1 $\Delta\eta \times \Delta\phi$ patch of BEMC towers, to trigger on one leg of the decay hadrons for high p_T K_S^0 and Λ [33]. Using the hadron response of BEMC trigger has been demonstrated to be feasible to provide a reasonable measurement up to very high p_T with controlled systematic uncertainties. We will employ this methodology to the charm hadron measurements at high p_T in $p+p$ collisions. We will advance the measurement by utilizing other subsystems to get the systematic uncertainties under control. For instance, requiring the TOF hit in the same BEMC hit position can ensure a charged particle that fires the BEMC, and therefore may significantly reduce the neutral energy trigger bias on the charm measurement.

3.3 Charm hadron production in Au+Au collisions

We will carry out the precision measurements of various charm hadrons in Au+Au collisions. Typological reconstruction of the secondary decay vertices is essential to overcome large combinatorial background in heavy ion collisions. Full detector response simulation demonstrates very good projected significance in the reconstructed D^0 signal down to p_T ~0.5 GeV/c. High p_T charm hadron signals are anticipated to be almost background free. The measurement will be constrained by the recorded event statistics.

3.3.1 Nuclear modification factor at high p_T

With precision measurements on the cross sections in $p+p$ and Au+Au collisions, we will calculate the nuclear modification factor R_{AA} of D^0 and other charm hadrons up to high p_T (~8-10 GeV/c) to address the energy loss mechanism issue. Combining the measurements of R_{AA} of light hadrons, strange hadrons and charm hadrons, we should be able to nail down the details how energetic partons interact with the medium and lose their energy. We will study the centrality dependence of the R_{AA} for systematic understanding on the energy loss mechanisms.

3.3.2 Charm quark collectivity

Charm quark collectivity is one of the direct experimental evidences of light quark thermalization in heavy ion collisions. However, in a coalescence formation picture, the final state charm hadron can still have finite collectivity even though the charm quark has no collectivity. To pin down the charm quark collectivity, one needs precision measurements at low p_T. In addition, charm production at low p_T will carry sensitive information on the medium transport properties which can be directly connected to the η/s quantity. We will measure both the charm hadron production yield (thus the R_{AA}) and the elliptic flow parameter down to $p_T \sim 0.5$ GeV/c. We will compare these results to the hydrodynamic model prediction to test its applicability in the charm sector. We will further compare both the R_{AA} and v_2 with realistic model calculations to extract the charm quark diffusion constant in the medium and then deduce the η/s value.

3.4 Heavy quark correlations

The full azimuth coverage and wide pseudorapidity acceptance of the STAR detector is well suited for correlation measurements. With the full HFT+TPC+TOF+BEMC+MTD subsystem combination, we will be able to carry out an extensive program of heavy flavor correlation measurements, which will provide us another unique way to investigate both the heavy quark production mechanisms as well as the heavy quark interaction strength with the sQGP medium.

At the leading order in $p+p$ collisions, the heavy quark and anti-quark should be created as a pair with exact back-to-back azimuthal angular correlation if the initial transverse momentum smearing (k_T) is negligible. Higher order processes (flavor excitation, gluon splitting, etc.) will have a different azimuthal correlation distribution. Heavy quark angular correlations will help us learn about the heavy quark production mechanism in a differential way. It is expected that at RHIC energies, the leading order is still the dominant contribution for charm and bottom quark production, which gives us a unique opportunity to use the heavy quark correlation as a probe to gain insight of the sQGP medium properties created at RHIC. The left panel of Figure 2 shows the $D\overline{D}$ azimuthal angular correlation with two different D-meson p_T cuts in $p+p$ collisions at $\sqrt{s} = 200$ GeV calculated in PYTHIA [13]. The right panel of Figure 2 shows the modified $D\overline{D}$ azimuthal angular correlations in central Au+Au collisions calculated in a non-relativistic Langevin approach to describe the random walk of charm quarks in a QGP. One can see the back-to-back angular correlation that is apparent in $p+p$ collisions is suppressed, smeared or may be even completely washed out in central Au+Au collisions at RHIC depending on the interaction strength between the charm quarks and the medium light quarks and gluons in the strongly interaction QGP matter [13, 14]. The interaction strength between charm quarks and the medium in this calculation is characterized by the parameters a for the charm quark drag coefficient, while the drag coefficient can be related to the momentum space diffusion coefficient D which is connected with the medium η/s [11, 12]. Therefore the heavy quark correlation strength observed in Au+Au collisions compared to $p+p$ collisions will be another sensitive probe to quantify the medium transport properties.

We will carry out heavy quark azimuthal angular correlation analyses in $p+p$ and Au+Au collisions. The measurement in $p+p$ collisions will be used also to test and constrain the pQCD calculations, and provide a baseline to be able to interprete the Au+Au results. With the full STAR subsystem combination at mid-rapidity, we will conduct this study through many experimental observables which will be discussed in the following:

3.4.1 $D\overline{D}$ correlations

The direct measurement will be the $D\overline{D}$ angular correlations while the D mesons are reconstructed via topological hadronic decays with help of the HFT detector. By utilizing the jet patch (a combination of BEMC towers within $\Delta\eta \times \Delta\phi \sim 1 \times 1$) triggers with the EMC detector, we will be able to maximize the recorded luminosity. Since the angular correlation is a coincidence measurement, the absolute trigger efficiency doesn't need to be understood at the same precision as the cross section measurement, which makes this measurement more flexible. Trigger bias effects on the correlation spectrum need to be studied.

The $D\overline{D}$ correlation measurements will suffer from the necessity to reconstruct both charm

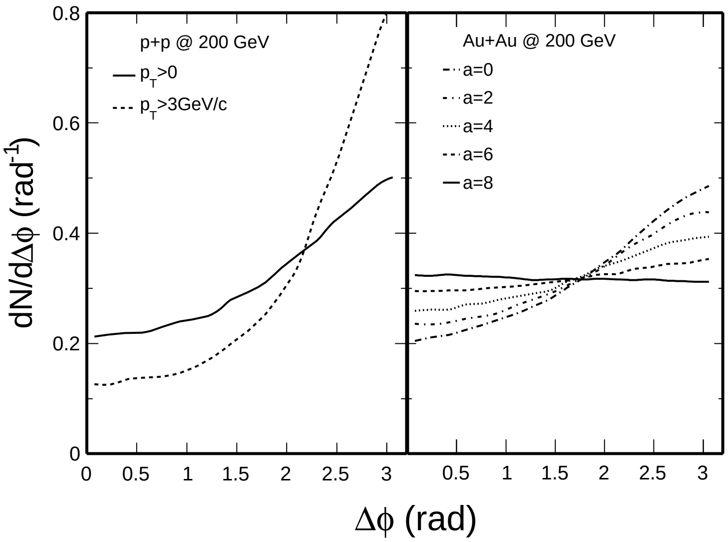

Figure 2: Left: The $D\overline{D}$ azimuthal angular correlations in $p+p$ collisions at $\sqrt{s} = 200$ GeV calculated in PYTHIA. The p_T dependence is shown by the cuts on single D-mesons. Right: The modified (with no p_T cut) $D\overline{D}$ azimuthal angular correlations in central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV calculated by the model [13]. The calculation shows that with different medium properties (characterized by the drag coefficient $\gamma(T) = aT^2$ and a in the unit of 10^{-6}(fm/c)$^{-1}$MeV^{-2}), the back-to-back angular correlation that is apparent in $p+p$ collisions is suppressed, smeared or may be even completely washed out.

meson legs. It will be penalized by two small hadronic decay branching ratios, that reduce the correlation statistics. However, the $D\overline{D}$ correlation approach at RHIC should be direct and clean, and the bottom feeddown contribution at RHIC is small and measurable.

3.4.2 e or μ triggered correlations

An alternative approach to improve the statistics is to use the e or μ (e/μ) as the heavy quark proxies to study the heavy quark correlations. The decay kinematics determine that at $p_T > 3$ GeV/c, heavy flavor decay leptons can reflect the parent heavy flavor hadron direction well. Electrons and muons can be triggered at high efficiency, thus the measurement involving e/μ triggers can take the advantage of the full RHIC II luminosity. The separation of charm and bottom contributions to the triggered e/μ is complex. HFT will be very helpful for this purpose, and the precision and systematic uncertainty using the lepton triggered approach need detailed simulations to quantify. The e/μ triggered correlation measurements include e/μ-hadron, e/μ-D, e/μ-e/μ correlations. Different observables have their own pros and cons on statistics and systematics. All these measurements together will give us the opportunity to systematically and coherently understand the heavy quark in-medium interactions and to quantify the medium properties. Among these different methods, the $e-\mu$ correlation will be extremely interesting and unique, particular for understanding the charm correlation contribution in the dilepton spectra in heavy ion collisions.

3.4.3 Correlations with full heavy quark jet reconstruction

Fully reconstructed heavy quark jets are interesting because they define the hard scattering axis and energy scale since the leading order back-to-back heavy quark pair production is dominant at RHIC. Heavy quark correlations involving the fully reconstructed heavy quark jets will allow systematic investigations on the medium response to heavy partons with defined kinematics.

The technical difficulty for these measurements has been described in section 3.2.2, which is the detector trigger bias on the charm jet reconstruction. There was some initial attempt to correlate the charm hadrons with the fully reconstructed jets. Figure 3 shows their azimuthal angular correlation from STAR data. Both D^{*+} mesons and jets cover large momentum regions. The near side correlation is attributed to the gluon jet fragmentation, while the hard fragmentation contribution from direct charm quark is suppressed due to the trigger. The away side correlation is likely to have originated from charm quark hard fragmentation. We will carry on a precision study in $p+p$ collisions, and investigate the opportunity to study such correlations in the heavy ion collisions.

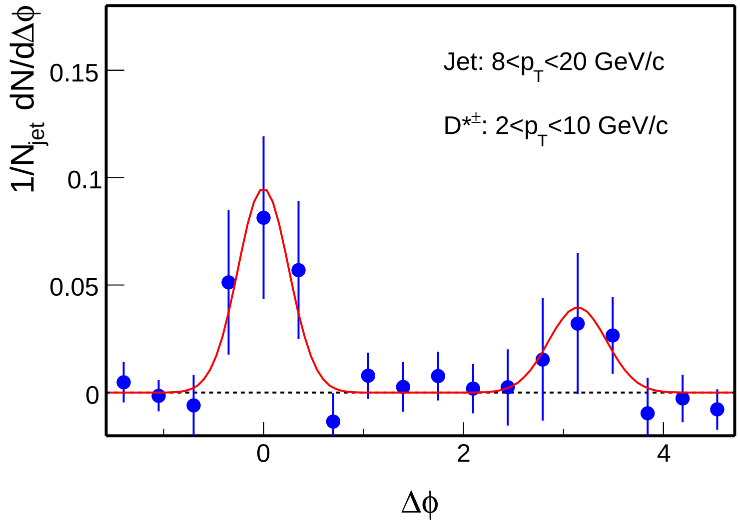

Figure 3: Azimuthal angular difference between the D^{*+}-meson and the reconstructed jet from the STAR data [27].

Understanding the charm quark correlations in Au+Au collisions is also very critical to access the possible QGP thermal radiation production in the intermediate mass of the dilepton spectra. Systematic study of the charm quark correlations in heavy ion collisions will significantly enhance the physics outcome of the dilepton program.

4 Timeline of Major Research Activities

The PI will lead the research effort to finish the project within the five-year period of this proposal. The postdoc research associates and the students will be intensively involved in the research program. The research results will be published in a timely fashion. We divide major activities into following two categories.

4.1 HFT commissioning and calibrations

In the first two years of this project, we will provide significant FTE support and lead the commissioning and calibrations of the HFT system. Here we list the major activities:

- **2012/7-2013/6:** The HFT PIXEL prototype will be installed in the summer shutdown in 2012. We will participate in and lead the prototype detector commissioning, and physics data taken in run 2013. We will finish the survey of the pixel detector and necessary calibrations. We expect to extract some key performance quantities (e.g. pointing resolution) from the prototype run for the HFT system. We will continue developing the HFT offline software to get ready for physics analysis.

- **2013/7-2014/6:** We will provide strong support and lead the commissioning of the full PIXEL detector as well as other detector subsystems. We anticipate a significant physics run and data taken in run 2014. We will continue supporting strongly the online QA and offline calibration tasks for the full HFT system. We will extract the performance quantities that is needed for the DOE HFT project CD4 review. We will finish the major parts of offline tracking, analysis and simulation software construction to allow timely physics analysis.

- **2014/7-2017/6:** In the later three years of this project, we will continue to provide support on the operation, maintenance, QA and calibration tasks that are associated with the HFT running. But we will shift our focus on the physics analysis in this period.

4.2 Physics Analysis

The major activities in physics analysis to be carried out in each budget year are listed in the followings. This plan is based on the current best estimate on the RHIC run program.

- **2012/7-2013/6:** We plan to carry on and finish the analysis with the existing STAR $p+p$ data to understand the EMC trigger effect on the reconstruction of charm hadrons and jets. We will also carry out a systematic simulation study with the full STAR detector on the heavy flavor correlation analysis.

- **2013/7-2014/6:** With the significant physics data taken in year 2014, we will start the preliminary analysis of the charm hadron spectra and elliptic flow analysis. The analysis will firstly focus on the D^0 p_T spectra, nuclear modification factor R_{CP} and v_2 in this period.

- **2014/7-2015/6:** In this period, we will finish the analysis of the charm hadron spectra and elliptic flow analysis to address the parton energy loss and medium thermalization issue. We anticipate the DOE CD-4 review for the HFT project during this year. The detector performance with beam as well as the physics results will be necessary for a successful review. We anticipate another RHIC run with $p+p$ collisions. We will start the analysis of baseline charm hadron spectra and heavy quark correlation measurements in $p+p$ collisions.

- **2015/7-2016/6:** We will perform a systematic study on charm hadron spectra, particularly with EMC triggers to measure the high p_T charm hadron production in $p+p$ collisions. This will be essential for charm hadron R_{AA} measurement up to high p_T. We will carry out the heavy quark correlation analysis with various correlation observables to precisely understand the charm production mechanism at RHIC, and provide baselines for further Au+Au measurements. We plan to analyze data taken in year 2016 with full HFT to achieve a significant Au+Au sample for further systematic studies on the heavy quark production.

- **2016/7-2017/6:** We will carry out systematic measurements of charm quark correlations with the large $p+p$ and Au+Au data samples, including $D\bar{D}$ correlations, e/μ-triggered correlations as well as heavy quark jet triggered correlations. We anticipate to quantify the modification of heavy quark correlations in Au+Au collisions compared to $p+p$ collisions and obtain a unified picture to interprete these results, thus learn quantitatively how the medium response to heavy quark jets and also infer the medium properties η/s etc.

Besides physics analysis activities, we plan to organize regular workshops related with the HFT physics at either LBNL or BNL to involve theoreticians for our physics analysis. Such workshops will also allow us to compare our physics results to that from higher energy LHC experiments for a systematic understanding on the heavy quark production and the sQGP medium properties.

This research will benefit from synergies with the Nuclear Science Division theory group and the NERSC computing group at LBNL.

5 Summary

In summary, I propose a comprehensive project on measuring the heavy quark production to study the strongly-coupled QGP properties at RHIC. The project will utilize the STAR Heavy Flavor Tracker (HFT) to allow precision measurements on heavy flavor hadrons. We will play a leading role in the key physics analyses that are described in STAR HFT proposal [30, 31]. Furthermore, we propose to carry out extensive and systematic measurements of heavy quark correlations in $p+p$ and Au+Au collisions to further address the medium response to the heavy quark jet and its properties. The heavy quark correlation measurements will be unique at RHIC with the STAR HFT because of the state-of-the-art silicon pixel detector, the large and uniform acceptance of the STAR detector and the clean kinematic features of heavy quark production at RHIC.

The proposed project is critical, highly interesting, feasible, and fully aligned with the 2007 NSAC Long Range Plan [34] as well as the supported directions in the funding announcement. It is also in-line with the STAR physics program and run plan during FY2012-2016. The STAR experiment is strongly in support of this proposal. The proposed research will address fundamental questions, such as “what are the phases of strongly interacting matter?”, and will significantly impact our understanding of the strongly coupled quark gluon plasma.

At the time of completion of these projects, we expect to provide precision measurements on the heavy quark production at RHIC in $p+p$ and heavy ion collisions. These results will significantly improve our knowledge of the heavy quark production mechanism at RHIC, the parton energy loss mechanisms in the hot dense sQGP matter, as well as the degree of medium thermalization. By combining the experimental results with theoretical model calculations, we will be able to quantify medium properties, such as the η/s and other Equation-of-State parameters, with controlled accuracy.

Appendix 1: Biographical Sketch

Xin Dong

Education and Training:

B.S. Physics, University of Science and Technology of China (USTC), Applied Physics, 2000

Ph.D. Physics, USTC, Particle and Nuclear Physics, 2000

Postdoc Fellow, USTC, Particle and Nuclear Physics, 2005-2006

Postdoc Fellow, Nuclear Science Division, Lawrence Berkeley National Lab, Berkeley, 2006-2010

Research and Professional Experience:

Staff Scientist, Nuclear Science Division, Lawrence Berkeley National Lab, Berkeley, Oct. 2010 -

Project Scientist, Nuclear Science Division, Lawrence Berkeley National Lab, Berkeley, Aug.-Oct. 2010

Selected Publications:

H. Agakishiev *et al.* [STAR Collaboration], *High* p_T *non-photonic electron production in p+p collisions at* $\sqrt{s} = 200$ *GeV*, *Phys. Rev.* **D 83** (2011) 052006.

M.M. Aggarwal *et al.* [STAR Collaboration], *Measurement of the Bottom contribution to non-photonic electron production in* $p+p$ *collisions at* $\sqrt{s} = 200$ *GeV*, *Phys. Rev. Lett.* **105** (2010) 202301.

B.I. Abelev *et al.* [STAR Collaboration], *Measurement of* D^* *Mesons in Jets from* $p+p$ *Collisions at* $\sqrt{s} = 200$ *GeV*, *Phys. Rev.* **D 79** (2009) 112006.

X. Dong *et al* (for the STAR Collaboration), *Heavy Quark Results from STAR*, *Euro. J. of Phys.* **C** 61 (2009) 659.

B.I. Abelev *et al.* [STAR Collaboration], *Transverse momentum and centrality dependence of high-*p_T *non-photonic electron suppression in Au+Au collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, *Phys. Rev. Lett.* **98** (2007) 192301.

P. Sorensen and X. Dong, *Suppression of non-photonic electrons from enhancement of charm baryons in heavy ion collisions*, *Phys. Rev. C* **74** (2006) 024902.

X. Dong, *Open Charm Production at RHIC*, *Nucl. Phys.* **A 774** (2006) 343.

M. Shao, O. Barannikova, X. Dong, Y. Fisyak, L. Ruan, P. Sorensen and Z. Xu, *Extensive particle identification with TPC and TOF at the STAR experiment*, *Nucl. Instrum. Meth.* **A** 558 (2006) 419.

J. Adams *et al.* [STAR Collaboration], *Open Charm Yields in d + Au Collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, *Phys. Rev. Lett.* **94** (2005) 062301.

X. Dong, S. Esumi, P. Sorensen, N. Xu and Z. Xu, *Resonance Decay Effects on Anisotropy Parameters*, *Phys. Lett.* **B 597** (2004) 328.

Synergistic Activities:

STAR group leader of Nuclear Science Division, LBNL, Aug. 2011 -

Physics Analysis Coordinator of STAR Collaboration, Aug. 2011 -

Co-convener of STAR Heavy Flavor Physics Working Group, Jan. 2009 - Aug. 2011.

Co-Organizer, Workshop on Heavy Quark Physics in Nucleus-Nucleus Collisions, UCLA, Jan. 2009.

Co-Organizer, Workshop on RHIC Future: New Physics Through Upgrades, BNL, May 2008.

Collaborators (in the past 48 months):

James Dunlop (BNL), Huan Z. Huang (UCLA), Peter Jacobs (LBNL), Spyridon Margetis (Kent State University), Hiroshi Masui (LBNL), Bedanga Mohanty (VECC), Kunso Oh (Pusan National University), Hans Georg Ritter (LBNL), Lijuan Ruan (BNL), Alexander Schmah (LBNL), Ming Shao (USTC), Ernst Sichtermann (LBNL), Paul Sorensen (BNL), David Tlusty (NPI, Czech), Flemming Videbaek (BNL), Qun Wang (USTC), Wei Xie (Purdue University), Nu Xu (LBNL, Central China Normal University - CCNU), Zhangbu Xu (BNL), Yifei Zhang (USTC), Jie Zhao (Shanghai Institute of Applied Physics, LBNL)

Graduate and Postdoctoral Advisor and Advisees:

Ph.D. advisors: Ziping Zhang (USTC), Nu Xu (LBNL, CCNU)
Postdoctoral advisors: Hongfang Chen (USTC), Ernst Sichtermann (LBNL)
Ph.D. students: Yi Guo (USTC)
Postdoctoral associates: Hiroshi Masui (LBNL), Alexander Schmah (LBNL)

Appendix 2: Current and Pending Support

The PI and his group are an integral part of the Relativistic Nuclear Collisions (RNC) program which is funded through DOE KB0201022. RNC will provide the necessary environment support for the proposed project. In particular, RNC plays a leading role in the HFT upgrade project. Synergies with the RNC program in particular in the area of HFT instrumentation will be very helpful for the proposed project.

Appendix 3: Biography and References Cited

References

[1] I. Arsene *et al.* [BRAHMS Collaboraiton], *Nucl. Phys.* A **757**, 1 (2005); B.B. Back *et al.* [PHOBOS Collaboration], *Nucl. Phys.* A **757**, 28 (2005); J. Adams *et al.* [STAR Collaboration], *Nucl. Phys.* A **757**, 102 (2005); K. Adcox *et al.* [PHENIX Collaboration], *Nucl. Phys.* A **757**, 184 (2005);

[2] Z. Lin and M. Gyulassy, *Phys. Rev.* C **51**, 2177 (1995).

[3] B. Mueller, arXiv: nucl-th/0404015.

[4] Yu.L. Dokshitzer and D.E. Kharzeev, *Phys. Lett.* B **519**, 199 (2001).

[5] M. Djordjevic *et al.*, *Phys. Rev. Lett.* **94**, 112301 (2005); M. Djordjevic *et al.*, *Phys. Lett.* B **632**, 81 (2006).

[6] H. van Hees, V. Greco, and R. Rapp, *Phys. Rev.* C **73**, 034913 (2006).

[7] R. Sharma, I. Vitev and B.W. Zhang, *Phys. Rev.* C **80**, 054902 (2009).

[8] B.I. Abelev *et al.* [STAR Collaboration], *Phys. Rev. Lett.* **98**, 192301 (2007); Erratum: *Phys. Rev. Lett.* **106**, 159902(E) (2011).

[9] A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev. Lett.* **96**, 032301 (2006); A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev. Lett.* **98**, 172301 (2007).

[10] W.A. Horowitz, M. Gyulassy, *J. Phys.* G **35**, 104152 (2008).

[11] G. Moore and D. Teaney, *Phys. Rev.* C **71**, 064904 (2005).

[12] H. van Hees and R. Rapp, *Phys. Rev.* C **71**, 034907 (2005).

[13] X. Zhu, P. Zhuang, and N. Xu, *Phys. Rev. Lett.* **100**, 152301 (2008).

[14] X. Zhu *et al.*, *Phys. Lett.* B **647**, 366 (2007).

[15] M. Younus, U. Jamil, and D.K. Srivastava, arXiv: 1108.0855.

[16] R. Rapp, *Phys. Rev.* C **63**, 054907 (2001).

[17] E. V. Shuryak, PRC **55**, 961 (1997);

[18] A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev.* C **81**, 034911 (2010).

[19] J. Zhao [STAR Collaboration], arXiv: 1106.6146.

[20] M. Cacciari, P. Nason and R. Vogt, *Phys. Rev. Lett.* **95**, 122001 (2005).

[21] H. Agakishiev *et al.* [STAR Collaboration], *Phys. Rev.* D **83**, 052006 (2011).

[22] A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev. Lett.* **97**, 252002 (2006).

[23] Y. Zhang [STAR Collaboration], arXiv: 1106.6078.

[24] A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev.* C **84**, 044905 (2011).

[25] M. M. Aggarwal *et al.* [STAR Collaboration], *Phys. Rev. Lett.* **105**, 202301 (2010).

[26] A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev. Lett.* **103**, 082002 (2009).

[27] B. I. Abelev *et al.* [STAR Collaboration], *Phys. Rev.* D **79**, 112006 (2009).

[28] W. Xu [STAR Collaboration], arXiv: 1106.6020.

[29] A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev.* C **83**, 044912 (2011).

[30] STAR Heavy Flavor Tracker Proposal, `http://rnc.lbl.gov/~wieman/hft_final_submission_version.pdf`.

[31] STAR Heavy Flavor Tracker Concept Design Report, `http://drupal.star.bnl.gov/STAR/system/files/HFT_CDR_Final-1.pdf`.

[32] STAR Muon Telescope Detector Proposal, `http://drupal.star.bnl.gov/STAR/system/files/MTD_proposal_final.pdf`.

[33] G. Agakishiev *et al.* [STAR Collaboration], arXiv: 1110.0579.

[34] 2007 NSAC Long Range Plan. http://science.energy.gov/np/nsac/
Nucl. Phys. A **858**, 86 (2011).

Appendix 4: Facilities and other Resources

The major part of the experiment in this proposed project will be carried out in the STAR detector at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab. We need to use the STAR detector to collect the necessary data from heavy ion and proton-proton collisions provided by the RHIC machine. Data calibration and physics analysis will be performed using RHIC Computing Facility (RCF) at BNL and computing resources at National Energy Research Scientific Computing Center (NERSC) at LBNL. Part of the PIXEL calibration work - the full pixel-to-pixel spartial mapping will be carried out using a vision coordinate machine in the machine shop at LBNL. The Nuclear Science Division commits to provide office spaces for postdoc fellows and graduate students involved in this project.

Appendix 5: Equipments

Major items of equipment already available for this project:

The STAR detector has started operation since 2000. With various subsystem upgrades, it will continue to function in the next decade. The HFT subsystem will be installed into STAR in the year 2013 shutdown, and expect to start operation from year 2014. The RCF and NERSC computing facilities are available to support the computing resource needs for this project.