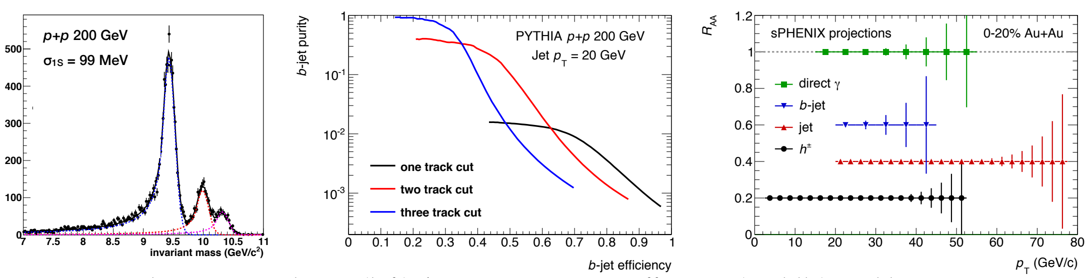
Dear Committee Chair,

In this document we provide responses to the Findings, Comments, and Recommendations in the "Department of Energy Office of Nuclear Physics Report on the Science Review of the sPHENIX Upgrade Proposal." We quote directly from the official DOE Report (in blue), followed by our responses and specific pointers (in red and electronically linked) to updated sections of the proposal document.

We want to thank the Department of Energy Office of Nuclear Physics and the Review Panelists for their timely, careful, and constructive input that we believe has led to a substantially strengthened physics program and proposal document. As iconic indications of the work that has been incorporated into this updated proposal, we show in the figure below three examples of improved and strengthened results that have been developed since the July review.



Upsilon mass resolution (left), *b*-tagging purity vs efficiency (middle), and kinematic reach for direct photons, *b*-tagged jets, inclusive jets, and charged hadrons (right).

We highlight here a few specific items upon which we will elaborate further in our detailed responses and in the updated proposal.

- The perfect fluidity of the Quark-Gluon Plasma is a surprising, emergent phenomenon of QCD. sPHENIX aims to answer how an asymptotically free theory gives rise to such a strongly coupled fluid. Unique capabilities of the experiment will crucially expand the range of length scales and temperatures over which QGP dynamics are known, and will do so in the region of strongest coupling (see Figure 1 of the Executive Summary). sPHENIX will probe this parameter space with a comprehensive and precise set of measurements which will overlap with, and further expand, those explored at the LHC.

- The sPHENIX tracking reference design has been significantly optimized using detailed GEANT4 studies and new pattern recognition software and evaluation tools. We document good efficiency and purity even in central Au+Au collisions and have demonstrated an Upsilon mass resolution of 100 MeV/c^2 (the benchmark suggested by the Review Panel).

- We have optimized the data acquisition rate capabilities, obtained updated luminosity projections from the RHIC Collider-Accelerator Division, and performed detailed trigger studies, which will result in significantly higher statistics being sampled in p+p, p+Au and Au+Au. The increased p+p statistics are particularly beneficial for the Upsilon projections. For events within $|z| < 10$ cm, sPHENIX can record 100 billion minimum bias Au+Au events. For purely calorimetric measurements of jets and direct photons, these updated projections imply sampling of 0.6 trillion minimum bias Au+Au collisions.

- We have carried out detailed beauty-jet tagging studies that indicate robust capabilities for measuring the quark mass dependence of quenching which also benefit from the optimized tracking reference design.

- We have carried out substantial new full simulations on observables that extend the reach of the sPHENIX jet program and incorporate new techniques and jet algorithms. As a specific example, we have access to jet energy distributions out to $R = 0.6$ on the away-side with triggers on narrower jets and direct photons, which selectively sample away-side gluon jets and quark jets respectively.
- We have carried out new full simulations to further evaluate the $p+A$ capabilities of sPHENIX, and based on those, we show very encouraging results for $p+A$ trigger performance and jet and Upsilon physics.

Sincerely,

The PHENIX Collaboration

DOE Recommendation

An expanded proposal to further elaborate the case for sPHENIX should be prepared and submitted to the Office of Nuclear Physics by November 3, 2014. The report should address the following items raised during the review:

1. The physics case for sPHENIX needs to more clearly articulate the improvements in our physics understanding that can be achieved by sPHENIX in the context of ongoing jet physics studies at RHIC and the LHC. This articulation should include a discussion of the capability to use a range of observables to discriminate among different physical mechanisms of jet and heavy flavor production and modification in the QGP.

   We have significantly expanded the discussion relating how specific measurements with sPHENIX at RHIC provide crucial constraints on the temperature dependence, virtuality evolution, and QGP constituents. These are detailed in the three Sections 1.2–1.4. The substantial additional parameter space covered by sPHENIX is further emphasized in both the jet and Upsilon physics case — see Figure 1.18 and Figure 1.51. Full simulations of heavy flavor tagged jets are now included, and these simulations show clearly how such data would add important constraints on the balance between collisional and radiative energy loss. Using the JEWEL parton energy loss Monte Carlo, we also demonstrate that the steeper jet spectra at RHIC compared to the LHC give greater sensitivity to medium parameters — see Figure 1.33. The sPHENIX detector, with the enhanced tracking reference design, is able to address this full suite of observables to overconstrain calculations and gain key insight into the underlying physics.

2. Explore the possibility to provide an unbiased sample of heavy-flavor tagged jets with the vertex tracker in the b sector and, if possible, also in the charm sector.

   We have explored two possible approaches to *b*-jet tagging within sPHENIX in detail. The first method requires a number of charged tracks within identified jets to have a large impact parameter with respect to the primary vertex, indicating that they originate from a displaced heavy flavor vertex. The efficacy of this method depends on the transverse distance of closest approach (DCA) resolution of the tracking configuration. The second method requires an associated electron with a large momentum transverse to the jet axis, preferentially selecting jets containing a heavy flavor hadron decaying semileptonically. This method relies on the ability of the sPHENIX calorimetry to identify electrons with good efficiency while maintaining a high rejection factor against charged pions. In Section 4.7, we describe our studies of the first method, which is the more fully developed of the two approaches we have investigated.

   Although performed at the "truth + parameterized response" level, these studies incorporate the latest GEANT4-based quantitative understanding of the performance of the current tracking arrangement for reconstructing the transverse DCA (Section 3.6) and of the electromagnetic calorimeter for electron identification (Section 3.7) in sPHENIX. By varying the strength of the *b*-jet tagging cuts, we have quantitatively mapped out the trade-off between the *b*-jet selection efficiency and the purity of *b*-jets in the selected jet sample. Furthermore, we have studied how the *b*-jet tagging performance varies in the high-multiplicity Au+Au environment, by evaluating different assumptions of the tracking efficiency and the effect of the underlying event pedestal in the jet cone. The first results are promising and indicate that sPHENIX will be able to select a sample of *b*-jets with high ($\gtrsim$ 50%) purity while maintaining a high enough efficiency to yield a good statistical sample (Figure 4.35).

   Finally, using FONLL calculations of heavy quark production cross-sections and the latest RHIC luminosity projections, we have calculated the projected statistical uncertainties on the nuclear modification factor for b-jets in central Au+Au events. These appear together with projections for photons, light jets and single hadrons in Section 4.10. In the future, these initial studies will be followed up with more sophisticated full simulations of the b-jet tagging performance in $p+p$ and Au+Au events.

We have performed simulations for reconstructing D mesons via the $\pi+K$ decay channel. The good secondary vertex resolution and large acceptance with high statistics allow for a good measurement of the D meson R_{AA} over a broad p_T range. These results are complementary to results expected from the STAR HFT. The advantage in sPHENIX is the ability to reconstruct fully the jet associated with the D meson and the partner momentum-balancing jet in the event. Results on D meson signal to background are shown in Section 4.7.

3. The possibility to further improve the upsilon state resolution and statistics.

We agree that the Upsilon measurements including all three states with high statistics are important. The sPHENIX tracking reference design has been significantly optimized with detailed GEANT4 studies and new pattern recognition software and evaluation tools. We now fully demonstrate very good efficiency even in central Au+Au collisions and have achieved the Upsilon resolution benchmark of 100 MeV/c^2. The statistics are further improved when updated luminosity projections from the Collider-Accelerator Division for both $p+p$, $p+A$, and Au+Au are included. All together we document a substantially improved Upsilon measurement that fully enables constraining the temperature and screening length at RHIC compared with higher energy collision results from the LHC. The updated Upsilon physics case is presented in Sections 1.9–1.10, the updated tracking reference design in Section 3.6, the rates and triggering capabilities in Sections 3.7 and 3.8, and the Upsilon performance plots in Section 4.11.

4. An investigation of areas where more complete simulations may be needed to better understand the measurements proposed, such as studies to quantify the degree to which instrumental effects play a role in discrimination against fake jets.

We have investigated the degree to which detector effects influence the measured underlying event E_T in finite regions of the acceptance by quantitatively comparing the mean and width of its distribution at the true hadron, fast parameterized, and full GEANT4 simulated levels, as detailed in Section 4.4.2. Our studies show that while there are modest differences in the shape of the fast parameterized and GEANT4 simulated distributions, the broad features of the underlying event E_T distributions are driven by event to event fluctuations in the underlying event and not the details of the detector resolution.

We have also carried out additional full GEANT4 simulations of jet purity when looking at the away-side jet opposite a trigger hadron, a narrow $R = 0.2$ jet, or a direct photon. These results detailed in Section 4.6 indicate good purity over a broad range in jet radius and energy with the GEANT4 detector simulation and detailed underlying event subtraction applied.

5. A study of the limits on physics imposed by the limited eta range and whether some instrumentation at larger eta would increase the scientific reach and be cost effective.

As detailed in Chapter 2, the containment of the away-side jet and hadronic fragments for trigger jets or direct photons above $E_T = 20$ GeV is greater than 80%. As the jet E_T increases, the containment fraction rises and thus the acceptance of $|\eta| < 1.1$ is a good match to the kinematics at RHIC. The underlying event characterization appears to work quite well and utilizes exactly this coverage. Before the acquisition of the BaBar solenoid, the sPHENIX concept was based around a purpose-built magnet and had calorimeters and tracking providing the same $|\eta| < 1.0$ acceptance as in the current reference design.

That said, new physics capabilities would be opened up with more forward coverage. We divide this extended coverage into two categories. One option is to instrument the endcaps, which in the current design are passive steel doors helping to return the magnetic flux of the solenoid. Initial GEANT4 simulations using the endcaps as hadronic calorimeters are detailed in a new Appendix A.

These simulations indicate that in $p+p$ and $p+A$ collisions at 200 GeV, one can reconstruct jets with a relatively simple hadronic calorimeter design over at least an additional two units in pseudorapidity $|\eta| = 1$–3. This extended coverage is particularly interesting in light of recent results from ATLAS and CMS which indicate an unexpected centrality dependence in the rate of high-p_T inclusive jet and dijet production in p+Pb collisions. The indication from the experimental data is that the rapidity dependence of the effect may be the key to understanding the underlying physics responsible for the modifications. Thus, analogous measurements in p+Au collisions at RHIC with a large lever arm in rapidity may help crucially to clarify the picture.

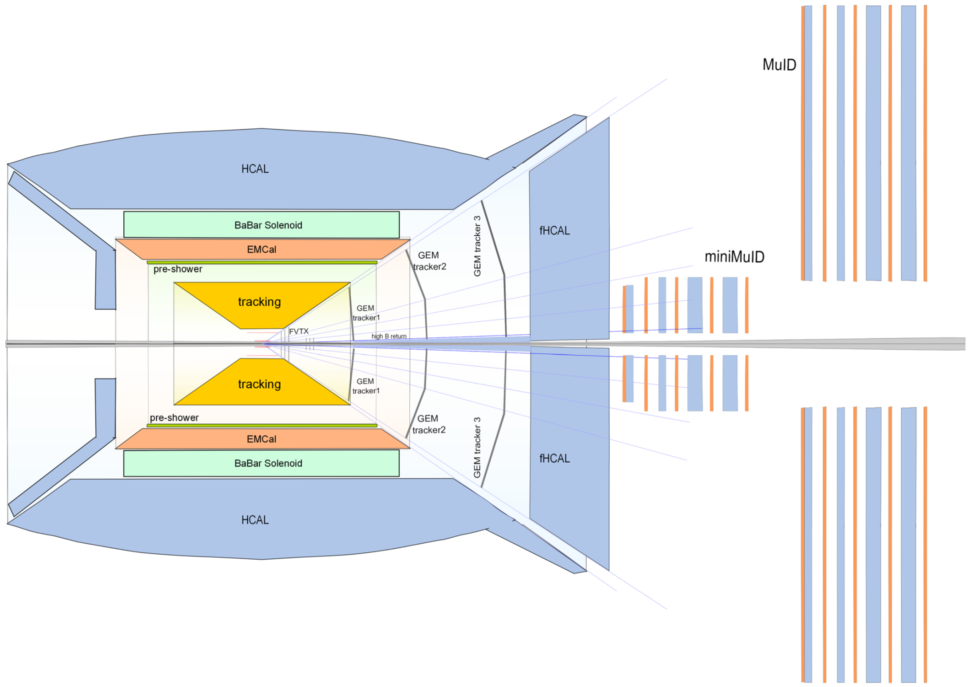
In addition, in heavy ions, the extended coverage allows for reaction plane characterization, and additional handles on the underlying event which are further removed from observables at mid-rapidity. Note, however, that within the ATLAS-style underlying event subtraction algorithm that we have used, the subtraction is done in slices in pseudorapidity and thus does not explicitly benefit from this coverage.

There is strong collaboration interest in such additional calorimeter coverage, and specifically the RIKEN group in Japan is working towards a full design.

Additional tracking in the forward pseudorapidity range is another option. We have previously documented such a forward spectrometer focused on transverse spin physics (see the fsPHENIX White Paper, http://www.phenix.bnl.gov/phenix/WWW/publish/dave/sPHENIX/pp_pA_whitepaper.pdf). The limit on how far from the interaction point one might locate a forward spectrometer arm is informed by the current Electron-Ion Collider (EIC) design, where the nearest magnetic focusing element is 4.5 m from the nominal collision point along the beam line. As detailed in Appendix B of the proposal, there is a strong potential for the sPHENIX detector to be utilized as the basis for an EIC detector and thus these boundary conditions are important. In order to have sufficient magnetic bending for momentum reconstruction with tracking, the flux return design incorporates a lamp-shade design as shown in Figure 1 of the fsPHENIX White Paper (reproduced below). This then incorporates GEM tracking. The cost of such an upgrade is currently being fully evaluated and is a substantial enough modification that we do not consider it in this reference design.

6. The limitation to data rates of 10 kHz in AuAu and prospects for increasing that rate. Similar considerations extend to pp.

Updates on the sPHENIX data acquisition Level-1 trigger rate limitations and RHIC Collider-Accelerator luminosity projections are detailed in a new proposal Section 3.8. For Au+Au collisions, the luminosity projections are higher than what was achieved in Run-14 by approximately a factor of 2.5; for $p+p$ collisions the updated luminosity projections are a factor of almost 6.5 higher. The new reference tracking design no longer incorporates the existing PHENIX strip-pixel silicon layers which have a significant radiation thickness and also limit the data rates to less than 10 kHz. The inner silicon pixel layers have been tested with readout Level-1 rates in excess of 15 kHz. A new sPHENIX reference bandwidth of 15 kHz is now specified. This rate is consistent with the current calorimeter electronics design and the overall global Level-1 architecture. The rate is also a reasonable match to the delivered luminosity within $|z| < 10$ cm in Au+Au and provides sufficient bandwidth for selective triggering in $p+p$ and $p+A$ collisions, with additional details



Schematic view of the combined sPHENIX/fsPHENIX detector, showing the location of the vertex tracker, intermediate tracker, HCal, MuID, and piston field shaper in the forward region.

provided in Section 3.9. Significantly extending the Level-1 rate beyond 15 kHz incurs a large additional cost and with only modest physics gain for minimum bias trigger samples.

7. An investigation of alternate jet observables and background suppression techniques that would enhance the useful range of jet finding with jet radii > 0.2.

There is important information on the parton shower evolution and medium interaction encoded in the single inclusive jet spectra and even more in differential measurements, for example dijet, γ-jet, hadron-jet, and hadron-hadron correlations. For single inclusive jet spectra, as documented in Section 4.4, for measurements in a relatively background free region (i.e., low fake jet contributions), one is restricted to smaller jet radii or higher energies in the most central Au+Au collisions — approximately $E_T > 20$ GeV for $R = 0.2$ and $E_T > 40$ GeV for $R = 0.4$. Note that as soon as one moves away from the most central events the range of accessible jet energies and radii increases rapidly, which is also a significant physics interest — see for example Figure 1.10.

As the Panel Reviewers note, there are two approaches for extending these inclusive jet ranges in the most central events. One is to apply "fake jet" rejection criteria, which include: (i) requiring a minimum p_T for all constituents; (ii) requiring a track jet match with some minimum p_T constituents; (iii) applying a jet shape selection; (iv) requiring some away-side jet with an opposite axis match; (v) requiring a large core electromagnetic energy; and others. All of these criteria introduce at some level a bias for rejecting real jets that are highly modified in the medium. We have explored the second rejection method with matching of a charged track jet as employed by the ATLAS collaboration, and this is detailed in Section 4.5. In fact, since sPHENIX will have a very large sample of unbiased jets in p+p (see the trigger details in Section 3.9) and in Au+Au from minimum bias triggers, we will be able to employ all of these methods for comparisons and cross-checks. The ability to incorporate charged track information into the jet algorithms, see Section 4.2, allows for a full suite of surface bias engineering measurements over a much broader range of jet energies and R values by applying p_T selections.

Additionally, much of the physics information can be more cleanly obtained through correlation measurements — with the best example being γ-jet and γ-hadron correlations. We have detailed with full GEANT4 simulations a set of these results in Section 4.6. We also highlight that models such as JEWEL predict very large away-side jet radius dependencies from $R = 0.2$–0.6, shown in Figure 4.31, that can be measured with precision by sPHENIX.

Significance of Science Questions

Findings:

The sPHENIX collaboration proposes to construct a large-acceptance, high-rate detector for relativistic heavy-ion physics, incorporating electron and photon identification, a vertex tracker, and full calorimetric coverage at central pseudo rapidity, |eta| < 1.1, and with a 1.5-tesla solenoidal magnetic field. Data taking would occur in 2021 and 2022. A key capability of sPHENIX is the possibility to collect large unbiased jet samples in AA and minimally biased jet samples in pA collisions with a minimum-bias trigger. Precision tracking enables the identification of heavy-quark flavors.

The collaboration proposes to study jet quenching to elucidate the mechanisms for parton transport and energy loss within the quark-gluon fluid, using jet, dijet, and photon-jet probes in Au-Au, p-Au, and p-p collisions. In addition, sPHENIX would map the characteristics of quarkonium melting and recombination by studying the relative production rates of the three narrow Upsilon vector mesons in pp, p-Au, and Au-Au collisions. The proposed measurements complement the results obtained by the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) in a new kinematical regime, where the production of b-bbar pairs is significantly lower than at the LHC.

Comments:

The concept of a high rate detector focused on jet physics, capable of recording a very large sample of min-bias events, is compelling, and the collaboration with such a detector could potentially carry out a science program of very high impact and merit.

The phenomenon of jet quenching offers a tool to probe the nature of the quark-gluon medium that may reveal the relative importance of collisions and excitation of the medium as energy-loss mechanisms and help determine the composition of the medium. Jet measurements at the Relativistic Heavy Ion Collider (RHIC) would explore regimes of temperature and length scales that complement those accessible at the LHC. The comparison of results from RHIC and the LHC will shed light on the interpretation of quarkonium yields in both energy regimes.

The measurement of jets and jet correlations to study energy loss mechanisms, parton shower formation and propagation in strongly interacting matter, including the flavor dependence, and quarkonium melting address central issues in relativistic heavy ion physics.

Recommendations:

None

Impact of the Scientific Program

Comments:

The proposed sPHENIX detector and its planned program have a strong potential to impact important science questions.

A very attractive aspect of the sPHENIX proposal is the capability to collect jet physics data in an untriggered mode. The application of jet quenching to the measurement of the properties of the Quark-Gluon Plasma (QGP) is compelling and of broad interest. However, fundamental issues in this area remain open at present. An essential component to address these issues is a comprehensive set of jet measurements in heavy ion collisions at RHIC, which is to be carried out over the next 10 years. The panel feels that the proposed sPHENIX detector, combined with other measurements at RHIC, must address the full scope of such a comprehensive program.

We have documented a much more comprehensive program fully utilizing the capabilities of the RHIC accelerator and the sPHENIX detector, also now incorporating the updated tracking reference design. In particular, we highlight in Figure 1.51 the kinematic reach of the sPHENIX measurements, including for beauty-tagged jets. The broad p_T reach significantly extends what has been measured at the LHC, and critically with overlap in p_T and reconstructed techniques between RHIC and the LHC.

The increased precision of the Upsilon program is now documented. The ability to measure beauty-tagged jets is now documented. We also highlight a broader suite of jet capabilities that increase the range of jet energies and radii and note their sensitivity to the different models of medium coupling, radiative and collisional energy loss, and virtuality evolution in the medium. We have documented our ability to collect a large unbiased jet sample in $p+p$ and Au+Au collisions over the full centrality range, which then enables detailed surface bias engineering measurements that are very sensitive to details of the parton-QGP interactions — see Section 4.6 for example.

We have also carried out projections for the full jet and Upsilon programs in proton-nucleus collisions — see Sections 4.8 and 4.11. This is a rich program that is no longer considered a simple extended cold-nuclear matter baseline.

The proposal details many areas of interest such as jet-jet and photon-jet correlations, but leaves open other important issues such as: is there a parton flavor dependence of the energy loss? The measurement of the energy dependence of charmonium production from RHIC to LHC energies has provided significant new insights, and hence we expect similar impact in the analogous b quark sector.

As detailed in our response to DOE Recommendation Item #2 above, we have explored two promising approaches to the identification of beauty quark-initiated jets within sPHENIX. In Section 4.7, we discuss a workable b-jet tagging approach based on the identification of charged tracks with a large impact parameter with respect to the primary vertex. These studies, together with the latest projections of the luminosity delivered by RHIC, would allow sPHENIX to study the energy loss and other modifications of b-jets. The projected statistical reach for the light jet and b-jet R_{AA} values as a function of p_T in central Au+Au events is shown Section 4.10.

The suppression of the upsilon (Υ) states in Pb-Pb collisions compared to pp results has been measured at the LHC with significant precision. Because of the very different number of b-quarks in the QGP fireball at LHC and RHIC energies it is very important to have a similar quality measurement at RHIC, in pp as well as AuAu, with sufficient resolution to resolve the 3 Υ states and with sufficient statistics to also explore the transverse momentum dependence of the effect. The latter has not yet been measured at the LHC but is crucial to the understanding of the data. The resolution and statistics demonstrated by sPHENIX for the Υ measurements seem not yet fully optimized and possibly marginal to achieve these goals. The collaboration should explore all options to get the resolution for the Υ measurement into the 100 MeV range. This may be achieved by improving the tracking and analysis techniques, but also by rearrangements of the hardware in the vertex tracker. Furthermore, Υ statistics may be improved by recovering some of the events outside the ± 10 cm vertex cut or by triggering. An important priority for sPHENIX should also be the measurement of the transverse momentum dependence of the suppression. Care needs to be taken to get enough statistics for all three Υ states also in pp collisions.

As detailed in our response to DOE Recommendation Item #3 above, a fully updated set of Upsilon performance plots are presented in Section 4.11. The 100 MeV mass resolution is achieved with this new tracking reference design and using optimized pattern recognition software and Kalman track fitting. Relative to the earlier proposal document, from a combination of increased Level-1 trigger bandwidth and updated accelerator luminosity projections, the $p+p$ statistics are increased by nearly an order of magnitude and the Au+Au statistics by a factor of two. We believe these are more than sufficient to deliver the physics.

The updated reference tracking design maintains the inner silicon pixel ladders whose coverage extends over $|z| < 10$ cm. One could consider replacing these inner ladders with a new, three-layer pixel detector with larger z coverage. One option would be to employ the STAR Heavy Flavor Tracker technology with higher speed readout, though having this extend over a larger z-vertex coverage than the STAR HFT of $|z| < 5$ cm would entail significant cost. At this point, we believe funds are best optimized for the resolution and efficiency within the $|z| < 10$ cm range, as we have done in the proposal.

We have included specific projections for the transverse momentum dependence of the Upsilon suppression — see Figure 4.46. Also, the $p+p$ reference statistics are no longer a limiting factor for the Upsilon measurements — see the documented higher luminosity projections and Level-1 trigger capabilities in Sections 3.8 and 3.9. We also highlight the growing physics interest in making such quarkonia measurements in proton-nucleus collisions — see Section 1.10 and the sPHENIX performance in Figure 4.49.

The physics case for sPHENIX needs to more clearly articulate the improvements in our physics understanding that can be achieved by sPHENIX in the context of ongoing jet physics studies at RHIC and the LHC. Some plots showing the increased phase space were presented, however this point could be better emphasized. The case would be improved by presenting the physics case in a way that highlights the unique features of sPHENIX and summarizes the measurements that can only be done by sPHENIX as well as indicating how well the data will be able to constrain or rule out existing theories.

To better emphasize the increased kinematic range for high-p_T probes of the QGP available to sPHENIX within the first two years of running, we have included Figure 4.43 in Section 4.10 which shows the projected statistical uncertainty on R_{AA} in central Au+Au events for photons, inclusive jets, b-quark jets and charged hadrons. The figure illustrates the substantial increase in phase space that sPHENIX would provide for measurements of jet quenching at RHIC.

We have added a discussion, illustrated by several new figures, of how the steeper p_T spectrum at RHIC and the different medium evolution result in greater sensitivity to medium coupling and the detailed evolution. Direct photon-jet correlations detailed in Section 1.7 are an excellent example. Also, the difference in virtuality evolution is manifestly different at RHIC and the LHC in Figures 1.16 and 1.18. Figure 1.33 with JEWEL calculations for a host of quantities indicates where key observables — such as, jet and charged hadron R_{AA}, modified jet fragmentation functions, jet azimuthal correlations, dijet asymmetry, and dijet nuclear modification — show greater sensitivity at RHIC compared to the LHC, and, in some cases, would be uniquely measured at RHIC by sPHENIX.

Recommendations:

An expanded proposal to further elaborate the case for sPHENIX should be prepared and submitted to the Office of Nuclear Physics by November 3, 2014. The report should address the following items raised during the review:

The physics case for sPHENIX needs to more clearly articulate the improvements in our physics understanding that can be achieved by sPHENIX in the context of ongoing jet physics studies at RHIC and the LHC. This articulation should include a discussion of the capability to use a range of observables to discriminate among different physical mechanisms of jet and heavy flavor production and modification in the QGP.

Explore the possibility to provide an unbiased sample of heavy-flavor tagged jets with the vertex tracker in the b sector and, if possible, also in the charm sector.

As detailed in our response to Recommendation Item #2 above, we have explored the feasibility of b-jet tagging based on the identification of charged tracks in the jet with a large transverse impact parameter relative to the primary vertex. These studies incorporate our updated understanding of the performance of the tracking configuration in sPHENIX, based on full GEANT4 simulations. The initial results, detailed in Section 4.7, are promising and indicate that sPHENIX will be able to select a high-purity sample of b-quark initiated jets with good statistics using this method.

The possibility to further improve the upsilon state resolution and statistics.

See details in our response to Recommendation Item #3 above. The fully simulated Upsilon resolution of 100 MeV/c is achieved (the benchmark suggested by the Review Panel) and the statistics are improved. Fully updated performance projections are given in Section 1.9.

An investigation of areas where more complete simulations may be needed to better understand the measurements proposed, such as studies to quantify the degree to which instrumental effects play a role in discrimination against fake jets.

See details in our response to Recommendation Item #4 above.

A study of the limits on physics imposed by the limited eta range and whether some instrumentation at larger eta would increase the scientific reach and be cost effective.

See details in our response to Recommendation Item #5 above.

The limitation to data rates of 10 kHz in AuAu and prospects for increasing that rate. Similar considerations extend to pp.

See details in our response to Recommendation Item #6 above.

An investigation of alternate jet observables and background suppression techniques that would enhance the useful range of jet finding with jet radii > 0.2.

See details in our response to Recommendation Item #7 above.

The New Experimental and Technical Capabilities Needed

Findings:

A description of the detector requirements was presented that was motivated by the physics program and the key observables. The detector design was outlined, including details such as silicon photomultipliers (SiPMs) used to readout the calorimeter. The performance of parts of the detector has already been evaluated in test beams. Monte Carlo (MC) studies were presented for physics object reconstruction such as jets, photons, electrons, and upsilons. In addition, simulation results were presented for jet reconstruction using the anti-kt clustering algorithms for different radius parameters.

Comments:

The detector design appears to be basically sound and able to meet the physics objectives as presented. The design choices use existing technology and do not require significant Research and Development (R&D) giving confidence that they can be successfully implemented. Optimization of some components could potentially improve the physics performance. For example, the design reuses the BaBar magnet which imposes some limitations on the eta coverage, and the location of the vertex layer could benefit from further study.

The CMS Phase 1 upgrade will make use of SiPMs for the hadronic Barrel and EndCap calorimeters, and there have been significant advancements in SiPM technology. In particular the quantum efficiency and radiation tolerance have been improved. A market survey will be needed to ensure that a suitable SiPM device is chosen.

We agree and have worked up a detailed market survey of SiPMs. In addition, we are closely coordinating with the CMS collaboration and their development work with SiPMs.

The jet reconstruction method presented does not make use of the track information. The possibility of making use of the track information to help improve the jet reconstruction performance should be explored. There are track+calorimeter based algorithms as well as particle flow algorithms that may provide a significant improvement in the reconstructed jet. In addition, alternate methods for underlying event mitigation exist. Exploration of these alternatives should be conducted to determine whether these new methods can extend the performance of sPHENIX.

With the new reference tracking configuration, the momentum resolution and track efficiency is quite good even in central Au+Au events. Thus, incorporation of the tracking into different jet algorithms is beneficial. We have had extensive exchanges with CMS experts on particle flow including Florian Beaudette, Matt Nguyen, and Gunther Roland. It is well documented that the jet energy resolution improves substantially in p+p collisions in CMS from the particle flow algorithm, via contributions from the corrected momentum vector of the track compared to the calorimeter clusters in the strong magnetic field, the much better tracking resolution compared to the hadronic calorimeter up to very high momentum, and the ability to select charged tracks as coming from different collisions occurring in the same beam crossing. There is no apples-to-apples comparison in the Pb+Pb environment to demonstrate the improved jet resolution from CMS. One expects that the improvement is much less significant as the ability to match tracks and clusters where the cluster does not have significant multi-particle contributions is reduced.

In order to evaluate the benefit of the particle flow algorithm at RHIC, we have implemented an updated clustering algorithm for the sPHENIX calorimetry, and we have implemented a first pass particle flow algorithm; the details are described in the Section 4.2. We currently find modest resolution improvement and are developing more sophisticated iterative algorithms. This algorithm allows one to select specifically on track constituent p_T, while preserving the calorimetric measurement of neutral particles with greater hermeticity.

We had previously implemented a pure track based jet algorithm and utilized that for "fake jet rejection", as detailed in Section 4.5. With the new tracking reference design having tracking resolution better than, and the electromagnetic calorimeter having resolution comparable to, STAR we have also implemented a track + EMCal algorithm. This gives sPHENIX the powerful ability to span this full suite of algorithms that have different sensitivities and systematic uncertainties, and enables comparison with other experimental results at RHIC from STAR, and LHC from ALICE, ATLAS, and CMS.

It appears that some studies were done using a parameterized detector simulation and not a full GEANT simulation. Some features like energy sharing across calorimeter cells may affect isolation variables. The effects of the tracker material may not be properly taken into account by the parameterized studies. Fake jets may not be properly simulated. Future studies should make sure that any key conclusions from the studies are not strongly dependent on having a full GEANT simulation.

See details in our response to Recommendation Item #4 above. With the updated detector reference design we have simulated more than 10K full HIJING events passed through the full GEANT4 model of the sPHENIX detector. Note that the HIJING events are with quenching effects turned off such that local mini-jet fluctuations are significantly larger than expected in real data. We have performed studies of how the underlying event (UE) E_{T} distributions in HIJING Au+Au events in finite-sized regions may differ when moving from a parameterized detector response to a full GEANT4 simulation. These are detailed in Section 4.4.2. The results indicate that although there are modest changes in the shape of the UE E_{T} distributions, the shape is dominantly controlled by the role of event-to-event fluctuations rather than the details of the detector response. Thus, we believe that our key conclusions regarding the role of the UE in determining the jet performance are robust.

Recommendations:

None

New Theoretical Efforts Needed

Findings:

The sPHENIX jet physics program is motivated by precision determination of the properties of the QGP including: (a) transport parameters, sheer viscosity to entropy density; (b) the nature of the medium quasi-particles; and (c) non-trivial behavior at different length scales and discrimination between weak coupling and strong coupling.

Comments:

The theory community should quantify the enhanced sensitivity of near-threshold (high transverse momentum) jet production to the QGP properties.

The sPHENIX jet physics program is facilitated by emerging theory tools: a host of Monte Carlo parton shower codes, higher order calculations, and effective field theory approaches (SCET). Current theoretical efforts have an overemphasis on medium modeling and phenomenological parameter tuning in contrast to mock-up applications of energy loss or medium-induced parton showers not based on rigorous theory in Monte Carlo codes. For jet and heavy flavor applications there is a need to put the emphasis back on field theory and QCD factorization. These should be priority areas for the next generation heavy ion theorists who should seek input and expertise from particle physics. The theory community is encouraged to incorporate recent advances in perturbative quantum chromodynamics (pQCD), SCET results into the largely phenomenological Monte Carlos, and advance traditional energy loss approaches to treatment of vacuum and in-medium parton showers on the same footing.

The collaboration should assess the potential of reconstructed jets in the region of T = (1-2)Tc to probe the medium and its properties beyond what can be learned through inclusive hadrons from the Beam Energy Scan (BES) (and upcoming BES II). Singular behavior of the transport coefficient near Tc is strongly disfavored in some theoretical calculations.

We have included additional discussion of mapping out the temperature and virtuality evolution dependence, and the key role of sPHENIX measurements in Sections 1.2–1.4. We emphasize that extracting the temperature dependence of the medium coupling is a goal, and that this may (or may not) in the end support a surprising enhancement near the transition temperature. We agree that while a number of recent calculations favor this enhancement (as detailed in Section 1.2), others favor only a running of α_s to provide a description of the current data.

Full confrontation of data at lower energies is necessary including for example the PHENIX published neutral pion R_{AA} at $\sqrt{s_{NN}} = 39$, 62, and 200 GeV, though caution is warranted since there are significant uncertainties from the p+p reference and a lack of proton-nucleus data at the same energies. Full jet observables at lower energies and in lighter ion systems are discussed in Section 4.9 and would enhance the overall sPHENIX program if sufficient running time is available. We note that the BES II at RHIC is focused on collision energies below 20 GeV and is thus unlikely to shed light on these hard process questions.

The collaboration needs to revisit the important jet observables that have become available after the ATLAS and CMS measurements and explore the discriminating power of a jet radius scan, intra-jet observables (jet shapes, fragmentation functions), photon-tagged momentum imbalance with respect to theoretical models and the 3 axis of interest (a),(b),(c) beyond qualitative discussion.

Each of the three Sections 1.2–1.4 on the three axes of temperature, length scale, and virtuality evolution has been significantly expanded with detailed theoretical calculations for observables sensitive to the underlying physics. We then detail the precision measurements enabled by sPHENIX to address these questions. For example, the virtuality evolution has clear implications for the flatness or rise in single hadron R_{AA} over the broader p_T range out to 50 GeV/c. sPHENIX with calorimetric triggering in $p+p$ and high statistics in Au+Au will make just such precise measurements as shown in Figure 1.51. Similarly, the question of path length dependence and stronger coupling at RHIC is directly addressed through the reaction plane dependence observables, with sPHENIX projections for reconstructed jets shown in Figure 1.10.

sPHENIX has the potential to provide unique insight into the physics of cold nuclear matter effects on the Upsilon states, discriminate between co-mover dissociation and initial-state effects. However the case for heavy flavor physics is not well developed in the proposal, and the full scope of detector capabilities is not utilized. More detailed simulations could provide projected discriminating power with respect to theoretical models of heavy flavor dynamics.

See details in our response to Recommendation Item #3 on the Upsilon physics above, and details in our response to Recommendation Item #2 on the beauty-tagged jet physics above. We have added a new discussion in Section 1.9 on the physics of Upsilon measurements in proton-nucleus and demonstrate the sPHENIX measurement capabilities in Figure 4.48. We have also added a new discussion on the jet program in proton-nucleus collisions in Section 4.8 with measurement projections shown in Figure 4.38. We strongly agree that the proton-nucleus program is a very exciting part of the sPHENIX comprehensive set of measurements.

Recommendations:

None

The Feasibility of the Approach

Findings:

The PHENIX collaboration has proposed a new detector, called sPHENIX, to carry out a comprehensive program of jet measurements in heavy ion collisions at RHIC. The new detector utilizes existing components of the current PHENIX detector (Data Acquisition (DAQ), infrastructure, and reconfigured vertex (VTX) detector) and the existing BaBar magnet, together with new EM and Hadronic Calorimeters.

The collaboration presented projections of measurements based on 20 weeks of Au+Au running and 10+ weeks each of p+p and p+Au, all at sqrts=200 GeV. This corresponds to the recording of 50 billion unbiased events and the sampling of 200 billion events in AuAu. The unbiased recording rate is 10 kHz.

See details in our response to Recommendation Item #6 above. We note that we now have a design that is consistent with a Level-1 recording rate of 15 kHz. This rate is a good match for the Au+Au luminosities and quite sufficient for more selective triggering in p+p and p+A collision systems. The new projections with 22 weeks of Au+Au running include recording 100 billion unbiased events and for purely calorimetric triggerable observables (including jets and direct photons) sampling over 0.6 trillion events.

The collaboration presented studies of jet reconstruction performance in heavy ion collisions for a number of observables that have been measured at the LHC, based primarily on simulations of jets in Au+Au collisions at sqrts=200 GeV. The heavy ion jet analysis utilizes the FastJet anti-kT algorithm, with discrimination of background based on the ATLAS approach. The approach to jet reconstruction presented follows standard conventions including a choice of cone radius of 0.2 and 0.4 providing a benchmark consistent with LHC results. The choice of underlying event subtraction following the same general strategy as ATLAS allows for a benchmark with current physics. The clustering of the calorimeter energy deposits is used to minimize effort and avoid additional tedious studies in simulation. In addition, a first study of jet-hadron correlations was presented.

Photon identification and electron identification benefit from the use of shower shape and property measurements. Full simulations are used, and the tracker is incorporated into the simulation. This allows for a first estimate of backgrounds originating from fake hadrons and also conversions. Electron resolutions are confirmed in test beams.

Comments:

Utilization of existing equipment, while a cost-effective and even enabling approach to the construction of sPHENIX, may at the same time constrain the phase space coverage of the detector and limit the possibilities for new instrumentation. The collaboration should document the considerations that went into adoption of the BaBar magnet, and compromises, if any, that it imposes on the physics scope of the proposal. They should also document the limitations, if any, that the reconfigured VTX detector imposes on significant measurements in the Heavy Flavor sector, relative to a newly constructed vertex detector and whether the Forward Vertex Detector (FVTX) could complement the capabilities.

See details in our response to Recommendation Item #5 above. The BaBar magnet is an excellent match to the physics driven requirements of sPHENIX. In fact, the shaping of the field also allows for a forward spectrometer design necessary for an EIC detector as documented in Appendix B.

In terms of tracking, in the new reference design only the two inner layers of VTX pixels are maintained. The detector and electronics are a good match to the necessary DCA resolution and readout speed (see also the response to Recommendation Item #6). We have discussed at a later stage replacing the pixels with three-layers of thinner pixels. At this stage, we do not consider that part of the baseline design.

For forward tracking, as discussed in the response to Recommendation Item #5, one can use a lampshade to shape the field in the forward direction and provide appropriate momentum resolution. The current FVTX could be reconfigured in orientation to give DCA and tracking pointing in combination with additional GEM trackers. These are considered options as part of the fsPHENIX concept (see the fsPHENIX White Paper, http://www.phenix.bnl.gov/phenix/WWW/publish/dave/sPHENIX/pp_pA_whitepaper.pdf).

Tracking acceptance is currently limited to |eta|<1.1. Measurements, such as that carried out by CMS, showing that momentum is balanced by soft radiation at large angles to a quenched jet, may require larger tracking acceptance. The collaboration should investigate extending the tracking acceptance beyond |eta|=1.1, for instance with the addition of silicon or Gas Electron Multiplier (GEM) end wheels to the VTX detector.

See details in our response to Recommendation Item #5 above.

The large unbiased event sample in Au+Au collisions enabled by the deadtime-free sPHENIX DAQ is unique and extremely valuable for jet measurements of many kinds. The usable event rate is limited, among other factors, by the acceptance of the VTX to events with |zvtx|<10 cm. However, in 2020 the BNL Collider Accelerator Department (CAD) may be able to deliver a higher rate within this acceptance than is currently projected. Exploration of increasing the min-bias rate capability beyond 10 kHz is therefore warranted. The collaboration should clarify the origin of the 10 kHz limit for recording min-bias events and investigate means to increase it.

See details in our response to Recommendation Item #6 above.

Unbiased jet measurements in pp collisions may be equally valuable, though harder to obtain. The collaboration should assess the requirements for truly unbiased jet measurements in pp collisions. These requirements will depend on the choice of jet observable.

We have explored possible approaches to triggering on jets in p+p collisions in an unbiased manner in Section 3.9. We conclude that "jet patch" triggers (which require some minimum ΣE_T in a large sliding window of EMCal and HCal towers) are very well suited to triggering on jets in p+p collisions in sPHENIX, providing high efficiency down to low jet p_T without a bias on the jet flavor, while giving the large rejection factors required for the expected high rate of minimum bias p+p events. These triggers give good rejection in p+p through peripheral Au+Au. Even in central Au+Au there is adequate rejection for sampling the entire delivered RHIC luminosity for the highest energy jets.

The collaboration has made significant progress with the initial studies of the sPHENIX detector capabilities. The current studies on jet reconstruction for single particle and for the combined reconstructed jets with GEANT simulation reflect the classical effects seen in jet performance. This demonstrates that for a single well identified jet, the simulated jet performance appears to be okay. The resulting resolution is similar to the current resolution seen in the LHC detectors. The panel finds that the projected jet energy resolution is adequate. However, some discussion about the resolution limitations is absent. An example is the influence of the magnet separating the inner and outer portions of the hadronic calorimeter and the resulting effect on the linearity of the response of single particles/jets and on their respective resolution (both for particles and jets). In addition, purely calorimetric jet measurements in a high magnetic field may have limited performance for the low p_T hadronic component of jets. Current approaches to mitigate these limitations combine tracking in addition to calorimetric measurements. Such algorithms should be explored for the sPHENIX design, and the relative performance documented for jets in both pp and AuAu collisions.

See details in our response to Recommendation Items #4 and #7 above.

We detail the influence of the magnetic field and the placement of the calorimeters, and explore additional jet algorithms in Section 4.2. The detailed radial placement of the magnet and calorimeters has very little influence on the jet resolution. We have full GEANT4 simulation comparisons with the full hadronic calorimeter outside the magnet cryostat with no change in performance. We also have implemented alternate jet algorithms and are optimizing their performance.

Studies of heavy ion jet reconstruction tend to emphasize the "easy cases" of small R and large jet p_T. R=0.2 is the most common choice to illustrate performance. The reported physics performance is substantially poorer for more challenging configurations, for instance the inclusive yield in central Au+Au collisions for R=0.4 jets, for which only limited phase space at high p_T appears to be accessible to well-controlled measurement. A comprehensive jet program requires techniques with broader coverage at large R and low p_T.

See details in our response to Recommendation Items #7 above.

Additional improvements could be made in photon and electron identification. Incorporation of Gaussian sum filtering tracking can incorporate high bremsstrahlung electrons, and the use of shower shapes will result in an improved detector performance. Additional studies on the effect of uncertainty in the material budget and the resulting impact on the hadrons faking photons and electrons would strengthen the claims about photon and electron identification. Nonetheless, the quoted efficiencies are conservative.

We have documented further the electron identification in Section 3.7. As we work towards a final detector design, optimization of the photon and electron identification are important considerations. The option of extending the single photon from two photon separation (from neutral pion decay) is considered in Appendix A with a possible pre-shower detector in front of the electromagnetic calorimeter.

Recommendations:

None

The Likelihood of Significant Results in the First Three Years

Findings:

The collaboration presented projections of measurements in the first two years of sPHENIX operation, based on 20 weeks of Au+Au running and 10+ weeks each of p+p and p+Au, all at sqrts=200 GeV. This corresponds to the recording of 50 billion unbiased Au+Au events and the triggered sampling of 200 billion Au+Au events. The unbiased recording rate is 10 kHz.

Comments:

Fundamental aspects of jet quenching remain open. Experimental strategies to obtain high statistics datasets for comprehensive jet quenching studies must be designed with care, in order not to bias the recorded jet population in ways that cannot be corrected offline. The large unbiased dataset of Au+Au collisions that sPHENIX will record in its first two years of operations, which is enabled by the deadtime-free sPHENIX DAQ, is therefore a unique and extremely valuable resource for measurements of many kinds.

The basic design of the experiment appears sound and appropriate to achieve significant results once operational.

Recommendations:

None