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A Comprehensive New Detector for Detailed Study of the QGP, Initial Conditions and Spin Physics at RHIC II

J.W. Harris,[1] R. Bellwied,[2] N. Smirnov,[1] P. Steinberg,[3] B. Surrow[4] and T. Ullrich[3]

[1] Yale University, New Haven CT, USA 06520-8124
[2] Wayne State University, Detroit MI, USA 48201
[3] Brookhaven National Laboratory, Upton NY, USA 11973
[4] Massachusetts Institute of Technology, Cambridge MA, USA 02139-4307

Abstract. A case is presented for compelling physics at a high luminosity RHIC II collider. A comprehensive new detector system is introduced to address this physics. The experimental focus is on detailed jet tomography of the quark gluon plasma (QGP), measuring gluon saturation in the nucleus, investigating the color glass condensate, measuring effects of the QCD vacuum on particle masses, determining the structure and dynamics within the proton and possible new phenomena. The physics and detector capabilities are introduced.

Keywords: quark gluon plasma, quarkonium, deconfinement, jets, jet fragmentation, parton energy loss, color glass condensate, quark mass, proton spin, Relativistic Heavy Ion Collider)
PACS: specifications see, e.g. http://www.aip.org/pacs/

1. Overview

There are compelling physics questions that can be addressed at a future, high-luminosity RHIC II complex. These include: What are the properties of the quark-gluon plasma? To what extent is there gluon saturation or a color glass condensate in the nucleus at low Bjorken-x (x_{BJ})? If present, how does a color glass condensate evolve into a quark-gluon plasma? What is the chiral structure of the QCD vacuum and its influence on, or contributions of different QCD vacuum states to, the masses of particles? What is the structure and dynamics inside the proton (including spin, possibly orbital angular momentum) and to what extent is parity violation significant and important in understanding the proton in the Standard Model?

The RHIC II complex will be the only QCD facility to have the capability to address these questions. In this paper a comprehensive new detector system is proposed for RHIC II to address these in an effective way. This detector would utilize precision tracking and particle identification to large transverse momentum (~ 20 GeV/c) in a 1.5 T solenoidal magnetic field, with electromagnetic and hadronic calorimetry and muon identification over $-3 < \eta < 3$ with complete azimuthal coverage. An in-depth experimental program utilizing the unique features of this detector system and that of RHIC II is proposed to answer these compelling physics questions (above) in an era with heavy ions in the Large Hadron Collider (LHC). Furthermore, this physics is complementary to the LHC ion program and a future eRHIC (electron-ion collider) program.

2. Jet Physics

A compelling focus of $A+A$ physics at RHIC II is the use of hard scattering, in the form of jets and large transverse momentum (high $p_\perp$) particles, to perform a "tomographic" study (with partons in a multi-parameter space) of the QGP formed at RHIC [1, 2, 3]. These studies will be carried out as a function of geometry (colliding system and impact parameter), reaction plane, $\sqrt{s_{NN}}$, $p_\perp$, rapidity, and particle type. To be able to accomplish this the detector system should contain full coverage of electromagnetic and hadronic calorimetry for measurements of jets and photons, triggering and correlations. High resolution tracking in a large integral magnetic field and track-length ($\int$ B · dl) with particle identification up to large transverse momenta (~ 20 GeV/c) is essential for flavor dependence of leading particles and detailed jet fragmentation studies. High rate data-acquisition and triggering capabilities are necessary to utilize effectively the high luminosity for low cross section measurements and photon-, particle-, and jet-correlations. It should be emphasized that the flavor dependence in photon-jet, photon-leading hadron, di-hadrons, and di-jets will be studied as a function of x_{BJ} and orientation relative to the reaction plane. This complex set of correlation data will be necessary for detailed determination of the energy loss mechanism and properties of the QGP.

In order to study the flavor dependence of jet quenching [4], displaced vertices will be used to identify and trigger on heavy flavor decays. A high $p_\perp$ electron in coincidence with a leading hadron, both emanating from a vertex displaced from the primary $A+A$ reaction vertex, will provide a trigger for heavy flavor decays. Examples of other specific decay modes of interest for a displaced vertex, heavy flavor trigger are $B \rightarrow J/\psi + K^0_s$, and D-mesons through their hadronic decay modes.

We know that the Higgs field is solely responsible for the mass of particles in a chirally symmetric medium. The quark condensate adds a significant part of the mass of each light or strange particle, when chiral symmetry is broken. The contributions of the various (u, d, s, heavy) quarks can be determined by measuring the fragmentation function of each particle in $p+p$ interactions. The contributions of the light (u,d,), strange (s), and heavy (Q) quarks to the octet baryons (p, λ, Σ, and Ξ) are presented as a function of x_{BJ} in Fig. 1 [5]. 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 the propagation of the various types of quarks in a dense medium and should reflect these quark contributions to the particle masses in the medium. It would be extremely exciting if these fragmentation functions were to reflect properties of a chirally restored medium, although this 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 Λ particles) may provide information on parity violation and chiral symmetry restoration [6].

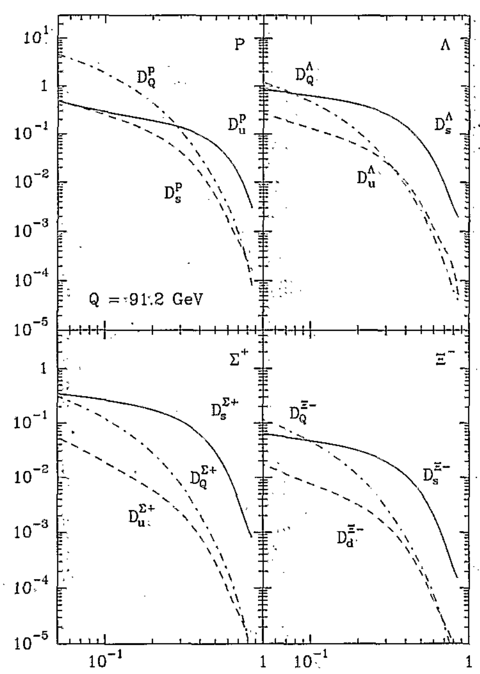

Fig. 1. Fragmentation functions (D_{quark}^{baryon}) for the octet baryons (p, λ, Σ, and Ξ) as a function of x_{BJ} [5]. Contributions of the light (u,d), strange (s), and heavy (Q) quarks are denoted by subscripts.

In p+p interactions selective kinematic cuts can be implemented in two-parton scattering to study quark versus gluon jets in away-side $p_\perp$ distributions and their particle content. In $A+A$ interactions the ratios of leading anti-particles to leading particles, such as $\overline{p}/p$ and K^-/K^+, at high $p_\perp$ can be used to distinguish energy loss differences between gluon and quark jets [2] in the medium by comparing to results from $p+p$ and $p+A$ interactions. Although gluon jets dominate at the highest RHIC and LHC energies, pQCD calculations of jet production predict that quark jets will become dominant below $\sqrt{s_{NN}} \sim 50$ GeV at transverse momenta above 8 - 10 GeV/c. The flexibility and high luminosity of RHIC II will allow detailed study of both the gluon- and quark-dominated regimes. These studies require particle identification at large $p_\perp$.

It is essential to measure the nuclear parton distributions at low-x_{BJ} and distinguish x_{BJ}-dependent effects in the initial stages in order to characterize the evolution of the system from the initial stages to formation of the QGP. Measurements at large (forward) rapidities require that faster partons in one projectile be used to probe soft low-x_{BJ} partons in the other. Thus, at large rapidities, we probe aspects of the nuclear wave function where parton densities are sufficiently large that saturation phenomena should occur (nuclear shadowing, possibly a color glass condensate [7, 8, 9]). This also requires studies of $p+p$ and $A+A$ collisions with instrumentation and measurements in the forward direction in correlation with those at mid-rapidity. Jet correlation measurements over a large pseudorapidity interval with large acceptance in azimuth are necessary to distinguish the x_{BJ}-dependent evolution of the collision process and the different properties in the propagation of light- and heavy-quark jets and gluon jets. All of this is necessary to understand completely the overall collision process from a possible color-glass condensate at low-x_{BJ} in the colliding nuclei to the formation of the QGP.

3. Quarkonium Physics

The production of quarkonium states in $p+p$, $p+A$, and $A+A$ collisions provides an excellent tool to probe deconfinement in strongly interacting matter [10]. To date, studies have focused on measurements of the charmonium states, which have large production cross-sections compared to the bottonium states. Bottonium spectroscopy in $A+A$ has other advantages compared to charmonium spectroscopy. Bottonium is massive ($m \sim 10$ GeV/c^2) and its decay leptons have large momenta making them easy to distinguish from background electrons. Furthermore, interpretation of charmonium suppression is complicated by the rather large cross-section for absorption by co-moving matter, while bottonium absorption by hadronic comovers is expected to be negligible [11].

Studies of the dependence of the heavy-quark potential on the in-medium temperature in QCD lattice calculations with dynamical quarks [12] indicate a sequence of melting of the quarkonium states. Because of its low binding energy the $\Upsilon(3S)$ is expected to dissolve at temperatures below the critical deconfinement temperature T_c. The $\Upsilon(2S)$ dissolves at similar temperatures as the J/ψ, while the $\Upsilon(1S)$ remains unsuppressed to temperatures well above T_c. Therefore, a measurement of the yields of the various bottonium states will shed light on the production (via Υ(1S)) and suppression mechanisms (Υ(2S) and Υ(3S)) of quarkonia avoiding many difficulties inherent in charmonium measurements. These measurements are challenging, requiring excellent momentum resolution to resolve the bottonium states and very high rate (luminosity) and trigger capabilities because of the low production cross-section. These states can be resolved in the comprehensive new detector system that is proposed, as will be seen later in this document.

Quarkonium production is not understood to a large extent and requires further detailed investigation. Since the octet production matrix elements of NRQCD lead to a polarization pattern different from the color singlet model, a polarization measurement can provide significant insight into quarkonium production. For example, quarkonia at large $p_\perp$ are predicted to be almost completely transversely polarized, as they result primarily from gluon fragmentation. At smaller $p_\perp$ around $p_\perp \sim 5$ GeV/c, the quarkonia are predicted to be produced essentially unpolarized. Determination of the polarization as a function of $p_\perp$ is essential to test the underlying theory. Recently the measurement of quarkonium polarization in $A+A$ collisions was suggested to be an indication of QGP formation [13]. Since gluon fragmentation begins to dominate quarkonium production at $p_\perp > 5$ GeV/c, the $p_\perp$ dependence of quarkonium suppression should provide a better understanding of the transition from heavy-quark pair propagation to gluon propagation. Furthermore, the quarkonium mass establishes the degree of virtuality of the fragmenting gluon, thus the dependence of the energy loss on the extent to which the gluon is off-shell can be studied. These measurements all require a large acceptance detector and large statistics.

At relatively large transverse momentum typical quarkonium suppression effects such as color screening become negligible, and any color octet can suffer jet quenching. This quenching can provide a unique experimental probe for studying energy loss and color diffusion [14]. The relative yields of charmonium resonances is an experimental tool for studying such phenomena because each resonance may have a different octet contribution. Since a variety of competing charmonium production models exist, it is essential to investigate production mechanisms in $p+p$ and $p+A$ interactions, all at low x_F (central region) and high x_F (forward region) [15, 16]. Dead cone or other effects can be important for heavy quark systems [4]. Studies of very high $p_\perp$ charmonium can provide additional information to resolve these issues.

4. Forward Physics

One of the major recent developments in high energy nuclear physics is the *color glass condensate (CGC)* [7, 8]. At very low x_{BJ}, gluons can be coherent over large longitudinal distances. The coherence reduces the entropy of the final state. This leads to the importance of studying high $p_\perp$ processes away from midrapidity. A signature of the CGC in the forward region is a systematic hardening of the particle spectrum due to gluon recombination, associated with a suppression relative to p+p physics [9]. This may already be visible in recent d + A data taken by BRAHMS at forward rapidities [17], although it must still be determined whether this is a true saturation effect. Particle identification (PID) whether measured directly or by means of weak decays, will be important in elucidating the various particle production mechanisms, which have different sensitivities to the quark and gluon components of the hadronic wave functions. Saturation provides a natural theoretical explanation of the phenomenon of "nuclear shadowing", a depletion of the nuclear structure function at low x_{BJ}. This should have effects on many hard physics observables which depend directly on the gluon structure, e.g. minijet rates and heavy flavor production, which can be clarified by comparisons of $p+A$ physics with $p+p$.

One approach to forward physics at RHIC II is to extend substantially the detector acceptance forward to allow *unique global measurements* that are unavailable at the LHC. These include measurement of high $p_{\perp}$ particles as a function of rapidity out to the kinematic limit, extensive PID capabilities, and acceptance sufficient to measure total energy flow event-by-event. To take full advantage of physics in the forward region, one must be able to perform momentum measurements and PID up to $p_{\perp} \sim 2$-3 GeV/c, a challenge with longitudinal momenta of 20-30 GeV/c at large rapidities. It is also important to understand the process of energy deposition in the collision process. Thus, both from the global variable and "parton" perspectives, there are compelling reasons to fully instrument the forward region.

Important components of understanding the collision dynamics at RHIC are the physics underlying the longitudinal particle and energy distributions and collective flow at mid- and forward-rapidities. This will require extension of high resolution particle tracking and calorimetry to forward rapidities. It remains to be determined how charge, flavor and baryon number are distributed over all of phase space in RHIC collisions. These measurements address fundamental concepts like baryon number conservation, whose dynamics are not fully understood in QCD.

5. Spin Physics

The potentially exciting topics in polarized proton-proton collisions that are of interest for a new spin physics program at RHIC II can be divided into four areas: heavy quark production, jet physics, electroweak physics, and physics beyond the Standard Model. The strength of a RHIC II polarized $p+p$ program to probe effectively these rare processes will depend on the capabilities of this comprehensive new RHIC II detector.

The *production of heavy quarks* is dominated in $p+p$ collisions by gluon-gluon fusion. In a leading order approximation [18] heavy-quark production in polarized $p+p$ collisions constrains the underlying gluon polarization. Next-to-leading-order (NLO) QCD corrections to the production of heavy flavors [19] are important for reliable predictions. Charm and bottom production access different regions of x_{BJ}.

Heavy flavor measurements will rely on leptonic decay channels. In addition, B-tagging via the J/ψ ($B \rightarrow J/\psi + X$) through displaced electron vertices provides identification of open beauty and probes the gluon polarization.

The *unpolarized production of heavy flavors* has attracted much attention recently, since beauty production has exhibited significant discrepancies between theory [20] and the data reported at HERA [21] and LEP [22]. This has led to descriptions of bottom production in terms of physics beyond the Standard Model (SM). RHIC II could play an important role in understanding this discrepancy through investigation of the energy- and spin-dependent charm and bottom production.

The production of *jets in polarized p+p interactions* probes the gluon polarization [23] in the proton. The quark-gluon Compton, gluon-gluon and gluon-quark processes are important to jet production. The addition of hadronic energy information in the comprehensive detector would allow precision jet measurements, correlations and triggering, while extending the RHIC II polarization program to larger jet $p_\perp$ and pseudorapidity.

Measurement of the *parity-violating longitudinal single-spin asymmetry* A_L in W production is a probe of the underlying polarized quark and anti-quark distributions [24]. Results obtained in polarized DIS experiments suggest that the QCD sea is significantly polarized [25]. It is crucial to explore W production in polarized $p+p$ collisions to determine if the polarization of the QCD sea is shared by quarks and anti-quarks and if there is any flavor dependence. The difference of the unpolarized anti-quark distributions is nonzero in the region of small x_{BJ} [26]. This strong breaking of SU(2) symmetry has several possible explanations in non-perturbative QCD [27]. The measurement of W production through the electron/muon decay channels at high $p_\perp$ provides a clean separation of the underlying quark distributions. A hermetic detector system as proposed would allow measurement of the missing energy in the unobserved final-state neutrino and reconstruction of the underlying kinematics.

There may be *physics beyond the standard model (SM)* in the form of new parity-violating interactions. Parity violation arises within the SM for quark-quark scattering through an interference of gluon- and Z^o-exchange. There are differing predictions for various scenarios of physics beyond the SM, e.g. contact interactions and supersymmetric models [28]. A polarized RHIC II program will place constraints on several models by selection of a specific region of phase space unconstrained by the experimental efforts at the Tevatron. RHIC II would therefore be in a unique position to explore physics beyond the SM, and the capabilities of a comprehensive new detector benefit these studies.

The present understanding of the origin of spin asymmetries is based on the propagation of polarized quarks and gluons in external color fields of the hadron. One can understand this physics better if the strength of the color field can be varied by utilizing nuclei in polarized $p + A$ collisions.

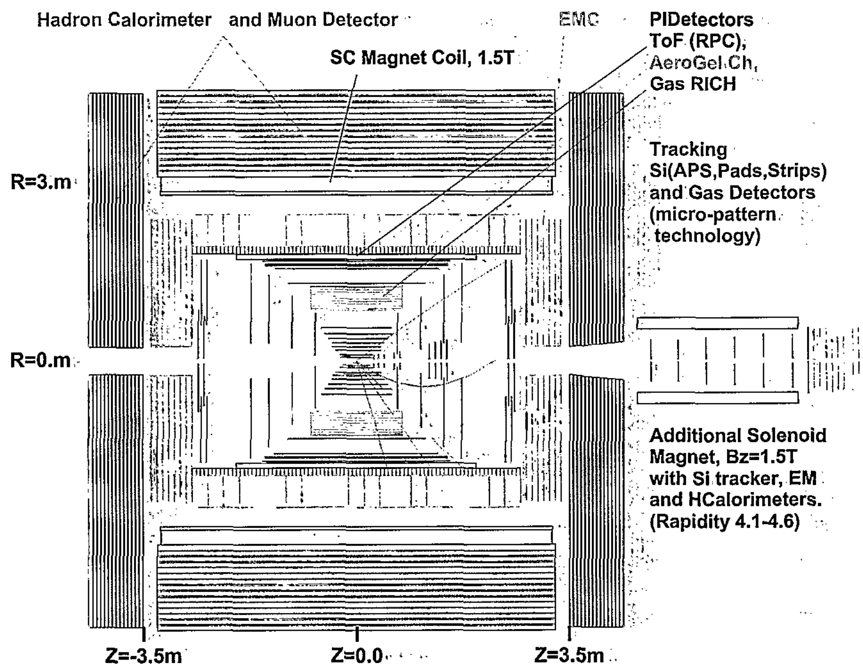

Fig. 2. Diagram of the new detector using the SLD magnet.

6. Comprehensive New Detector and Performance

The requirements for a new RHIC II detector are well defined by the physics topics discussed in the previous sections and are quite stringent. The primary requirements are: 1) excellent charged particle momentum resolution to $p_\perp = 40$ GeV/c in the central rapidity region; 2) complete hadronic and electromagnetic calorimetry over a large phase space ($\sim 4\pi$); 3) particle identification out to large $p_\perp$ ($\sim$ 20 - 30 GeV/c) including hadron (π;K,p) and lepton (e/h, π/h) separation in the central and forward region; 4) high rate detectors, data acquisition, and trigger capabilities.

In particular, we expect to procure an existent high field magnet, muon tracking, and a large amount of electromagnetic and hadronic calorimetry. As a proof of principle, we employ the SLD magnet, which is available, with additional superconducting coils to increase the field strength to B = 1.5 T. The inner radius of the magnet is 2.8 m, with an inside length of 6 m. The large magnet diameter is necessary for tracking and particle identification detectors and electromagnetic calorimetry (EMC). This provides a bending power of 3.0 T·m over a tracking volume of radius 2 m. The SLD magnet comes with hadronic calorimetry and muon detection embedded in the iron covering $-3 \leq \eta \leq 3$. A possible layout for a RHIC II detector using the SLD magnet is shown in Fig. 2.

A very high resolution vertex detector made from 4 - 5 layers of thin silicon will be necessary for unambiguous track-seed determination and for displaced-vertex tagging of b- and c-jets. With silicon and micro-pattern pad detectors in the SLD magnet we should reach a momentum resolution of $\delta p_\perp / p_\perp \sim 1$ % at 20 GeV/c and ~ 3 % at 40 GeV/c. The momentum resolution from full-scale simulations of the detector setup of Fig. 2 are presented in Fig. 3. The two-track resolution for any charged-particle pair will not exceed 500 μm.

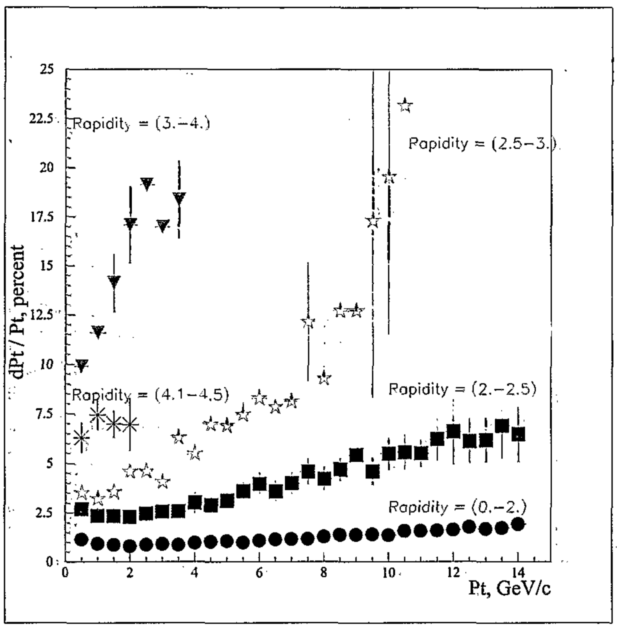

Fig. 3. Momentum resolution $dp_\perp/p_\perp$ in percent for pseudorapidity cuts $0 \leq \eta \leq 2$ (•), $2 < \eta \leq 2.5$ (■), $2.5 < \eta \leq 3$ (∗), $3 < \eta \leq 4$ (○), and $4.1 \leq \eta \leq 4.5$ (▲).

The requirement to identify all hadrons in a high $p_\perp$ jet requires good hadron identification 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 dE/dx in the tracking ($p_\perp < 1$ GeV/c), a time-of-flight device ($p_\perp < 3$ GeV/c), and a combination of two different Aerogel Cherenkov-threshold counters and a RICH detector with gas radiator (up to $p_\perp \sim 20$ GeV/c). The time of flight device should be based on resistive plate chambers with operation in a large magnetic field. For more details on the comprehensive new detector see [29].

An EMC would be installed directly in front of the SLD magnet coil, i.e. at 2.8 m radius covering the barrel and in front of the endcap hadron calorimeter. Different technologies are presently foreseen for the EMC barrel and endcap sections. A fine-granularity crystal detector, such as the existing CLEO crystal calorimeter with its excellent energy resolution, would be superior and is under consideration. With the high luminosity at RHIC II and fast detectors there will be sufficient statistics in the away-side jet and particle spectra for photon-tagged jets out to a photon $p_\perp \sim 20$ GeV/c in this detector.

Studies have shown that an energy resolution of better than $10\%/\sqrt{(E)}$ is required to resolve the quarkonium states with calorimeter information alone. This clearly shows that the quarkonia physics can only be fully realized when using the EMC in combination with high resolution tracking and a muon chamber. Displayed in Fig. 4 are the results of simulations using the experimental setup of Fig. 2.

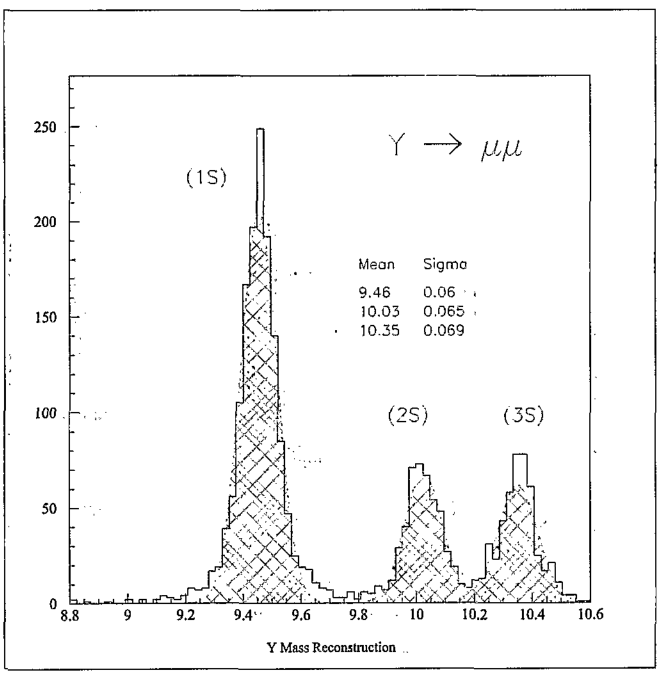

Fig. 4. Mass resolution for the Υ(1S), Υ(2S) and Υ(3S) states from reconstructed muon tracks in simulations. The background is not realistic for $A+A$ collisions.

The detector envisioned here requires acceptance far exceeding the current RHIC experiments, both in terms of particle tracking and calorimetry. This is driven by requirements of both the proton-proton program, which needs forward coverage (e.g. to detect the decay products of vector bosons) as well as the $p+A$

and $A+A$ program, that are concerned both with the dynamics of nuclear stopping and the details of nuclear shadowing.

With respect to bulk matter measurements in the forward direction, precise tracking is required to identify any modification in spectral shape with increasing rapidity. To make heavy flavor and jet measurements, several approaches can be taken in the forward region. Beyond $\eta = 3$ dedicated particle identification and tracking become complicated. A high precision 'plug' calorimeter consisting of a crystal-based electromagnetic section and a hadronic calorimeter based on Si-W could be used in the small opening of the SLD magnet in the forward direction. Finally, very forward hadron detectors based on Roman pots instrumented with scintillating fiber spectrometers can be located at very large distance (30 - 50 m) from the interaction vertex. These detectors allow measurement of the forward protons for triggering on diffractive processes (e.g. pomeron exchange, rapidity gap measurements). Using a combination of additional strong dipoles (e.g. RHIC DX design) in the forward direction, tracking modules (GEM and Si strips) near the beam-pipe, and calorimeter modules just outside these, one may be able to achieve full coverage for complete tracking and energy measurements out to very large pseudo-rapidity.

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29. for more detailed information see http://star.physics.yale.edu/users/harris/.