STUDIES OF HOT AND DENSE NUCLEAR MATTER

Continuation Progress Report
DOE contract DOE DE-FG02-96ER40982

Relativistic Heavy Ion Physics Group
Department of Physics and Astronomy
The University of Tennessee
Knoxville, TN 37996-1200

GROUP MEMBERS

Faculty: Prof. Soren P. Sorensen (PI), Assoc. Prof. Kenneth F. Read.

Research Associates: Dr. Vasily Dzordzhadze.

Graduate Students: Irakli Garishvili, Andrew Glenn, Jason Newby, Donald Hornback.

FUNDING SUPPORT (2001 – 2005)

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Overview and Personnel

2003 was the 8th year that the Relativistic Heavy Ion Physics (RHIP) group at the University of Tennessee (UT) has had its own research contract. The contract started June 1, 1996. Since its inception, the RHIP group has focused its research on four topics within the large domain of Relativistic Heavy Ion Physics: a) Nuclear matter at extreme temperatures and densities, b) Nuclear stopping power and attained energy densities, c) Charm production in general and modification of charmonium, in particular, in hot and dense nuclear matter, and d) Proton spin physics. The group is primarily involved with and responsible for the Muon Identifier sub-detector in PHENIX and the data analysis efforts related to the data obtained from the PHENIX muon detectors. Additionally, we have signed up for ALICE, but have not yet allocated substantial effort to this experiment.

The RHIP group members in 2003 were:

Soren P. Sorensen: Principal Investigator, Professor and Department Head. Member of PHENIX, ALICE and WA98. Primary advisor for Andrew Glenn and Jason Newby.

Kenneth F. Read: Associate professor at UT and senior research staff member at ORNL. Detector Council representative and Subsystem Manager for the PHENIX Muon Identifier. Member of PHENIX and ALICE. Primary advisor for Irakli Garishvili and Donald Hornback.

Vasily Dzordzhadze: Post-Doctoral Research Assistant. Vasily is our BNL on-site muon identifier expert. Vasily has contributed substantially to the installation and commissioning of the PHENIX north muon arm, and the maintenance and operation of the south muon arm. In particular, he has worked on all aspects of the MuID shielding issues, the muon identifier (MuID) high voltage system and the development of the Level 2 trigger. In addition, he has been responsible for our MuID simulation package. This has been especially important in tracking down the origin of various background problems.

Jason Newby: Jason graduated in September 2003 with a Ph.D. His thesis topic was “J/Psi Production in Au-Au Collisions at sqrt(s) = 200 A GeV.” He has been involved in testing and implementation of PHENIX MuID front-end electronics, testing and developing MuID offline event reconstruction software (in particular the road finder module), and developing Level 2 trigger algorithms. In October 2003 he commenced a post-doc position with Ron Soltz’s group at LLNL.

Andrew Glenn: 7th year graduate student. Andy has been involved with on-site testing and implementation of PHENIX front-end electronics. He has been responsible for noise and timing studies, online monitoring of high voltage and detector performance, and studies of the efficiencies of the MuID detector. He has also worked on the installation and commissioning of the north MuID and on the development of an improved mu/pi separation algorithm. Andy is scheduled to finish during the summer semester 2004 and...
is currently writing his doctoral thesis on “Single Muon Production” based on Run 2 Au+Au data.

**Donald Hornback:** 2nd year graduate student. He has been an undergraduate physics student at University of Tennessee and joined our group as a graduate student in January 2003. He has spent time at BNL with Andy and Vasily learning to be a MuID on-call expert. He has contributed to the MuID high voltage monitoring software.

**Irakli Garishvili:** 1st year graduate student. Irakli joined us as a graduate student in August 2003. He has a M.Sc. in Physics from Tbilisi State University in Georgia. He has helped set up a new laboratory and begin test the performance of Iarocci tubes (identical to those used in the MuID) containing flammable gas mixtures.

**Highlights for 2003 (elaborated below)**

- Critical role in successful operation of the PHENIX MuID
- Critical role in successful effort to implement tunnel shielding for Run 4
- Major contributor to the PHENIX single muon analysis effort
- $J/\psi$ analysis of Au+Au RHIC Run-2 data
- $R_{cp}$ analysis in d+Au

**Budgetary Issues**

The proposed budget for the period June 1, 2004 – May 31, 2005 is $205,000 and is unchanged from the revised 3rd year budget submitted as part of the renewal proposal in the spring of 2002. As of January 31, 2004 (8 of 12 months) we have spent $161,000 of the total allocation of $205,000. Since we are collecting data during the period February through May 2004, we expect significantly travel during this period. Our financial projection to May 31, 2004 indicates that we will have no surplus, nor a deficit on May 31, 2004.

The aims of this proposal are unchanged from the original renewal application.
PHENIX Related Research

After almost a decade of preparation, and three years of successful data collection, PHENIX now enters its fourth year of operation as an established successful experiment. Both muon arms are now fully operational. The installation of extensive shielding in the RHIC tunnel has reduced the background in the Muon Identifier dramatically and the data taken currently as part of the Run 4 seem to be of outstanding quality. The first paper based on data from the muon arms has been published and multiple publications are now in preparation. We can truly claim that the Muon Identifier has finally come of age!

University of Tennessee is one of the top two most active institutions on the Muon Identifier team. Our contributions have been indispensable. This past year we maintained a larger continuous presence at BNL than any other MuID institute. There presently are more FTEs from our institute actively involved on the MuID project than any other institute. We played a pivotal role in the construction and commissioning of both arms of the MuID, are one of the lead institutes maintaining the successful operation of the MuID, and are a primary source of graduate student involvement in muon arm physics. With four graduate students, one postdoc, and two faculty members involved, we also play a major role in development of muon reconstruction software and data analysis.

Our group continues to carry out major responsibilities within the PHENIX Muon Arms subsystem. This work is performed in close collaboration with ORNL, which has the overall responsibility for the Muon Identifier System. The main accomplishment in 2003 was the design and installation of the shielding in the RHIC tunnel that has had a dramatic effect in reducing the background in the Muon Identifier. This on-time, on-budget, successful effort was essential to securing satisfactory muon arm data quality for Run 4.

In 2003 two of our graduate students, Jason Newby and Andy Glenn, both concentrated on their thesis research and the write-up of their theses. A large part of this annual report will focus on their work on J/Ψ and single muon production based on analysis of the Run 2 Au+Au data. This data analysis has been a tour-de-force since Run 2 was the first run for which the South Muon Arm was operational. Major efforts have gone into debugging and understanding this initial dataset. Jason’s analysis demonstrated that the limited size of the good data sample from Run 2 proved to be too marginal to reach firm conclusions concerning J/Ψ suppression and/or enhancement.
**J/ψ Analysis (Jason Newby)**

**Data Production**

In 2002 our group led the development of a new compact data format for muon data suitable as input for nearly complete reprocessing that successfully allowed future improvements to tracking and pattern recognition software to be incorporated while avoiding the substantial overhead of completely reprocessing the PHENIX raw data. The muon arms team continues to benefit from this contribution. In March of 2003 the initial processing of the Run 2 Au+Au data was completed. In the mean time, we worked with the muon pattern recognition group to improve the MuID aspect of tracking through recovered efficiency and ghost rejection. The low occupancy of the proton-proton environment provided an important arena to bootstrap the J/ψ analysis in a reasonably clean environment. In April, we performed the first reconstruction pass on the compact-format Au+Au data at the RHIC computing facility applying the reconstruction improvements from the proton-proton analysis. A total of 7.6 million minimum bias Au+Au events were fully reconstructed.

**Evaluation Software**

While many improvements were made to the muon reconstruction and pattern recognition, finite non-zero inefficiencies and associated kinematic and event class dependencies of those inefficiencies are inescapable. The embedding procedure our group developed in the previous year facilitates a mechanism by which these effects can be quantified. The response of the muon detector to a J/ψ signal is simulated and then combined with the signals recorded from a real Au+Au collision. By using the real data we are assured the backgrounds are properly represented over the varied event classes of the Au+Au collision environment. The embedding procedure allows identical reconstruction software to be applied to the embedded event and real data.

After a signal has been embedded in a real event, evaluation algorithms must determine if the signal was properly reconstructed. As part of Jason’s thesis analysis of J/ψ production, evaluation software was developed to determine the reconstruction efficiency for a dimuon signal for each class of Au+Au collision centrality. Thousands of J/ψ signals were simulated under a variety of detector configurations, tripped high-voltage channels, dead read-out electronics, et.c associated with the actual detector performance at the time the Au+Au collisions were recorded. The acceptance loss and reconstruction efficiency for the J/ψ is shown in 1. The hit occupancies in the recorded data are a factor of two more than anticipated from previous simulations. The result is an efficiency dependence varying by a factor of three with collision centrality.
Figure 1. The combined acceptance and efficiency for the J/ as a function of collision centrality is determined by embedding a simulated signal into a measured Au+Au collision.

J/ψ Production

On September 17, Jason successfully defended his Ph. D. Thesis entitled “J/ψ Production in Au+Au Collisions at √s_{NN} = 200 GeV.” In this work, he presented the first analysis of J/ψ production at forward rapidity in the RHIC heavy-ion program. Ultimately, 5.6 million Au+Au events were considered in the analysis after data quality selections were made. The J/ψ signal would be expected in an invariant mass spectrum of unlike-sign muon pairs. An extrapolation of measurements from lower energies indicates that about 20 J/ψ’s were produced within the acceptance of the detector in these 5.6 million recorded events. This small signal would lie on top of a large combinatoric background estimated at 36,000 counts within a 2σ (600 MeV) mass window. Single track and track-pair quality cuts were optimized to reduce this background while minimizing impact on the signal efficiency. The combinatoric background is well described by forming the same invariant mass spectra for like-sign muon pairs as shown in Figure 2.

Figure 2. The invariant mass of like sign-pairs (circles) and unlike-sign muon pairs (crosses).
A statistically significant signal was not observed in this small dataset or in any other centrality class subset as discussed in his thesis. While limited statistics prevent a determination of the production cross section, upper limits on production may be extracted from the data in a log-likelihood analysis. The 90% confidence level upper limits are shown for three centrality classes in Figure 4. The results are consistent with a binary scaling of the PHENIX proton-proton measurement and in fact even the most extreme enhancement scenarios. More statistics will be required for this analysis to provide any discrimination of competing theoretical predictions. Based on the initial indications from the current Run 4, this year’s data definitely have the potential to provide the additional needed statistics.
Figure 3. The dimuon unlike, like, and subtracted invariant mass spectra are considered in three centrality classes: first row (0-20%), second row (20-40%), and third row (40-90%).

Figure 4. The $J/\psi$ invariant yield per binary collision is shown for both the PHENIX proton-proton analysis and the thesis analysis of Au+Au collisions for three centrality classes.
Single Muon Analysis (Andrew Glenn)

The cross section for single muon production directly reflects the open charm production cross section, since the charmed mesons all have a substantial semileptonic decay branch. It is important to measure both the open charm and the charmonium cross sections in order to unravel the relative contributions from charmonium suppression, a possible consequence of color screening, and charmonium enhancement, as predicted by coalescence/recombination theories. Since charm, which predominantly is produced through gluon fusion, is sensitive to the gluon distributions, single muon production may be subject to interesting initial state effects such as gluon saturation and the postulated color glass condensate. At UT Andy Glenn made substantial progress this year in the analysis of the complicated data on single muon production in RHIC collisions.

There are in general three main sources of what looks like single muons. The signal for this analysis is muons originating from “prompt” decays of heavy flavor mesons. The background for this prompt component are (a) muons from decay of lighter meson (primarily pions and kaons) anywhere in the detector, and (b) hadrons that punch through the MuID and therefore look identical to a penetrating muon.

Muon/Hadron separation

Muon/hadron separation can be done at a fairly effective level with a combination of particle momentum information from the Muon Tracker, and Muon Identifier depth information as seen in Figure 5. While this method does help with getting a fairly clean sample of hadrons to study for particles stopping before the last gap, it is not directly applicable to particles which penetrate the entire MuID. Cuts on road and track parameters and searching for hadronic showers can help with reducing the hadronic contribution to the last gap sample, but these have not yet been proven very effective in the Au+Au Run 2 high multiplicity, partially shielded environment. Quantifying the fractions of roads which are shortened by tube inefficiencies or extended by combinatorics is also important for momentum/depth matching. Simulations with embedded data and realistic tube efficiencies have been crucial in understanding these issues. Upgrades, such as a Cherenkov detector placed after the MuID, are under consideration which would significantly enhance muon/hadron separation for high momentum particles.
Figure 5. Longitudinal momentum distributions of muon candidates, as measured at the MuTR station closest to the MuID. The right figure shows a comparison of peripheral data to muons from HIJING simulations. The data and simulation are normalized by the peak. The peak is associated with muons which range out and stop in the MuID steel. The long tail of the distribution comes mainly from hadrons which interact strongly in the absorber and stop earlier than a muon with the same momentum would.

**Decay Muons**

The first line of defense against muons from hadron decays is an absorber which is located 40 cm from the nominal collision vertex. This absorber stops most hadrons before they have a chance to decay. Collisions farther from the absorber will contribute more decay background than those which are close. Since $\gamma \tau >> 40$ cm for relevant hadrons, $c \tau = 780$ cm for $\pi^\pm$, we should see a linear rise in the decay background with increasing vertex. This effect is demonstrated in Figure 6 which contrasts the vertex distribution of particles which penetrate the MuID with the vertex distribution of stopped particles with high longitudinal momentum, which should be hadron dominated as described above. This property can be exploited to study properties of the decay component. By subtracting a distribution for particles of near events, $Z = \{-20,9\}$, from that of far events, $Z = \{9,38\}$, while correcting for a non-flat event vertex distribution, properties of the decay muons can be examined. This has been done for transverse momentum in Figure 7.
Figure 6. Event vertex distributions, as measured by the Beam-Beam Counter, for different particle classes. These have been divided by the raw minimum bias BBC vertex distribution. The large contribution of muons from hadron decays is responsible for the linear rise of the left distribution. The right figure is for particles which stopped before the last gap of the MuID and had a longitudinal momentum greater than what would be expected for a muon stopping at the given gap. The flat vertex distribution demonstrates that there is no significant decay muon contribution.

Figure 7. Raw transverse momentum spectrum of the decay muons. Not efficiency or acceptance corrected.
Simulations used to extract the single muon signal

Some initial work was done to estimate the background contributions using HIJING simulations, but this method suffers from large computing requirements and more importantly from problems with the tuning of K to π ratios and kinematic distributions at RHIC energies. With the recent release of preliminary π and K data from BRAHMS for muon arm rapidities, we have developed a data driven simulation input. Due to differences in interaction and decay lengths it is essential that realistic yields and p_{T} distributions are used for simulation input. Currently the data is only for the 5% most central collisions, so we would like to make use of the PHENIX data at mid-rapidity since information for more centralities and broader p_{T} ranges is available. This would require that the production as a function of y and p_{T} can be approximately factorized. If we use the BRAHMS dN/dy distribution to scale the BRAHMS p_{T} distributions at muon arm rapidities to y = 0 we can compare them to the PHENIX distributions. This is shown in Figure 8 for π and K. There appears to be very good agreement between the PHENIX and the scaled BRAHMS data. We have used the BRAHMS p_{T} and dN/dy distributions as the foundation for a particle generator. These are run through the full simulation and reconstruction which includes our best estimate of detector efficiencies. From this initial study, the hadron to decay contribution of stopped particles goes from roughly 3:2 at gap 2 to 1:10 at gap 4. The hadron component is quite sensitive to which hadron shower package is used by GEANT. These quoted results are based on FLUKA. Currently GEISHA is being investigated.

Figure 8. The BRAHMS dN/dy shape, right, is used to scale the forward rapidity data to mid-rapidity. The good agreement of this scaled BRAHMS data with PHENIX data for 5% most central collisions is shown left.
Future Single Muon Analyses and Simulations

As just discussed, our group is very active in pursuing single muon analyses. Andy’s thesis concerns Run 2 Au+Au data and we expect to be a key player in an eventual publication concerning Run 2 single muons. Ken has recently been quite involved coordinating a roadmap to unite a variety of approaches initiated in 2003 concerning single muon physics. This analysis is one of the most challenging that PHENIX has yet attempted. Pioneering this effort has been a major development. Ken has been leading the development of an optimized program of simulations that should be feasible to complete on our timescale. We look forward to an important publication on this topic by late 2004.

RCP Measurements

Backgrounds for a prompt muon analysis, such as muons from hadron decays and interacting hadrons, are actually of significant physics interest, particularly in d+Au collisions. The rapidity and centrality dependence of hadron production in p(d)+A is important in examining possible effects of shadowing and the color glass condensate. The ideas described above in the single muon analysis section for separating these backgrounds have been used by PHENIX to measure the ratio of hadron production for various centrality classes relative to the peripheral collisions at forward and backward rapidities using data from the muon arms. The preliminary measurements are shown in Figures 9 (stopped hadrons) and 10 (decay muons). Although UT did not have a lead role in this analysis, Ken and Andy were active in the associated analysis discussions.

![Figure 9](image)

**Figure 9.** The ratios of central (0-20%) to peripheral (60-88%) charged hadron production in $\sqrt{s_{NN}} = 200$ GeV d+Au collisions. Black points were measured using stopped hadrons detected in the muon arms.
Figure 10. The ratios of central (see graph) to peripheral (60-88%) muon production from hadron decays in $\sqrt{s_{NN}} = 200$ GeV d+Au collisions.

Contributions to the hardware development of the PHENIX Muon Arms

The south muon arm is now entering its third year as a fully commissioned, operational part of PHENIX. The north muon arm installation was completed in 2002, and is now in its second year of operation and is functioning extremely well. One of us (Ken) is the Detector Council representative for the MuID. He has lead responsibility for coordinating a wide range of efforts that have concerned the MuID design, installation, and on-going maintenance. Recent contributions concern playing a lead role in coordinating shielding efforts, data production issues, and high voltage monitoring and control developments. He also chairs the weekly muon arm group meeting.

High Voltage

Our group has continued to play a major role in performing maintenance on the MuID HV system and in improving the associated monitoring and control software. We have developed new software to display and log slow control data from the MuID HV system. This has been of particular interest recently since the MuID HV current draws provide important indications of the location and intensity of beam related backgrounds from the RHIC tunnel.
Shielding

A tremendous accomplishment this year was the design and installation of additional shielding in the RHIC tunnel to reduce the beam-related backgrounds in the Muon Identifier. We observed that there was much higher hit rates in the back plane of the MuID, gradually reducing when moving towards the vertex. This behavior of the hit rates indicates that the source of particles is located in the RHIC tunnel, behind the MuID detector.

The primary source of the tunnel background are the beam particles scraping somewhere along the ring, falling out of orbit and showering in the beam pipe upstream of the MuID.

Figure 11. High Voltage and Currents for the Muon Identifier under High Background Conditions during Run 3

Figure 11 illustrates the problem of the tunnel background. It shows for each south MuID HV channel the voltage and current values at a particular period during Run 3. Green corresponds to the normal normal current draw, yellow indicates high current draw, and red indicates a channel which has tripped. The background conditions during the 2003 RHIC run were so severe that it was occasionally necessary to switch off the MuID at the beginning of spills, thus losing some of the highest intensities available. High background rate creates other problems, like too many false hits in the MuID channels and possibly premature aging of tubes.

RHIC personnel conducted a study to determine a shielding configuration and composition of the shielding material. A study was performed by RHIC, using the MCNPX code, to determine an optimal tunnel shielding. This study concluded that the
total interaction length is the most crucial factor for the suppression of the background, even for slow neutrons. Therefore it is useful to use a lot of steel.

Figure 12. Muon Identifier tunnel shielding configuration implemented for Run 4 (on either side of PHENIX)

Figure 12 shows the MuID tunnel shielding configuration for Run 4. The configuration was chosen by available shielding material sizes, crane operation features in the RHIC tunnel and the necessity to have access of the tunnel apparatus. It was impossible to locate shielding at the closest possible location to MuID, because of existing obstructions just after the MuID plates.
To estimate the impact on the MuID, we used the FERMILAB code MARS. These calculations show that it is primarily neutrons that are causing the large currents in the MuID Iarocci tubes. Figure 13 shows the MARS calculations of the neutron impact on the last layer of Iarocci tubes. The calculation correctly describes the excess of hits in upper part of the MuID due to the up-down asymmetry in the RHIC tunnel.
Figure A5:

Figure 14 shows the MuID HV system voltages and currents for Run 4. A comparison with Figure 11 reveals to what extent the installation of the tunnel shielding blocks dramatically improved the picture (*literally*). Most of the HV chains are green, which indicates normal operation. The MuID has come of age! Run 4 is positioned to be a great success. Our tunnel simulation effort and coordination helped secure this successful development.

Gas Mixture Optimization Studies at the Tennessee Campus (Donald Hornback, Irakli Garishvili)

With the goal of improving MuID detector performance, we are studying alternative gas-mixtures for use in the MuID. While the gas mixture and voltage settings currently used in the MuID were determined from studies performed at Oak Ridge National Laboratory in 1997, possible further increases in gas gain performance are now being considered for the MuID. The goal is to explore a possible increase in the efficiency of the limited streamer tubes while operating at lower voltages, relative to present detector performance.

The MuID currently operates with a two-gas mixture comprised of ~92% CO₂ and ~8% isobutane ((CH₃)₃CH). Previous studies in the literature suggest that the introduction of Argon as an additional gas component to the pre-existing two-component gas mixture in the MuID might provide the desired improvement in detector performance.

Use of Argon as an additional component in the present MuID two-gas mixture was first studied in limited fashion at PHENIX in June 2003. Results from this initial study did not show the desired improvements in detector performance, and it was determined that further, more flexible, study on this subject was desired, allowing for the adjustment of the various gas components and to allow for the total mixture to exceed the flammable gas limit of 8% isobutane.

Preparations for further study of this subject at the University of Tennessee began in August of 2003. The performance of various ternary gas mixtures is currently being analyzed in a test facility at UT, assembled and comprised of the same detector components as that of the MuID, to include the electronics and the limited streamer tubes.

Design of a Proposed New Nosecone Calorimeter for PHENIX

We performed numerous simulations as part of an exploratory effort to optimize the design of proposed new forward Electromagnetic (EMCAL) and Hadronic calorimeters (HCAL). These calorimeters are proposed for the PHENIX Trigger Upgrade Project. The study indicate the feasibility of incorporating such forward detectors without undue degradation of on the muon arm detection efficiency and resolution for J/ψ particles decaying into muon pairs.
The EMCAL would replace the current PHENIX nosecone and the HCAL would be positioned after the central magnet wall in front of the muon tracking system. It is important to estimate the affect of the introduction of this material on the $J/\psi$ yield, resolution, and backgrounds. Several different carefully chosen options concerning different detector thicknesses and materials were simulated in order to scope out the possibilities.

Figure 15. Simulated dimuon mass spectrum with a 19 cm Cu nosecone.

As an example of the simulations we performed, Figure 15 shows the simulated dimuon invariant mass spectrum for the case of a nosecone calorimeter composed of 19 cm of copper. Other designs considered are shown in Figure 16.
The results have provided preliminary indication that the proposed new EMCAL and HCAL could be used in trigger upgrade project for PHENIX without jeopardizing the existing muon arm physics program.
Publications and Talks

Refereed Publications


Submitted Publications


Talks or Invited Participation


Conference Contributions

