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# The future of hard and electromagnetic probes at RHIC

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**Abstract.** Potential near- and long-term physics opportunities with jets, heavy flavors and electromagnetic probes at RHIC are presented. Much new physics remains to be unveiled using these probes, due to their sensitivity to the initial high density stage of RHIC collisions, when quark-gluon plasma (QGP) formation is expected. Additional physics will include addressing deconfinement, chiral symmetry restoration, properties of the strongly-coupled QGP and a possible weakly-interacting QGP, color glass condensate in the initial state, and hadronization. To fully realize the physics prospects of the RHIC energy regime, new detector components must be added to existing experiments, the RHIC machine luminosity upgraded, and a possible new detector with significantly extended coverage and capabilities added.

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## 1 Physics goals at RHIC

The primary physics goal of the Relativistic Heavy Ion Collider (RHIC) has been to establish the presence of the Quark Gluon Plasma (QGP) and to determine its properties. Future physics includes: 1) determining the extent of deconfinement; 2) establishing a signature of chiral symmetry restoration; 3) possibly distinguishing a strongly-coupled QGP from a weakly-interacting one; 4) determining whether a color glass condensate is formed in the initial state; and 5) understanding parton propagation and the hadronization process.

Many exciting results have been presented at this Conference that are consistent with the formation of the QGP. However, in recent overview and position papers on this topic, the experimental collaborations at RHIC state that the evidence for discovery is not presently conclusive [1–4]. Theorists have tended to disagree with the experimentalists, stating that the evidence exists [5]. This ongoing debate will be settled with data, and more detailed calculations.

## 2 Hard and EM probe physics at RHIC

Jets, heavy flavors and electromagnetic probes will play a key role in settling this debate, since they are sensitive to the initial high density stage, when formation of a QGP is predicted. Electromagnetic probes can be divided into two categories: direct photons which tell us about thermal radiation and shadowing, and virtual photons (electron-positron and $\mu^+\mu^-$ pairs) by way of their coupling to vector mesons may tell us about chiral symmetry restoration and possible bound states in a strongly-coupled QGP. Heavy flavors include open charm, open beauty, and quarkonia (charmonium and bottomonium states). Yields of quarkonia are predicted to be strongly sensitive to deconfinement. Properties of jets can be measured via leading particles, particle correlations, photon-jet correlations, heavy quark (charm or beauty) tagged-jets, and topological jet energy. These provide information on parton energy loss, properties of the medium through which the partons propagate, gluon shadowing, possible presence of a color glass condensate, and hadronization mechanisms.

### 2.1 RHIC detector capabilities

PHENIX and STAR continue to improve triggering and data acquisition capabilities in order to acquire data efficiently for jets, heavy flavor and EM probes. New detector capabilities will be added and apertures expanded. Additional detector capabilities [6,7] include micro-vertexing for identifying displaced vertices from heavy flavor decays in STAR ($\mu$VTX) and PHENIX (MVTX), adding better low-mass "hadron-blind" di-lepton capabilities in PHENIX (HBD), and extending particle identification in STAR (ToF) and PHENIX (Aerogel).

### 2.2 RHIC luminosities

In order to undertake extensive studies of heavy flavor production and jets at large transverse momenta ($p_{\mathrm{T}}$), which have low production cross sections and are often

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called rare probes, an upgrade in the RHIC luminosity will be necessary. The RHIC design luminosity for Au+Au is $L_0 = 2\times10^{26}$ cm$^{-2}$s$^{-1}$. RHIC now routinely reaches twice this value. Thus, the anticipated $\int Ldt$ per RHIC year (20 weeks operation) is approximately 2–3 nb$^{-1}$. Note that the reference data for p+p (to understand fundamental production mechanisms) and any comparison/control data for d+Au (to understand normal nuclear effects) also require statistics similar to those for Au+Au and extended RHIC running.

Many crucial measurements with hard and electromagnetic probes at RHIC require $\int Ldt > 20$ nb$^{-1}$. For a vital program with rare probes to continue at RHIC, the luminosity must increase. A luminosity increase to $40 \times L_0$ or $\int Ldt \sim 100$ nb$^{-1}$ is planned for RHIC (and will be called RHIC II), with a construction start possible in 2009 for operation in 2012.

## 3 Electromagnetic probes

### 3.1 Direct photons

Photons in A+A collisions may provide information on thermal photon radiation. In p+A interactions, photons establish the degree of shadowing. Photons in pp reactions are needed for reference data, to understand the underlying processes in p+A and A+A results. Preliminary results on photons in Au+Au and pp at RHIC have been reported by PHENIX at this Conference [9]. Photons measured in pp are consistent with next-to-leading order (NLO) pQCD calculations. Those measured in Au+Au exhibit no thermal photons within present statistics. Furthermore, the Au+Au direct photons are consistent with binary scaling of pp. A definite statement about direct photons in Au+Au at RHIC is anticipated from PHENIX from the recent RHIC 2004 high statistics Au+Au run [10].

### 3.2 Virtual photons via lepton pairs

Thermal photons (measured via $e^+e^-$ or $\mu^+\mu^-$ pairs) are expected to be radiated from the QGP. However, at RHIC energies, the thermal di-lepton spectrum in the intermediate mass range (1–3 GeV) may be dominated by charm. In addition to information on thermal radiation, virtual photons (measured via lepton pairs) investigate possible modifications of vector mesons in the medium. The behavior of vector mesons in medium may shed light on the existence of chiral symmetry breaking and/or bound states in a strongly-coupled QGP.

In order to effectively pursue low mass electron pair measurements, PHENIX has proposed to install a hadron-blind TPC (HBD) and STAR has proposed a barrel Time-of-Flight detector (ToF) for electron identification at $p_T > 0.2$ GeV/$c$. A calculation of the light vector meson yield as a function of invariant mass of $e^+e^-$ pairs is displayed in Fig. 1 [11]. Peaks for the $\omega$ and $\phi$ mesons are observed,

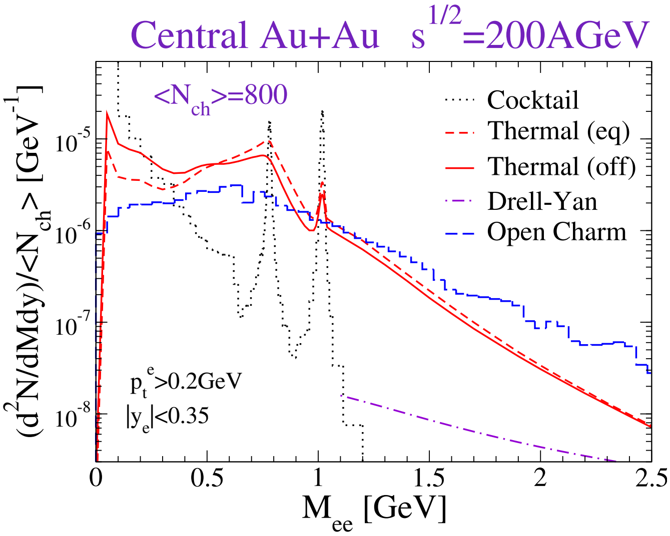


**Fig. 1.** Low mass $e^+e^-$ pair spectrum from [11]. Contributions from the hadronic "cocktail", thermal and non-equilibrium photons, Drell-Yan, and open charm are displayed as denoted in the figure

but are swamped by $e^+e^-$ pairs from thermal and non-equilibrium photons and open charm. Careful investigation of medium modification of low mass vector mesons requires measuring and understanding all contributions to the di-lepton spectrum including detailed charm studies that require RHIC II luminosities.

### 3.3 Heavy flavor (quarkonium)

The production of quarkonium states in pp, p+A, and A+A collisions provides a tool to study deconfinement in strongly interacting matter [12]. Studies of the dependence of the heavy-quark potential on the in-medium temperature in lattice QCD calculations with dynamical quarks [13] indicate a sequence of melting of the quarkonium states based upon their binding strengths: $T(\psi') < T(\Upsilon_{3S}) < T(J/\psi) \sim T(\Upsilon_{2S}) < T(\Upsilon_{1S})$, where $T(\Upsilon_{3S}) < T_c$ and $T(\Upsilon_{1S}) > T_c$, with $T_c$ the deconfinement phase transition temperature. Therefore, a measurement of the yields of the various bottomonium states will shed light on the production (via $\Upsilon_{1S}$) and suppression mechanisms ($\Upsilon_{2S}$ and $\Upsilon_{3S}$) of quarkonia, avoiding the difficulties inherent in charmonium measurements where such a clean separation between production and suppression effects is not feasible. These measurements are challenging, requiring excellent momentum resolution to resolve the bottomonium states and very high rate (luminosity) and trigger capabilities because of the low production cross-sections.

The larger production cross-sections for charmonium states compared to bottomonium states have led to studies of charmonium and the subsequent observation of charmonium suppression in collisions of heavy ions at the SPS. PHENIX anticipates its first results on charmonium suppression in Au+Au at RHIC from the large statistics 2004 data run. Bottomonium spectroscopy, on the other hand,

**Table 1.** PHENIX Quarkonium Program for Au+Au at RHIC and RHIC II [7,8]

| Channel | RHIC (1.5 $\mathrm{nb}^{-1}$) | RHIC II (30 $\mathrm{nb}^{-1}$) |
|---|---|---|
| $J/\psi \to e^+e^-$ | 2,800 | 56,000 |
| $\psi' \to e^+e^-$ | 100 | 2,000 |
| $\Upsilon \to e^+e^-$ (all states) | 8† | 155† |
| $J/\psi\ (\psi') \to \mu^+\mu^-$ | 38,000 (1400) | 760,000 (28,000) |
| $\Upsilon \to \mu^+\mu^-$ (all states) | 35‡ | 700‡ |

† requires MVTX upgrade
‡ requires $\mu$-trigger system upgrade

requires higher luminosities. Since bottomonium is massive ($\sim$10 GeV) its decay leptons have sufficiently large momenta above background processes facilitating high-level triggering.

The PHENIX mass resolution for $\Upsilon \to e^+e^-$ with the MVTX detector upgrade is $\Delta m = 60$ MeV. Without the MVTX it is 170 MeV, making resolution of the $\Upsilon_{1S}$ (9.460 GeV), $\Upsilon_{2S}$ (10.020 GeV), and $\Upsilon_{3S}$ (10.360 GeV) challenging. The PHENIX mass resolution in the muon arms is worse than 170 MeV making it difficult to resolve the individual $\Upsilon$ states in the muon decay channel. Statistics for the $\Upsilon$ states, combined in Table 1, are low. In STAR, the mass resolution for $\Upsilon \to e^+e^-$ is $\Delta m = 340$ MeV using the time projection chamber tracking alone. A $\mu$-vertex detector upgrade would improve this resolution to $\Delta m = 170$ MeV. Only with a planned data acquisition system upgrade, will STAR be able to detect a significant number of $\Upsilon$'s (1750 combined in all three states with 1.5 $\mathrm{nb}^{-1}$ Au+Au). In general, a meaningful bottomonium program at RHIC will require RHIC II luminosities ($\sim$100 $\mathrm{nb}^{-1}$) and large acceptances to obtain reasonable statistics.

The quarkonium statistics anticipated for Au+Au in PHENIX [7,8] are presented in Table 1.

### 3.4 Open heavy flavor

Heavy flavor (charm and bottom) yields are sensitive to the initial gluon density and are important components of understanding $J/\psi$ and $\Upsilon$ production. Measuring the energy loss of a heavy quark in the medium will indicate whether heavy quarks suffer less energy loss than light quarks in the medium, as predicted by the "dead-cone effect" [14].

Initial measurements of charm cross sections and charm flow have been made by identifying single electrons above background in STAR [15] and PHENIX [16]. These results indicate that low $p_\mathrm{T}$ open charm exhibits elliptic flow and are preliminary at the time of this Conference. Significant measurements up to moderate $p_\mathrm{T} \sim$ 5–6 GeV/$c$ of open charm and open beauty decays can be made with $\sim$3 $\mathrm{nb}^{-1}$ and upgraded detectors in STAR ($\mu$-vertex, ToF) and PHENIX (MVTX).

## 4 Jets

High $p_\mathrm{T}$ particles and jets can be used to probe the quark-gluon plasma (QGP), study its properties and gain a better understanding of high density QCD and hadronization. Measuring the modifications of fragmentation functions (FF) of partons traversing the QGP in A+A collisions relative to pp and p+A collisions should distinguish characteristics of the QGP compared to those of a nuclear medium. The RHIC energy regime appears to be ideal for these studies. Recent measurements in the forward direction at RHIC indicate possible gluon shadowing in the initial state at low $x$. Therefore, measurements over a specific part of phase space (e.g. forward- or mid-rapidities) selects the $x$ region of the dominant process of interest. The higher energy regime of the Large Hadron Collider (LHC) will provide increased particle yields at high $p_\mathrm{T}$ and at low $x$.

The contributions of the various (u, d, s, c, b) quarks to the mass of stable particles can be determined by measuring the fragmentation function of each particle in pp interactions. The contributions of the light (u,d), strange (s), and heavy (Q = c,b) quarks to the octet baryons (p, $\Lambda$, $\Sigma$ and $\Xi$) are presented as a function of $x_\mathrm{BJ}$ in Fig. 2 [17]. Measurement of these fragmentation functions requires particle identification of leading particles in jets at large transverse momentum. Such measurements in $A+A$ collisions will establish how fragmentation functions are modified by propagation of the various types of quarks in the dense medium and will reflect these quark contributions to the particle masses as they fragment in the medium. It would be extremely exciting if fragmentation functions of some of the particles were to reflect properties of a chirally restored medium. This latter connection has yet to be established theoretically. In addition to accounting for the constituent quark masses, the chiral quark condensate is responsible for inducing transitions between left-handed and right-handed quarks, $\overline{q}q = \overline{q}_L q_R + \overline{q}_R q_L$. Therefore, helicities of (leading) particles in jets (e.g. determined by detecting the polarization of leading $\Lambda$ particles) may provide information on parity violation and chiral symmetry restoration [18].

Full utilization of hard parton scattering to probe high density QCD matter requires measurements of photons (to establish the parton energy), jets (another potential measurement of parton energy), high $p_\mathrm{T}$ identified particles (for fragmentation functions of particles and flavor-tagging), and correlations from among these. In addition, measurements are essential over a multi-parameter space that can be divided into initial state (c.m. energy, system mass, collision impact parameter, $x_1$ and $x_2$ of the colliding beam partons, and $\mathrm{Q}^2$ of the collision) and final state ($p_\mathrm{T}^\mathrm{parton}$, $y^\mathrm{parton}$, $\phi^\mathrm{parton}$, $p_\mathrm{T}^\mathrm{jet/particle}$, $y^\mathrm{jet/particle}$, $\phi^\mathrm{jet/particle}$, $\mathrm{flavor}^\mathrm{jet/particle}$, $\phi^\mathrm{flow\ plane}$). Such a study requires large data sets and high luminosity to extend mea-

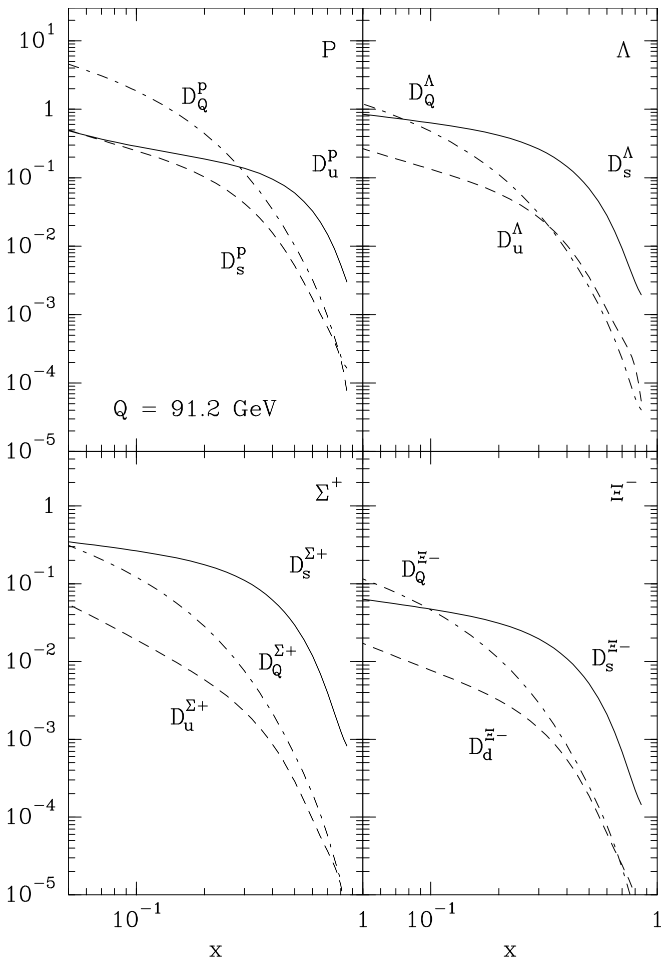


**Fig. 2.** Fragmentation functions ($D_{\rm quark}^{\rm baryon}$) for the octet baryons (p, $\Lambda$, $\Sigma$ and $\Xi$) as a function of $x_{\rm BJ}$ [17]. Contributions of the light (u,d), strange (s), and heavy (Q = c, b) quarks are denoted by subscripts

surements to large $p_{\rm T}$. Furthermore, it would be interesting to investigate the difference in quark versus gluon propagation by implementing kinematic cuts ($x_1$, $x_2$) in jet-jet correlations, and to utilize the anticipated differences in the yields of gluon and quark jets as a function of transverse momentum and $\sqrt{s}$.

### 4.1 Photon-tagged jets

The primary advantage of photons is that they do not re-interact with the medium through which they propagate. Thus, they can be used to determine the parton energy in the original hard-scattering that produces the photon and away-side jet. The away-side jet will suffer energy loss in the medium and thus the difference of the photon and measured away-side jet energy can be used to determine the energy lost by the parton on the away-side of the photon. Correlation of the flavor of the leading hadron in the jet on the away-side of a photon provides additional information with which to test energy loss mechanisms. Another advantage of photon-jet correlations is that there are only two production diagrams that produce photons in leading order: quark-antiquark annihilation and quark-gluon Compton scattering. However, there is one major issue to be dealt with when utilizing prompt photons to determine the momentum of the hard-scattered parton. One must distinguish direct (prompt) photons from those from fragmentation of partons. This is complicated and must be resolved through understanding the contribution of fragmentation photons and their momentum dependence.

STAR will undertake initial studies of photon-jet correlations up to 10 GeV/$c$ photon momentum by utilizing a few nb$^{-1}$ integral luminosity in Au+Au at RHIC. Since less than 1 % of the jets have a leading hadron above the background in a Au+Au collision at RHIC, a few years of Au+Au running with a total luminosity of 4–5 nb$^{-1}$ is expected to yield $\sim$ 8K charged hadrons in a spectrum on the away-side from a 10 GeV/$c$ photon, and $\sim$ 1K charged hadrons in a spectrum on the away-side from a 15 GeV/$c$ photon, in STAR. More detailed measurements, especially with identified particles on the away-side for fragmentation function modification for high $p_{\rm T}$ partons requires RHIC II luminosities.

PHENIX proposes to perform statistical photon-jet correlation analyses with approximately 1000 photon-jet events. The maximum photon $p_{\rm T}$ depends on the PHENIX detector complement. In the 2004 Au+Au run the maximum photon $p_{\rm T}$ ($p_{\rm T}^{\rm max}(\gamma)$) is expected to be $\sim$ 6 GeV/$c$; with a new time projection chamber (covering $-1 \le \eta \le 1$) at RHIC luminosity $p_{\rm T}^{\rm max}(\gamma) \sim 12$ GeV/$c$; with an additional nose cone calorimeter for expanded photon detection at RHIC II luminosity, $p_{\rm T}^{\rm max}(\gamma) \sim 23$ GeV/$c$ at mid-rapidity [8].

As we have seen in this Conference [19], jets in Au+Au collisions broaden significantly in pseudorapidity on the near-side as well as on the away-side. This can be attributed both to the variation of parton momentum fractions for partons of the incoming beam nuclei (parton momentum fractions $x_1$, $x_2$) and to possible quenching in matter. Calculations utilizing PYTHIA 6.2 show that photons from $\sqrt{s} = 200$ GeV pp interactions at RHIC extend with a fairly flat distribution over the pseudo-rapidity range $-3 \le \eta \le 3$. The same simulations show that the difference in pseudo-rapidity between the photon and away-side jet has a width $\sigma(\eta_\gamma - \eta_{\rm jet}) = 1.5$ units of pseudo-rapidity. Experiments seeking to undertake photon-jet measurements should have large acceptance for photons, high $p_{\rm T}$ particles and jet energy in order to cover a range of parton momentum fractions ($x_1$, $x_2$).

### 4.2 Flavor-tagged jets

Jets with a D or B meson as leading particles will serve to study the response of the medium to heavy quarks compared to light ones. A high $p_{\rm T}$ electron in coincidence with a leading hadron, both emanating from a vertex that is displaced from the primary reaction vertex, will provide a trigger for heavy flavor decays. Significant measurements at large $p_{\rm T} \sim$ 10–15 GeV/$c$ of open charm and open beauty as leading particles of jets require RHIC II luminosities and upgraded detectors in STAR ($\mu$-vertex, ToF) and PHENIX (MVTX).

## 5 A comprehensive new RHIC II detector

A comprehensive new detector has been proposed [20] for RHIC II to undertake measurements of jets, heavy flavors, and electromagnetic probes, and to take full advantage of the high RHIC II luminosities. New RHIC II physics opportunities can be studied by utilizing a high field ($\sim$1.5 T) solenoid magnet, extensive charged hadron tracking and identification, electron and muon tracking and identification, and extensive coverage of electromagnetic and hadronic calorimetry. The capabilities of a comprehensive new detector include: 1) excellent charged particle momentum resolution to $p_{\mathrm{T}} = 40$ GeV/$c$ in the central rapidity region; 2) complete hadronic and electromagnetic calorimetry over a large phase space, $-3 \leq \eta \leq 3$, $\Delta\phi = 2\pi$; 3) particle identification out to large $p_{\mathrm{T}}$ ($\sim$20–30 GeV/$c$) including hadron ($\pi$, K, p) and lepton (e/h, $\pi$/h) separation in the central and forward region; and 4) high rate detectors, data acquisition, and trigger capabilities. A possible layout for a new RHIC II detector, using the SLD magnet, is shown in Fig. 3.

In order to identify all charged hadrons in a high $p_{\mathrm{T}}$ jet, good hadron identification is necessary up to momenta of approximately 20 GeV/$c$. Lepton particle identification will be achieved through the e/h capabilities in the calorimeters and the muon chambers. Hadron and lepton particle identification will be achieved through a combination of d$E$/d$x$ in the tracking detectors ($p_{\mathrm{T}} \leq 1$ GeV/$c$), a time-of-flight device ($p_{\mathrm{T}} \leq 3$ GeV/$c$), and a combination of two different Aerogel Cherenkov-threshold counters and a RICH detector with gas radiator (up to $p_{\mathrm{T}} \sim 20$ GeV/$c$). For more details on the comprehensive new detector see [20].

### 5.1 Jets in a comprehensive new detector

Jet rates will be significant over the large acceptance of a new detector ($-3 \leq \eta \leq 3$, $\Delta\phi = \pi$ plus extended forward coverage to $\eta \sim 4.5$) at upgraded RHIC II luminosities. The anticipated jet yield for 40 GeV jets in such a new detector at RHIC II with 30 nb$^{-1}$ of Au+Au at top energy is $\sim$180 000. Around 19 000 $\gamma$-jet events are expected with $p_{\mathrm{T}}(\gamma) = 20$ GeV/$c$, and 1000 $\gamma$-jet events for $p_{\mathrm{T}}(\gamma) = 30$ GeV/$c$ with full away-side particle identification over $-3 \leq \eta \leq 3$ for determination of the modification of fragmentation functions of particles.

Extension of high resolution particle tracking, particle identification (PID), and calorimetry to forward rapidities will be important in elucidating the various particle production and hadronization mechanisms, which may be sensitive to the quark and gluon components of the

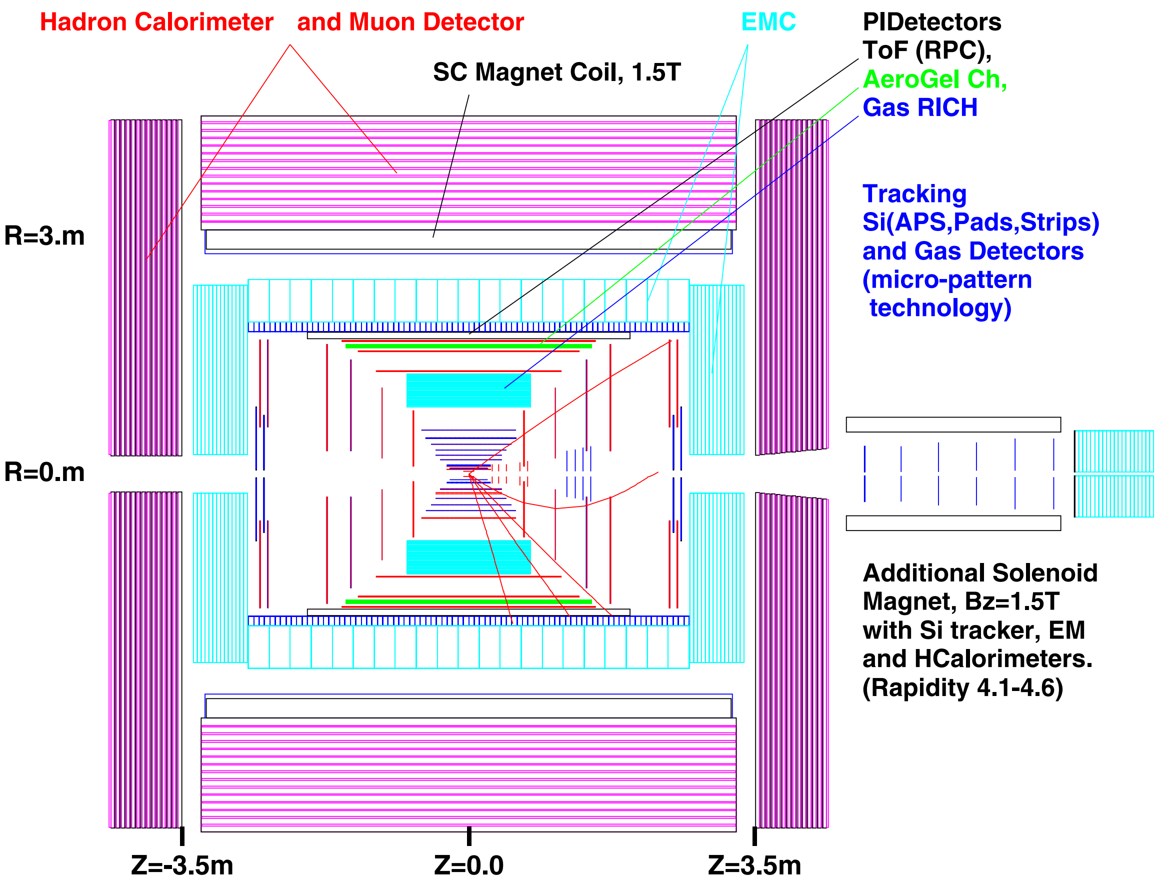


**Fig. 3.** Diagram of a possible, comprehensive new detector at RHIC II using the SLD magnet

**Table 2.** New RHIC II Quarkonium Program for Au+Au at RHIC II for $p_{\mathrm{lepton}} > 2$ GeV/$c$ for J/$\psi$, and $p_{\mathrm{lepton}} > 4$ GeV/$c$ for $\Upsilon$

| Channel | RHIC II (30 nb$^{-1}$) |
|---|---|
| J/$\psi \to$ di-leptons | 36 000 000 |
| $\psi' \to$ di-leptons | 1 000 000 |
| $\chi_c \to$ J/$\psi + \gamma$ | 680 000 |
| $\Upsilon \to$ di-leptons | 64 000 |
| $\Upsilon' \to$ di-leptons | 12 000 |
| $\Upsilon'' \to$ di-leptons | 12 000 |

hadronic wave functions. At very low $x_{\mathrm{BJ}}$, gluons can be coherent over nuclear distances and a color glass condensate [21,22] may form. This would have effects on many hard physics observables that depend directly on the gluon structure, e.g. minijet rates and heavy flavor production, but can be clarified by comparisons of p+A physics with pp. Thus, it is important to study high $p_{\mathrm{T}}$ processes away from mid-rapidity. To take full advantage of physics in the forward region, momentum measurements and PID must be undertaken up to $p_{\mathrm{T}} \sim$ 2–3 GeV/$c$, which is a real experimental challenge with longitudinal momenta of 20–30 GeV/$c$ at large rapidities.

### 5.2 Quarkonia in a comprehensive new detector

For determination of the quarkonium melting sequence an energy resolution of better than $10\,\%/\sqrt{E}$ is required to resolve the quarkonium states with calorimeter information alone. Thus, quarkonium physics at RHIC II in this new detector can be fully realized by using the EMC in combination with high resolution tracking and large acceptance muon chambers. The mass resolution for $\Upsilon \to \mu^+\mu^-$ in the new comprehensive detector is $\Delta m =$ 60 MeV. Furthermore, large acceptance in the Feynman $x_F$ variable is important for understanding quarkonium production and melting mechanisms. This leads to the need for large acceptance in $\eta$ for lepton pairs. The electron and muon coverage of the new detector extends over $-3 \leq \eta \leq 3$ and $\Delta\phi = 2\pi$. A similar acceptance in the new detector for charmonium feed-down photons from $\chi_c$ decays ($\chi_c \to$ J/$\psi + \gamma$) allows determination of the $\chi_c$ feed-down contribution to J/$\psi$ production and subsequent suppression.

The anticipated quarkonium statistics for Au+Au in the new comprehensive detector are presented in Table 2. These numbers for the new detector are to be compared to those for PHENIX in Table 1.

## 6 Conclusions

The future of hard and electromagnetic probes at RHIC is alive and well! There is much new data still to be accumulated at RHIC. From such data new physics will be uncovered, since jets, heavy flavors and electromagnetic probes are sensitive to the initial high density stage of RHIC collisions, when quark-gluon plasma (QGP) formation is expected. Questions that still remain to be addressed are whether 1) the system becomes deconfined, 2) chiral symmetry is restored, 3) in addition to a strongly-coupled QGP there is a weakly-interacting one, 4) a color glass condensate is formed in the initial state, and 5) whether we can gain new understanding of the hadronization process. Precise timescales for new detector implementation to improve capabilities for rare probes at RHIC is uncertain due to ambiguities in the availability of funding. Significant capabilities will be added with new detectors at RHIC and a possible comprehensive new detector at RHIC II. We look forward to significant progress in these directions and exciting physics from the hard and EM probe sector at RHIC and RHIC II.

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## References

1. J. Adams et al., STAR White Paper, nucl-ex/05010009
2. K. Adcox et al., PHENIX White Paper, nucl-ex/0410003
3. B.B. Back et al., PHOBOS White paper, nucl-ex/0410022
4. I. Arsene et al., BRAHMS White Paper, nucl-ex/0410020
5. M. Gyulassy, L. McLerran, nucl-th/0405013
6. STAR Decadel Plan, STAR Coll. (2003), http://www.star.bnl.gov/STAR/smd/whitepaper-18.pdf
7. PHENIX Decadel Plan, PHENIX Coll. (2003), http://www.phenix.bnl.gov/phenix/WWW/docs/decadal/2003/PHENIXDecadalPlan.pdf
8. A. Drees, U.S. Nuclear Science Advisory Committee Heavy Ion Review Panel presentation (2004), http://nsac2004.bnl.gov/pres/drees.pdf
9. K. Reygers, Eur. Phys. J. C **43** (2005)
10. I. Tserruya, Eur. Phys. J. C **43** (2005)
11. R. Rapp, nucl-th/0204003
12. T. Matsui, H. Satz, Phys. Lett. B **178**, 416 (1986)
13. S. Digal, P. Petreczky, H. Satz, Phys. Rev. D **64**, 094015, (2001) [hep-ph/0106017]; Phys. Lett. B **514**, 57 (2001) [hep-ph/0105234]
14. Y.L. Dokshitzer, D.E. Kharzeev, Phys. Lett. B **519**, 199 (2001) [hep-ph/0106202]
15. F. Laue et al. (STAR Coll.), mucl-ex/0411007
16. S.S. Adler et al. (PHENIX Coll.), nucl-ex/0409028
17. C. Bourrely, J. Soffer, Phys. Rev. D **68**, 014003 (2003)
18. D. Kharzeev, J. Sandweiss, private communication
19. D. Magestro et al. (STAR Coll.), Eur. Phys. J. C **43** (2005)
20. J.W. Harris et al., nucl-ex/0407021; P. Steinberg et al., nucl-ex/0503002
21. L. McLerran, Acta Phys. Polon. B **34**, 3029 (2003)
22. D. Kharzeev, E. Levin, Phys. Lett. B **523**, 79 (2001)