U.S. DEPARTMENT OF ENERGY

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Office of Nuclear Physics Report

Review Excerpts

"A Heavy Flavor Tracker for STAR"

February 25-26, 2008

EXCERPTS FROM PANEL MEMBER REPORTS

Excerpts from the reports of the review panel members regarding their evaluations are provided below according to the review criteria they were asked to address.

General Comments:

Reviewer:

"The STAR collaboration has proposed a Heavy Flavor Tracker (HFT) to extend the capabilities of the experiment to include topological reconstruction of particles with b and c quarks in heavy ion collisions. Reconstruction of secondary decay vertices in the complex environment of a gold-gold collision is extremely challenging. Star proposes innovative technology that utilizes Monolithic Active Pixel Sensors (CMOS MAPS) that are thinned to 50 microns and a new silicon pad layer to provide uniquely powerful pointing and pattern recognition capability. With this new HFT the experiment expects to explore the properties of the quark-gluon medium produced at RHIC by using the heavy quark, which is typically produced by the primary parton-parton interaction, as a gauge of quark propagation in the medium…

"Overall the HFT project is well designed to meet the goal of upgrading the capability of STAR to measure elliptic flow and R_{AA} of D mesons. Simulations show that the physics goals can be achieved if the detector performs as proposed. The CMOS APS technology is challenging, with risks associated the first large-scale deployment of a new detector type. The groups involved have world-class expertise and have a good chance of success."

Reviewer:

"The STAR collaboration has been a primary and outstanding contributor to the very successful research program in heavy ion and spin physics at the RHIC accelerator. A natural next step in developing an understanding the properties of the recently discovered strongly interacting Quark-Gluon matter (sQGP), particularly in view of recent surprising and puzzling results on heavy quark energy loss, is a comprehensive heavy flavor program to characterize completely the sQGP. To that end the collaboration proposes to install a very thin tracking detector which will allow complete topological reconstruction of open charm with complete azimuthal angular coverage down to very low transverse momenta. Among the important questions which will be addressed are the question of elliptic flow and the manner of thermalization of heavy quarks, their mechanism of energy loss in strongly interaction matter, and the systematics of their production.

"The design proposed utilizes a novel advanced CMOS technology for the intermost PIXEL detector which will provide very high precision particle tracking. As conceived the tracking resolution will provide a notable advance in event reconstruction capabilities. When combined with existing detector systems in STAR, the heavy flavor tracker (HFT) will access measurements of heavy-quark production over a near complete range of phase space, colliding particle types, and energies. There are also promising possibilities for exploiting the capabilities of heavy-flavor tracking to address important issues in the spin physics program at RHIC.

"In conclusion, the HFT is a timely addition which is well matched to the STAR detector. It provides an important increase in capability for a modest investment. It will address important physics topics including in the first 3 years of operation measurements of D-meson flow, the ratio R_{aa}, and the ratio R_{cp}. The physics potential for this instrument is much higher than competing devices since it provides access to much more detail in the measurements through complete topological reconstruction of D-meson decays."

The significance of specific scientific questions identified by the community and laboratory which they believe can be addressed by data acquired during the first three years of operations:

Reviewer:

"I have limited ability to judge the impact of the heavy quark measurements on Nuclear Heavy Ion Physics. I can, however, make some general statements. In experimental science our ability to discover is defined by the tools available to examine new processes. The proposed STAR upgrade substantially extends the capabilities of the experiment. To the extent that heavy ion collisions at RHIC provides different information on the quark gluon medium than that provided by the measurements at LHC, RHIC experiments need to have the capabilities to perform the crucial measurements. One of the most important is the flow of heavy quarks in the medium. It appears that without the HFT upgrade STAR will simply not be competitive for these measurements. PHENIX has limitations on solid angle coverage and cannot fully reconstruct D mesons. This means that measurements of heavy quark effects in PHENIX are subject to systematic errors due to the unfolding of production and decay distributions. STAR measurements of D^0 flow should be free from these systematics…

"The STAR group did not make a convincing case for heavy flavor physics that does not involve D mesons. All of their projections were rather qualitative and did not include careful assessments of backgrounds. I believe that the proposed detector has the capability to reconstruct states such as Λc baryons and B mesons; but without more careful study the significance of the signals and their impact on the physics produced by STAR is unclear. It is clear that a less capable detector than the one proposed will not be able to address this physics."

Reviewer:

"The primary physics goals identified by the collaboration are the measurement of the transverse momentum spectra and elliptic flow parameter (v_2) for multiple charm meson states down to low transverse momentum (500 MeV/c). In the first three years of operation the collaboration aims to make these measurements in both proton+proton and gold+gold collisions. The team demonstrated, reasonably conclusively, that the proposed detector was capable of delivering these measurements shortly after coming on-line. In fact, there seemed general agreement that the detector design was very well optimized to make these measurements.

“Currently PHENIX and STAR both measure charm through semi-leptonic decays (STAR through electron channels and PHENIX through both electron and muon channels). STAR has also published charm measurements through hadronic decay channels in light systems. The value of the semi-leptonic measurements is somewhat diluted because of the fact that the momentum and azimuthal angle of the daughter leptons are somewhat smeared relative to the parent charm meson through the decay process. Another limitation when inferring information about charm quarks from measured lepton distributions is the fact that the charm chemistry (ratios of different charm meson states) is not well known (and not known at all in heavy ion collisions) and the different states have different semi-leptonic branching ratios. There are also unknown kinematic correlations between the created charm and anti-charm quark pairs. The result of these various unknowns is a systematic uncertainty on the interpretation of the measured result that can only be reduced by measuring the charm mesons directly.

“However, the scientific impact of the reduction in the systematic uncertainty through the proposed measurements is not clear to this reviewer. To take one example, it was stated that it was important to determine whether charm quarks flow with the created medium in heavy ion collisions. However, this reviewer’s impression is that this has already been established, despite the larger systematic errors, through semi-leptonic measurements by both PHENIX and STAR.

“A laundry list of other physics goals was given in the written proposal, but not adequately addressed in the presentations to allow an assessment of their scientific impact:
Exploration of the meson/baryon ratio in the charm sector was proposed through measurement of the Λc. It seemed plausible that a measurement could be made, but given the relatively short decay length and the 3-body decay, a more detailed simulation is called for.

“It was proposed to measure bottom quark production through semi-leptonic channels, but such a measurement should be carried out with the PHENIX vertex detector upgrade already by the time the proposed detector comes online. The same is true for di-lepton measurements.

“Charm hadron correlation measurements were proposed, but additional simulations would be required to demonstrate scientific impact.”

Reviewer:

“There was no discussion in the presentations of measurements of unpolarized parton distributions or their mass dependence although there was some brief mention in the proposal text. The omission of this and any discussion of spin structure measurements in the scheduled presentations was taken as an indication that these topics were not considered sufficiently compelling.

“The prospects for probing proton spin structure using spin dependent heavy flavor production, upon closer examination, are less encouraging over the time horizon of the next five years, in part due to recent developments. Gluon-gluon fusion dominates heavy flavor production in heavy-ion collisions. Recent measurements at RHIC of spin asymmetries for neutral pions and also for 2-jet events signal a small value for ΔG, suggesting that the signal in heavy flavor production will be very weak. Furthermore, calculation of the "analyzing power" of heavy flavor production is not reliable because of the uncertainties in the theoretical models for the reaction. Current expectations are that such a measurement will be very difficult. The other potentially exciting possibility is the measurement of single spin asymmetries in charmed W production. But, here again the time horizon is of RHICII because of the high luminosity required.

"However, these conclusions point to the importance of a program of careful reference measurements of heavy quark production in p+p collisions in order to constrain the theoretical models for the production. The benchmark spin measurements presented as justification for the RHIC spin program retain their appeal, and provide the justification for a rigorous program of reference measurements. At this time in the development of the RHIC program, emphasis should be on understanding the details of heavy quark production.

"In spite of these qualifications on spin measurements, one very interesting spin measurement using heavy meson production was presented in the discussion on the second day of the review. The RHIC spin measurements to date have suffered from two defects. First, their sensitivities are such that they can not distinguish between small positive gluon polarizations and any negative gluon polarization value. Second, they provide no information on the shape of the gluon polarization distribution in x_{bj}. The measurement presented was a measurement of the double spin asymmetry in heavy-flavor production as detected with displaced electrons observed in the HFT. This measurement would provide a strong signal if ΔG is large and negative. Given the current state of experiments, such a measurement would provide an important result. Such a measurement is feasible at the luminosities projected in the first p+p run at RHIC for which the HFT would be available. There are technical issues to be resolved including beam bunch resolution and event pileup, but solutions to these problems appear to be feasible. A measurement of A_{LL} in charm production with displaced electrons should be pursued!!"

Reviewer:

"STAR proposes to build a Heavy Flavor Tracker (HFT) comprising three elements: an inner two-layer active pixel sensor array (Pixel) followed by an intermediate single layer of strip detectors (IST) and an outer strip detector (SSD). The scientific questions to be addressed with this detector running in conjunction with STAR after the implementation of the DAQ1000 upgrade are:

- measurement of the total charm cross section at RHIC,
- measurement of the elliptic flow (v_2) of charmed mesons down to very low $p_{t,}$
- charm quark energy loss,
- extension of the measurement of the baryon-to-meson-ratio for particles with charm,
- bottom meson production,
- and D-hadron correlations.

"I will not comment on potential measurements to be addressed with the HFT within the spin physics program at RHIC.

"All of the goals stated above have been identified by the scientific community as the prime motivation for the upgrade of existing RHIC detectors and continued RHIC running at high luminosity. The proponents of the HFT proposal have demonstrated that they will be able to perform a good measurement of R_{AA} and R_{CP} as well as v_2 for charm quarks over a broad range of p_t. Such a measurement will shed light on the time scale for thermalization in the RHIC energy regime. Moreover, the measurement of the total charm cross section down to very low transverse is of great theoretical interest. While these measurements are also performed via semi-leptonic decays, those bear much larger systematic uncertainties, which can be ruled out by the proposed measurement of complete topological decays with particle identification.

"While the goals stated above appear reasonable the collaboration has not produced tables detailing the expected harvest of charmed mesons, baryons, etc. for the first three years of running. A careful analysis of the D and Λ_c production is necessary to clarify the production mechanism of baryons vs. mesons emerging from hot and dense phase. This would help in the assessment of the prevailing coalescence picture for the formation of hadrons.

"Again, following the performance analysis of vertex detectors of other experiments it appears reasonable that STAR will be able to perform the anticipated measurements in the b-sector. However, the proposal is lacking numbers consolidating such a statement.

"The proposal also addresses the investigation of DDbar angular correlations. This has not been further detailed during the presentations although this potentially is an important probe for the thermalization of heavy quarks in the medium."

Reviewer:

"The STAR collaboration identified three deliverable science goals for the first three years of RHIC running with the HFT upgrade: (1) precision p_T spectra of D_0 and $v_2(D_0)$ in A+A collisions; (2) p_T spectra of D_0 in p+p collisions; and (3) Λc measurement in A+A collisions. The proposal also discussed various other measurements that can be achieved with the HFT upgrade.

"Being able to achieve these three science goals is very significant for understanding QCD dynamics, in particular, at extreme temperature and energy densities. The precise p_T spectrum of D_0 production in p+p collisions can help explore the QCD perturbative dynamics to produce charm quarks and QCD nonperturbative mechanism for the charm quarks to become charm mesons and baryons. The spectrum in A+A collisions can provide critical test of the existing theory of parton energy loss and jet quenching, and help extracting the properties of the strongly interacting QCD matter produced at RHIC. The precision measurement of $v_2(D_0)$ in A+A collisions for a wide range of p_T will provide direct information on the flow of charm mesons, which could be caused by the flow of charm quarks or the strong drag of light quarks. In combination with the flow measurement of heavy quarkonia and light hadrons, the flow of charm mesons could provide the critical hadronization information of these heavy-light QCD bound states, as well as the information on the flow of charm quarks and the nature of partonic thermalization if it took place. The measurement of Λc in A+A collisions can provide the first look of the baryon-meson ratios in the heavy flavor sector and new information on the hadronization of QCD heavy flavor bound states.

“Early RHIC results strongly indicate the creation of a dense and hot QCD matter with very interesting properties. Characterized by its opacity to jets and other evidences, the new QCD matter shows an unprecedented energy density well above the critical value predicted by lattice QCD for establishing quark-gluon plasma (QGP), a weakly coupled gas of quarks and gluons. On the other hand, the data from the observation of an unexpectedly large flow of hadrons indicate that the hot QCD matter interacts strongly with itself and behaves like an almost ideal liquid with low shear viscosity rather than a gas of quarks and gluons. These observations, as well as the contradictions to our current knowledge and understanding, have not yet had any fully consistent and satisfactory theoretical explanation due to the enormous complexity of QCD in the regime of strong coupling, even though a few promising approaches have started to emerge.

“Experimental measurement of the jet quenching (suppression of the leading light hadron) combined with the existing theory of parton energy loss provided the yet strongest evidence for the creation of dense and hot quark-gluon matter in relativistic heavy ion collisions at RHIC. “However, the observation of similar suppression of heavy quark mesons (from the measurement of non-photonic electrons) posed a strong challenge to the current theory of parton energy loss. The precise p_T spectra of D-mesons that the STAR collaboration is capable to measure with the HFT upgrade will provide the much needed and accurate information on the suppression of heavy quark mesons and provide the critical test of the current theory of parton energy loss. Understanding the theory of parton energy loss and jet quenching is critical for extracting the energy density of the hot medium produced in central gold-gold collisions. For many years, QCD calculations for p_T spectra of open charm and bottom mesons were far too smaller than Fermilab data. This anomaly in Fermilab data was recently resolved by improvement in theoretical calculations. The well-known 3σ B-meson anomaly was effectively removed by getting more reliable bottom quark fragmentation functions from LEP measurements. The even larger discrepancy in charm meson production was explained by re-summing final-state fragmentation logarithms into theoretical predictions. However, at RHIC energies, the fragmentation logarithms are not expected to be very large.

“But, still, QCD predictions for p_T and rapidity distribution of charm meson production are about a factor of four smaller than the STAR data on D_0 production and about a factor of two smaller than the PHENIX data extracted from the measurement of non-photonic leptons.

“Both STAR and PHENIX collaborations have made some indirect measurements of D_0 production, in particular, based on the p_T distribution of non-photonic electrons. But, the p_T distribution of the electrons is not very sensitive to its parent D (or B) meson’s p_T distribution. The collaboration made a good case for the need of the direct reconstruction of charm mesons.

“In both proposal and the oral presentations, the collaboration made a convincing case that with the HFT upgrade the STAR detector can have a good D_0 reconstruction efficiency from pT ~ 0.5

– 10 GeV. The expected precision of the measurement in p+p collisions will be sufficient to challenge the QCD predictions on charm production and gain new knowledge on the hadronization of charm mesons. The p+p measurement also provides a precise reference cross section for charm production in d+A and A+A collisions. Due to the two-scale nature of the charm mesons, the produced quark-gluon medium in A+A collisions could be a filter to influence the formation of a charm meson in nuclear collisions. A systematic analysis for the precise measurement of D mesons in p+p, d+A, A+A collisions can provide the comprehensive information on both the hadronization and the medium properties. With the upgrade,the STAR collaboration is in a unique position to make such precise measurements of p_T spectra for various D mesons in p+p, d+A, and A+A collisions.

"One of the surprises of RHIC measurements is the momentum space anisotropy of observed hadrons in semi-central gold-gold collisions, known as the elliptic flow or non vanishing v2. For light mesons and baryons, a universal scaling of v_2/n as a function of p_T/n with valence quark number n was predicted by the quark coalescence models of parton hadronization and was found to be consistent with RHIC data. The quark coalescence models assume that the mesons (baryons) are formed by a pair of quark and antiquark (three quarks) with the same momentum and the same constituent quark mass. All gluon degrees of freedom are included in the mass of constituent quarks. The collectivity of quarks in this model is intrinsically built in. Since charm quark mass is much larger than the temperature of the produced quark-gluon system, charm quarks are unlikely to flow with light quarks unless they interacted very frequently with light quarks and were dragged by the thermal light quarks. Due to its mass, heavy quarks should be produced at a very short time. Therefore, elliptic flow of D mesons indicates that the collectivity (or perhaps, the thermalization) of light quarks could be formed in the early stages of gold gold collisions at RHIC.

"With the HFT upgrade and its capability to reconstruct the D mesons at p_T as low as 0.5 GeV, the collaboration is in a position to greatly reduce the systematic error on the D mesons' v_2 measurement. A precise measurement of non-vanishing v_2 for D meson production will be significant for establishing the time scale when the collectivity of light quarks or the quark-gluon medium was formed in gold-gold collisions at RHIC energies. Furthermore, as indicated in the proposal and their oral presentations, the precision of the v_2 measurement can help distinguish the production models of charm mesons.

"In the intermediate p_T region, the ratio of light baryon v_2 over light meson v_2, as well as the ratio of baryon R_{AA} over meson R_{AA}, was enhanced in gold-gold collisions at RHIC. The enhancement was found to be proportional to the collision centrality. This surprising observation was interpreted by quark coalescence models as a result of a collective quark motion in the dense medium produced in gold-gold collisions. Since heavy quark mass is much larger than the typical temperature, it is unlikely to have the charm quark moving collectively with light quarks. Therefore, the ratio of R_{AA} or v_2 for Λc and D mesons provides a unique observable to test any theory for baryon and meson production, and to test the dynamics of heavy quark collectivity.

"The collaboration made a good case that the STAR detector with the HFT upgrade can make good measurements of nuclear modification factor, RAA, for charm baryon, Λc. These measurements when compared with the nuclear modification factor for charm mesons will provide new information on baryon – meson ratios as a function of p_T, and address the difference in baryon's and meson's hadronization mechanism.

"Although the collaboration did not emphasize it in their oral presentations while it was briefly mentioned in the proposal, the new capability of the precision measurement of D mesons can also help enhance the RHIC spin program. The double longitudinal spin asymmetry of the precise D-meson production could provide a complementary measurement of ΔG. With only one proton beam transversely polarized, measurements of single transverse-spin asymmetry, A_N, for production of D mesons could be an excellent observable to probe the gluonic Sivers effect (or the tri-gluon correlation functions) and to get the first look on gluon's "orbital" motion**.**

"In summary, the STAR collaboration made a convincing case that the three identified science goals can be achieved in the first three years of running with the upgraded detector. The science questions that can be addressed by the new precision measurements are very significant and are directly connected to the fundamental dynamics of QCD, in particular, at the extreme temperature and energy densities that can be created at RHIC."

The feasibility of the approach or method proposed to carry out the proposed program:

Reviewer:

"The simulation presentations from the STAR collaboration focused on the critical choices involved in the technologies and segmentation for the STAR pixels and Intermediate Silicon Tracker (IST). STAR is anchored by the large TPC, which is the basis of track reconstruction. The role of the IST, in conjunction with the existing SSD, is to allow extrapolation of tracks from the rather coarse TPC to the precision pixel layers. "Hand calculations", based on resolutions and track densities, were presented which made a plausible case for the segmentation chosen for the IFT. This segmentation allows tracks to be extrapolated from the TPC to the pixels. The pixels then can be used to provide a precise track segment for extrapolation to the primary or secondary vertex. These hand calculations were then verified utilizing full GEANT simulations of the proposed tracking system. The proponents made a strong case that the proposed detector is well matched to the existing STAR tracker and can successfully extrapolate tracks from the TPC to the pixels.

"The level of detail in the physics simulations for RHIC is constrained by the large overhead inherent in GEANT simulation of complex heavy ion collisions. STAR has chosen to concentrate on a demonstration of its ability to reconstruct D^0 mesons decaying to $K\pi$. For the STAR simulation 10,000 events were generated with a flat pT spectrum of D^0 decaying to $K\pi$ added the events. This allows the STAR group to access both signal efficiency and background levels. The full sample was then modeled by scaling the charm p_T spectrum by $1/p_T^{11}$, correcting for the branching ratio, scaling the background by 10^8 (the projected event sample)/10^4 (the simulated sample) and generating Gaussian distributions for the D^0 signal with the appropriate bin populations. Particle ID was simulated by assuming perfect identification below 1.5 GeV and no identification above that momentum. No vertex chi-square or momentum asymmetry cuts were used to purify the charm signal. Despite the shortcomings of the simulation, I was convinced that it was sufficiently realistic, and the associated cuts sufficiently conservative, to demonstrate the capability of the experiment to reconstruct D^0 mesons. Given the ability to reconstruct significant D^0 signals, STAR should also be able to reconstruct significant samples of D^{+-} and D^*. Although the group made its case for STAR's capability to achieve the central goals of measurements of R_{AA} and elliptic flow of D mesons, the committee felt that the case could be sharpened by increasing the sophistication of the simulations and associated analysis and recommended increased efforts to refine the physics simulation.

"The plan for a two-phase upgrade, with initial deployment of a system that covers a fraction of the solid angle with slower detectors, is a good one; which will allow the group to get experience with pixel operations as the final detector is assembled. The detectors are sufficiently similar that duplication of effort will be small. This plan has the advantages of gaining operating experience, driving the development of operations and analysis software, and the possibility of a significant increase in physics capabilities for STAR early in the upgrade project."

Reviewer:

"The proposed Heavy Flavor Tracker for STAR provides unique topological identification for the decay of charmed hadrons. The simulations were optimized for the detection of neutral D-mesons. Given the fact that all charged D-mesons have longer decay lengths, the HFT clearly facilitates an unambiguous measurement of the total charm cross section and of the pt-spectra of D-mesons at RHIC.

"The overall layout of the tracker was changed as compared to the original proposal. However, all presented simulations indicate that the respective pointing capabilities of the different layers are all well matched to the subsequent layers as well as to the TPC. From a technical point of view the concept of the HFT fits well with particle identification capabilities of STAR and the readout has been adapted to the capabilities of the anticipated DAQ1000 upgrade of the experiment.

"The proposal and presentations were very much focused on the measurement of charm most notably D0. While production cross sections for beauty are small at RHIC the collaboration should further evaluate the capabilities of the experiment in this respect. Given the large acceptance of the electromagnetic calorimeter it should be possible to devise triggers to enhance the sample of B-decays.

"It has been stated that at the anticipated luminosities track reconstruction in the TPC will be subject to systematic effects caused by the build-up of space charge. Simulations should show how this changes the significance of the D-meson measurement.

"The chosen active pixel sensor design significantly advances detector technology for vertex trackers in demanding heavy ion environments. However, the radiation hardness of such a device needs to be carefully tested. Simulations should further clarify whether it is really necessary to go to the anticipated extremely thin and fragile sensors or whether other services (power, readout, cooling) will finally dominate the overall material budget of the tracker.

"While the pixel detector relies on technique developed in Strasbourg, the Berkeley group was the first one to impressively demonstrate the successful operation of a prototype array under realistic conditions within STAR."

Reviewer:

"The detector as designed appears to be well optimized for the charm measurements. The HFT capabilities are well-matched to the existing STAR detector. The simulation and the estimation of the production rates for the various measurements, presented in the proposal and the oral presentations, are reasonable and could be improved.

"A reliable estimate for the production rate of charm and bottom quarks is crucial for the true event rate. Although the theory and experimental measurements seem to be consistent for the total charm production rate on a logarithmic plot, as shown in Fig. 3, it should be aware that the theory curves have large uncertainties in the choice of the charm quark mass and the factorization and renormalization scales (note: m_c=1.2 GeV used here while m_c=1.3-1.5 GeV used in other plots). Besides, the theory and experimental measurements have not been consistent in differential cross section, such as the p_T spectrum.

"The collaboration emphasized in the oral presentations (not in their proposal) that the new capability of reconstructing heavy mesons will enable them to explore the difference between various parton suppression mechanisms in A+A collisions. They claimed that with the HFT upgrade, they will be able to measure the double ratio of the nuclear modification factors, $R^c{}_{AA}(p_T)/R^bAA(p_T)$, as a function of p_T, and to distinguish the calculation of $R_{AA}(p_T)$ based on the parton energy loss from the calculation based on the classical gravity in 5-D Anti-de Sitter space. The later took the advantage of the holographic AdS/CFT correspondence between the supersymmetric conformal gauge theories and classical gravity in the 5-D space. It is certainly an interesting idea to use the double ratio to enhance the difference between these two calculations. However, with the limited number of reconstructed B mesons at the RHIC energy, much more work and simulation are needed for studying the nuclear modification factor for B mesons at large p_T, where the difference of these two calculations is most visible.

"In their proposal as well as the oral presentation, the collaboration pointed out that with the HFT upgrade, the STAR detector could do a good job in measuring the angular correlation of charm and anticharm mesons in p+p collisions. By comparing with the angular correlations of two light hadrons, such as $\pi^+\pi^-$ or $\pi^0\pi^0$, these measurements could do a good job in testing the short-distance production dynamics of QCD. Measuring the charm angular correlation in A+A collisions could provide an additional test of the jet quenching mechanism. A careful simulation of the charm angular correlation in A+A collisions could be valuable.

"In connection to the recent anomaly of charm production observed by Belle and BaBar collaborations, which were mentioned in both the proposal and the oral presentation to motivate the charm angular correlation, the collaboration should look into the possibility of measuring J/ψ

and D angular correlations. These correlations are closely related to the observed J/ψ-charm anomaly in e+e collisions and will shed some lights on the production mechanism of a heavy quarkonium. Simulation of the feasibility of such a measurement could be very valuable.

“The collaboration mentioned in the proposal and the oral presentation its unique capability to reconstruct the Λc baryon and to measure its R_{AA}, as well as Λc/D, the charm baryon-meson ratio. These measurements are very important for exploring the similarity and difference in the production mechanisms between the baryons and the mesons. The collaboration should expand its effort in simulation to explore this unique capability of the STAR detector with the HFT upgrade.

“In the proposal (not in the oral presentation), the collaboration also discussed the potential to measure the gluon polarization, ΔG, by measuring the double longitudinal spin asymmetry of the D-meson production. Existing measurements from RHIC and semi-inclusive deep inelastic scattering indicate that ΔG could be small. An independent as well as complementary measurement from the charm production could be very valuable. Additional effort on the simulation and the feasibility should be encouraged.

“Although it was not mentioned in the proposal or the oral presentation, it might be very interesting to look into the feasibility of measuring the single transverse-spin asymmetry of charm meson production. The asymmetry is directly proportional to the so-called gluonic Sivers effect, or the tri-gluon correlation functions in the twist-three factorization approach. Such measurement could provide the first and clean look of the gluon’s “orbital” motion. A simulation of the feasibility should be encouraged.”

The impact of the planned scientific program on the advancement of nuclear physics in the context of current and planned world-wide capabilities:

Reviewer:

“The proposed measurement suite, in particular the reconstruction of hadronic decay channels of numerous charm meson decays, will be unique at RHIC. In terms of comparison to theoretical predictions this will certainly be an improvement over heavy flavor measurements via semi-leptonic decays because the charm meson state will be known, there will be no contamination from bottom decays, and the charm meson carries more direct information about the charm quark than does the resulting decay lepton. The scientific impact of this improvement is not well articulated. This is not a criticism of the proposal, but rather one of the theoretical work on this subject.

“Bottom measurements, via semi-leptonic decay channels, and di-lepton measurements are proposed. But these measurements will be coming late relative to similar PHENIX measurements. A broad measurement program is discussed at a high level in the proposal, but was not discussed during the presentations. In general more simulations would need to be done to establish the viability of these measurements.

“Measurements similar to those proposed for the HFT will be carried out by LHC collaborations on a similar or earlier timescale. But measurements are RHIC and the LHC are certainly complementary due to the expectation that the hot nuclear medium will be quite different at LHC energies than at RHIC energies.”

Reviewer:

“The RHIC program has a capability to probe the spin structure of the nucleon which is unique. There is no competing facility on the near time horizon anywhere which can make comparable contributions to our understanding of the origin of the nucleon spin. The measurement of the spin properties of heavy meson production with displaced electrons will be an important contribution to this subject. Heavy meson production has the potential to evolve into an important probe of spin structure beyond the properties of the gluons. It is important to develop an understanding of the features of charm meson production in order to move in this direction. The program of reference measurements mentioned above is a step in this direction.

“In spite of the impending launch of the heavy ion program at LHC, RHIC is in a position to continue to make important contributions to our understanding of deconfined quark gluon matter. The systematics of recent results suggest that a triple point in the phase diagram may exist for the sQGP at lower temperatures. RHIC is well positioned to pursue this issue. Furthermore, the presentations to the HFT panel established 3 clear scientific deliverables for the HFT program in the first 3 years of operation.”

Reviewer:

“The scientific program identified by the collaboration in its proposal and the oral presentations will have the strong impact on the advancement of nuclear physics. As mentioned above, the success of this program will address some of the most urgent and fundamental questions facing the interpretation of existing RHIC data.

“The scientific questions that will be better addressed by this program are complementary to those to be examined by the PHENIX collaboration at RHIC. The unique role of the program in testing QCD dynamics in its heavy quark sector in both p+p and A+A collisions will certainly influence the upcoming p+p and A+A programs at the LHC.

“The unique capability of reconstructing the charm mesons could provide the first measurement of the gluonic Sivers function – the gluonic orbital motion inside a polarized proton. Such a measurement could impact the spin program at COMPASS and the possible future electron-ion collider.”

Reviewer:

“The current state of the sensor development and the prospects for funding of the HFT render it highly unlikely at the moment that the tracker will be available before June 2013, i.e. just in time for the run in FY 2014. Based on the planning outlined in the RHIC Mid-term Strategic Plan as provided by T. Ludlam, the VTX of PHENIX will have been operational for three years by then. For the general advancement of science on the issues discussed above, it would be much more desirable to have the tracker ready when the TOF system has been installed in order to fully exploit the highly competitive particle identification capabilities. In general the entire RHIC physics program has very much profited from the fact that both, STAR and PHENIX, have been able to carefully cross-check their respective measurements. At this moment there is a major discrepancy in the measurement of the charm cross section by the two experiments which clearly needs to be resolved.

"By the time the HFT will provide first data current planning foresees that ALICE will have measured all of the above mentioned observables in p+p and A+A collisions at √ snn = 5(14) TeV. This will however make precision measurements at the much lower RHIC energy even more important. It will be most useful to see e.g. how heavy quark energy loss evolves with center-of-mass energy…

"However, with a delay of three years between STAR's and PHENIX's tracker coming on-line, the importance of STAR's measurement could be diminished."

The experimental and theoretical research efforts and technical capabilities needed to accomplish the proposed scientific program:

Reviewer:

"From both the proposal and the oral presentations the collaboration made a convincing physics case for the HFT upgrade. The amounts of theory background, simulation, and experimental preparation are impressive. Sufficient efforts have been made to ensure the success of the proposed scientific program. As mentioned above, some of the proposed measurements, such as those in connection with the B meson measurements require additional theory input and careful simulation.

"Additional simulation beyond the charm meson measurements and those in connection with the three identified science goals will be needed for a sustainable program after the initial three years of running with the HFT upgrade. The effort in B-meson production, charm angular correlation, the spin asymmetry in charm production, etc, could be very valuable and will impact on other experiments."

Reviewer:

"The technology proposed for the pixels is both innovative and appropriate. The physics need for minimal material to limit multiple scattering drives the requirement for thin inner layers. Recently developed CMOS monolithic active pixel sensor technology is easily thinned to 50 microns and has the requisite resolution and signal/noise. Operating conditions at RHIC, with a relatively low data rate and modest radiation load, fit in well with the limited readout speed and radiation tolerance of CMOS MAPS. The STAR group has generated an integrated design, based on the powerful pattern recognition capability of the TPC. The intermediate detectors, the existing SSD and the new IST, are needed to extrapolate the coarse TPC tracks into the pixels. They also provide fast timing resolution, allowing selection of hits that correspond to the correct bunch crossing within the pixels.

"The proposed pixel detector is a challenging device. It depends on successful development of high readout speed, reticle-sized CMOS MAPS devices by IRES Strasbourg with good yield as well as the construction of a low mass support structure and associated cabling. It will take great care to maintain the low mass of the pixel system when details of power distribution, signal cabling, and cooling are designed in detail.

"CMOS MAPS detectors at RHIC have the advantage that the detectors can operate near room temperature without significant degradation of signal/noise. This is primarily because of the modest projected radiation dose. There was some discussion during the review of RHIC running scenarios with radiation doses in proton running well above those considered in the HFT proposal. RHIC management should discuss these scenarios with the experiments and develop a schedule that considers physics goals, detector capabilities, and accelerator performance that can be used for understanding what the radiation dose will be.

"The IST is a more conventional device than the pixels. The group proposes a single layer of pad detectors which utilizes APV25 chips developed for CMS. This will work in tandem with the SSD layers to provide track extrapolations from the TOF into the pixels. The design of the IST has changed fairly recently, going to a single layer with pads from two layers with short strips. The new design is well suited to the intended function of the IST and is a positive development. The group needs to develop a better understanding of support and cooling issues. In particular they need to understand the physics and technical tradeoffs associated with a possible choice of water cooling, which will increase the mass of the IST layer. The impact of additional mass on the performance of the tracker at low momentum should be simulated."

Reviewer:

"The Heavy Flavor Tracker consists of three components, a dual plane silicon pixel inner detector (PIXEL), an intermediate silicon tracker (IST), and an outer existing silicon strip detector (SSD). The assembly is designed to provide the best attainable pointing resolution from the STAR TPC to the interaction point in order to resolve secondary particles, and displaced decay vertices, and to facilitate the complete topological reconstruction of heavy meson decays. The IST will use "conventional technology." The inner PIXEL detector will employ an advanced state-of-the-art CMOS chip technology under development by the IPHC group at Strasbourg which is working in collaboration with the LBL/UCI group. The BNL STAR workers have specified a program of research and development which will lead to a final CMOS sensor design appropriate to operation at RHIC-II luminosities. Most of the detector requirements have already been demonstrated with the MIMOSA-5 chip.

"However, the discussion at the review suggested that there are still uncertainties regarding power dissipation (will air cooling be sufficient), radiation tolerance of PIXEL, and integration time. BNL has carried out important studies of radiation tolerances, but the performance of

PIXEL in particular, which will be subject to high radiation exposures during RHIC p+p running remains an important issue which must be addressed. The current design assumes a 200 μs integrating time for the PIXEL system, which appears to be acceptably short, but given the limitations imposed by event pileup, shorter times remain a desirable objective.

"The primary figure of merit for the HFT is the pointing resolution at the decay/interaction vertex. The design objective of 50μm is at least a factor of 2 more demanding than the FVTX planned for the PHENIX forward tracker. This capability will provide superior capability for reconstruction of decays at very low p_T, a region of strong discovery potential. The resolution of the PHENIX FVTX is expected to be 100μm radially and 300μm along the beam. These pointing resolutions in PHENIX are limited by multiple scattering of material between the primary interaction point and the detector.

"To date, the system performance has been evaluated using a mixture of hand-calculations and some GEANT simulations. The physics reach of large samples of Au-Au collisions were modeled by scaling the D^0 signal and associated backgrounds by the relative cross sections. The work presented to the committee is commendable, but this does not diminish the importance of pursuing the most detailed Monte Carlo simulations possible using the best available event generators.

"The pixel mechanical structure and in particular the insertion support design, is well conceived, and from technical point of view the concept of the HFT fits well with the overall capabilities of STAR. The ambitious design is not without its risks, but if successful it will advance sensor design for vertex trackers in hostile radiation environments."

Reviewer:

"The proposed program focused on the detection and full reconstruction of charmed particles at RHIC, using semiconductor detectors. Precision tracking with semiconductor devices and vertex detectors is an approach which came of age in the 1990's and has been widely used in collider and fixed target experiments since then. In the hadronic environment, the predominant application, to date, has been to the detection and measurement of bottom particles. On average, these have higher transverse momentum and longer decay lengths than charmed particles. Furthermore, bottom particles have been considered the more significant signal in high energy physics both for top detection, and for weak mixing and CP violation studies. In relativistic heavy ion physics the situation is, to some extent, reversed. At RHIC, charmed particles provide a critical signature for the dynamics of the extreme states of matter probed there. None-the-less the production dynamics still result in rather soft transverse momentum for the charmed particles produced. A precision vertex detector aimed at this environment benefits enormously by low mass, to reduce multiple scattering, and high granularity.

"The HFT collaboration has embraced the challenge of developing a detector capable of tracking soft particles in a high multiplicity environment. They have conceived a system which the committee [this reviewer] judged is capable of the full topological reconstruction of charmed final states in relativistic heavy ion collisions.

“In design and conception, this goal is achieved partly by the aggressive use of state-of-the-art microelectronic, semiconductor processing and packaging, and signal processing technology. In particular, the group has spear-headed the application of wafer thinning methods to silicon sensors for particle tracking. Through a long and deliberate collaboration with IPHC Strasbourg they have pursued the development of large scale monolithic active pixel sensors (MAPS) for this application. The design of these devices has evolved to include on-chip data sparsification processing in order reduce readout time and increase frame rate.

“Along with the thinned MAPS technology, the collaboration has embraced the application of high performance composite materials engineering. In particular this has utilized expertise at LBNL which developed for the ATLAS pixel detector program. Again this is an efficient and appropriate use of existing expertise and infrastructure (LBNL has a composites fabrication and engineering facility) which leverages significant prior investment. With regard to design, the pixel mechanical structure, and in particular the insertion support concept, appears to be promising and well conceived.

“Given the wide range of running conditions expected at RHIC-II, radiation damage may be an issue which warrants additional consideration, particularly at 500 GeV. This includes the disposition of the pixels, being easily removable. The utility of heavy flavor tracking at 500 GeV should be clarified.

“While the basic IST concept and technology choices are well motivated, and meet the CD0 level of development, it is clear that many detailed choices still need to be made. This includes cabling, hybrid technology, and ladder mechanics and support.

“The overall design presented, along with the outer IST and SSD layers, and the TPC, should be capable of the required reconstruction performance. Technical components and activities were presented, overall, at a level which meets or exceeds the requirements of a CD0 process.

“STAR at RHIC may be the unique setting for this approach. The STAR TPC provides the kind of large solid angle tracking needed for efficient reconstruction of these states. PHENIX, on-the-other-hand, is developing a vertex detector with relatively (normal) thick sensor which is aimed more at partial reconstruction and a statistical approach to measuring the charm signal. ALICE, at the LHC, like STAR tracks with a TPC, but has opted also for a relatively thick hybrid pixel detector at small radius.”

Reviewer:

“An experienced and capable team has been assembled that seems well matched to the task. The committee felt confident that proposed baseline measurements would be achieved.

“The committee agreed that proposed technical approach was well motivated. A graded approach was taken to minimize cost while retaining pointing ability from TPC to the HFT inner layers. There are significant technical challenges (beyond current state-of-the art) to the extreme thinness required in the two inner layers. However, an appropriate team has been assembled, and it was agreed that the selected approach would be of significant interest to future collider vertex detectors. In general, it was felt that if any detector could make the desired measurements, this detector was it.

"Some significant concerns were raised about the radiation hardness of the sensors. The expected dose rates for different systems at 200 GeV collision energies agreed with CDF and PHENIX measurements. At these levels it was stated that the sensors would need to be replaced annually at RHIC II luminosities. It was stated that this has relatively little impact on the project cost since the sensors are such a small fraction of the total budget. However, the prospect of commissioning a new set of sensors annually struck this reviewer as a daunting prospect. In addition, RHIC II luminosity projections at 500 GeV (which would cause significant radiation damage in a small fraction of one year's run) were essentially discounted with the statement that the RHIC Spin program would not know how to handle multiple interactions within the same beam crossing (a consequence of RHIC's stated luminosity goals). It was pointed out that the radiation hardness of this type of sensor is improving, and perhaps this will be a non-issue by the time the sensors are purchased. However, since a need for an extensive 500 GeV dataset with the vertex was not articulated, perhaps it makes sense to simply leave the detector (at least the innermost layer) out during most or all of the 500 GeV run."

Other issues relating to the proposed upgrades, such as a plan that identifies, as specifically as possible, research groups and leaders who will support and exploit the new capabilities to address the proposed scientific program:

Reviewer:

Workforce

"The manpower estimates that have been provided by LBL and the other HFT groups are consistent with the scale of the project. The groups have experience in these technologies; LBL has extensive experience with the ATLAS pixel system and MIT with the Phobos silicon pad arrays."

Reviewer:

Workforce

"The committee was given a detailed manpower profile for the HFT project in the form of a spread sheet which listed in detail the members of each institutional group participating in the HFT project. This document did not include the activities of the IPHC Strasbourg group in developing the CMOS sensors for the PIXEL detector. The committee judged the manpower effort and the time scale of the project to be "reasonable and adequate" with one qualification. It appeared that at least in one or two cases the contribution of students and post doc's in the testing and fabrication phases of the program were not included. Such efforts could be an important factor in the timely completion of the HFT program and should be part of the manpower profile."

Reviewer:

Management

"This project centers around the efforts of two main teams, LBNL on the inner pixel detector and MIT on the IST. Both teams are very experienced with considerable expertise directly relevant to these technical undertakings. Both teams are backed by extensive technical infrastructure which enables the work required to design and build these detectors. Realistic timescales have been factored in to both efforts.

"In the case of MIT and the IST, silicon experience and infrastructure developed for PHOBOS will be directed at the IST project. The scale of the IST, in particular the number of layers, has been reduced over the past year as a result of a careful evaluation of performance and the role played by the STAR TPC and the existing SSD layer. This reduction makes the IST project all-the-more manageable and do-able with the resources and time available. The team is to be commended on their willingness to benefit from prior developments, for example the existing APV25 chip will be used to read out the detector. The review committee [this reviewer] finds that the management of the IST project will be capable of a successful undertaking here.

"In the case of LBNL and the inner pixel layers, much "new ground" is being covered. This effort represents state-of-the-art in both material reduction and in the application of monolithic active pixel sensors to a high multiplicity collider environment. The LBNL group has taken a leadership role over some significant number of years, in developing the thinned MAPS concepts for relativistic heavy ion physics. The LBNL team has successfully managed large projects within STAR, notably the TPC, and the committee [this reviewer] is confident that the inner pixels will be well managed as well. LBNL as an institution also has considerable experience and expertise in composite materials engineering and fabrication which the inner pixel group will exploit.

"This project and collaboration have been reviewed within the STAR and BNL-RHIC structure on numerous prior occasions. It is clear that a number of comments and suggestions of previous reviews have been considered and factored into the present design. The group has been willing to look critically at project and evolve the design as appropriate.

"In summary, with respect to management, the technical teams and leaders on each aspect are well qualified and supported by strong infrastructure and experience bases. Technical components and activities were presented, overall, at a level which meets or exceeds the requirements of a CD0 process."