Hadronization and chirality in strongly interacting partonic matter - the future of the RHIC program

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Abstract. New physics and detector concepts for a future pp and heavy ion program at the RHIC-II accelerator facility will be discussed. I will focus on hadronic observables which enable us to gain a better understanding on the hadronization from a sQGP and the chiral symmetry restoration in a sQGP. The ultimate question of how matter acquires mass can be addressed by this program in a complementary way to the Higgs search in high energy physics. The contributions of the RHIC program to the study of QCD will be discussed in detail.

Keywords: RHIC-II, Relativistic Heavy Ion Collisions
PACS: 25.75.Ld, 24.60.Ky, 24.60.-k

1. Introduction

Over the past four years the ongoing RHIC-I program has attained an impressive set of data. The experimental findings and conclusions were summarized in four independent white paper documents by the four RHIC experiments [1]. All whitepapers concluded that a high density partonic matter state was formed, which exhibits very strong coupling. The collectivity of the state seems well described by hydrodynamical models assuming a very low viscosity [2]. In other words the system behaves more like an ideal fluid than a weakly interacting electromagnetic plasma, best shown by the good hydrodynamical description of the kinematic properties of the low momentum bulk matter formed in the interaction, in particular the elliptic and radial flow as a function of centrality [3],[4]. The strong mass dependencies of both measurements demonstrate the collectivity of most of the produced matter, i.e. the 99.5% of the particles with a transverse momentum of less than 2 GeV/c. The very small mean free path assumed in the hydrodynamical models hints at a rather strong coupling and large interaction rate among the relevant degrees of freedom, at least near the critical temperature. Furthermore the strength of the elliptic and radial flow can only be reproduced when one assumes a partonic equation of state.
for the early phase of the system evolution [5]. In these detailed calculations it was shown that about 80% of the collective flow is due to early partonic interactions, thus a purely hadronic phase can not account for most of the collective behavior. This is only an indirect and model dependent proof of a partonic state, though.

A more direct measure of the partonic nature of the new state is given by the interaction of hard probes, produced in the same collision, with the medium, in particular through measurements of nuclear suppression factors $R_{AA}$, elliptic flow $v_2$, and di-hadron correlations $\Delta \phi$ at high $p_t$ [3],[6],[7]. The nuclear suppression factors, i.e. the ratio of the particle momentum spectra in AA collisions compared to properly scaled pp collision spectra, shows that in AA collisions the spectrum is quenched at high $p_t$. A possible explanation of this effect is that in the dense partonic medium the fragmenting partons lose large amounts of energy due to radiative energy loss, i.e. gluon bremsstrahlung [8]. By comparing measurements of the suppression factor in central AuAu collisions at RHIC to central eA collisions at DESY, one can conclude that the energy loss in matter produced at RHIC is about 15 times larger than in cold nuclear matter [9]. The only possible explanation is the formation of matter with partonic degrees of freedom. This assumption is corroborated by the measurement of jet quenching through di-hadron correlations [7]. The away-side jet in a back-to-back di-hadron jet needs to traverse the medium and is apparently quenched in central AA collisions compared to pp collisions or peripheral AA collisions.

Finally the detailed particle identified measurement of elliptic flow and nuclear suppression factors at high $p_t$ seems to shed some light on the question of the nature of the partonic degrees of freedom above the critical temperature. In both measurements an interesting scaling has been found, which can be explained by assuming constituent quarks as the relevant degrees of freedom [10],[11]. There is a distinct baryon/meson difference in the kinematics which are dominated by patron interactions, i.e. the $v_2$ and the particle production above two GeV/c. Furthermore this baryon/meson difference seems to disappear at around six GeV/c which might signal the dominance of fragmentation as the main production mechanism at higher transverse momentum. Between two and six GeV/c the mechanism though seems to be recombination of constituent quarks, i.e. colored objects with a finite mass. Recombining quarks will not fragment. They need to be generated through strings, though, which means in order to have a pool of thermal partons to recombine, most strings have to dissolve during early times of the system evolution. This is most likely a $p_t$-dependent effect, i.e. lower momentum strings will dissolve whereas at higher momentum string fragmentation will still dominate.

In summary the RHIC-I measurements establish a new phase of matter, but the properties of this phase are unexpected and require further investigation, in particular because they seem to be sensitive to the hadronization mechanism from the plasma to the hadronic phase. This might enable us to answer a central question of QCD, namely how do hadrons attain their mass and how does the strong coupling evolve from the initial state down to the critical temperature. In the following I will discuss an experimental program which addresses the question of hadronization
and chiral symmetry by comparing detailed particle identified measurements in pp and AA collisions at RHIC-II.

2. Why is pp so important?

In order to understand the modification of the basic hadronization process in AA collisions we need to understand fragmentation in elementary collisions. This was a topic in high energy physics for many decades which culminated, from a theory point of view, in the so-called factorization theorem [12], [13]. Factorization means that in order to calculate the actual hadron production cross section in elementary collisions one needs to parametrize additional terms besides the hard parton cross section which can be calculated from first principles. The parametrization of a.) the initial parton distribution function PDF and b.) the fragmentation function FF is based on experimental results. These contributions to a next-to-leading order (NLO) perturbative QCD calculation have been studied in detail in the past [14], [15]. One conclusion was that fragmentation is universal, i.e. a FF parametrized for \(e^+e^-\) collisions can be applied to pp collisions [15]. This rule proved to be correct also at RHIC energies, where the early neutral pion measurements by PHENIX in pp collisions were very well described by FF deduced from \(e^+e^-\) experiments according to Kraemer, Kniehl and Poetter (KKP) [16]. When applied to higher mass mesons and baryons, though, the original parametrization failed, as shown in the comparison to preliminary STAR strange particle data [17] on Fig.1.

In a recent paper by Albino, Kraemer and Kniehl (AKK), it was shown that the RHIC data can be better described when quark separation in the FF is used, i.e. the contribution of each quark flavor to the final hadron is computed separately and then integrated to the final FF [19]. Interestingly the study by AKK on the strange mesons, and independently by Bourrely and Soffer on the strange baryons [20], shows that there are considerable contributions from fragmentation of non-valence quarks in the production cross section, in particular at low fractional momentum.
Fig. 2. Contributions of individual quark fragmentation functions to octet baryon production at $\sqrt{s}=91.2$ GeV in $e^+e^-$ collisions according to the statistical approach by Bourrely and Soffer [20].

z. Fig.2 shows the quark separated fragmentation function for octet baryons in elementary $e^+e^-$ collisions at $\sqrt{s} = 91.2$ GeV. Fig.3 shows a comparison of the AKK calculation using quark separated fragmentation functions to $K^0_s$ spectra from STAR and UA1.

One can conclude that the fragmentation process even in pp is more complex than originally thought, and measuring the particle identified yields of heavy particles in pp collisions at RHIC-II out to very high momentum is of utmost importance. In order to proof a particular quark contribution to a final hadron yield one might then be able use the medium modification of this traversing parton in the sQGP formed in AA collisions, as will be explained in the following section. One important point to keep in mind in the discussion of pp collisions is that a recombination model, which does not assume thermalized partons, but rather coalesces string partons with low momentum partons, can also describe the pp data [21], and in particular can describe certain measurements in elementary collisions such as leading particle asymmetries, which can not be explained by simple string fragmentation [22, 23].
3. Measuring medium modification in AA.

In order to determine a specific parton contribution to the hadronic cross section one might be able to use the medium modification of the fragmentation in AA collision, if one can show that different partons exhibit differing energy loss in the quenching medium. Most of the presently applied models assume that the energy is lost through gluon radiation, and they treat the partonic energy loss quite universal, i.e. no difference between parton flavors is assumed [24]. Recently though it was shown that in order to describe the large v2 at high pt it might be necessary to assume that there is also an enhanced elastic partonic cross section which leads to a stronger contribution from collisional energy loss [25]. This cross section will vary as a function of the parton momentum and the parton mass. In order to describe the high pt v2 this model overestimates the nuclear suppression factor, though. So a common description of R_AA and v2 at high pt is still an unresolved problem. Studying the nature of the energy loss in the medium in detail (collisional vs. radiative, quark vs. gluon, light vs. heavy quark, energy and density dependence, RHIC vs LHC) will require to measure the R_AA out to the highest pt, i.e. as close to the kinematic limit as possible using identified particles [26]. But even in the theory of purely radiative energy loss, differences between heavy quarks and light quarks (dead cone effect [27] and quarks and gluons (non-abelian energy loss [28]) have been postulated in theory and are presently being investigated by the RHIC-I experiments, thus it is probably safe to assume that it will be very unlikely that the medium modification of fragmentation will be universal among all partons. Therefore, by comparing the energy loss for different fractional momenta z, we might be able to determine the probabilities of each parton contributing to

![Graph showing STAR and UA1 K0 spectra compared to NLO calculations using quark separated fragmentation functions. Details of the calculation are explained in [19].](image)
each basic hadronic fragmentation function. In order to do this measurement at the required level of detail we need to be able to determine the fractional momentum of the produced hadron directly. An unambiguous z measurement can be accomplished in \( \gamma \)-jets, where the photon forms one jet in a di-jet event. The direct photon will not fragment and thus carries the full jet energy, which is then equivalent to the full jet energy of the hadron jet on the away-side. Thus the fractional momentum for any particle in the hadron jet can be determined by measuring the energy of the direct photon. Clearly in order to draw any conclusions from the \( \gamma \)-jet measurement it is important to measure the away-side hadrons in coincidence with the direct photon, and it is the acceptance window of the experiment for the away-side hadron jet which limits the \( \gamma \)-jet measurements at RHIC-II. A detailed simulation of the relative opening angles in gamma-jet events is shown in [29]. Table 1 shows the relevant yields in our proposed R2D detector per RHIC-II year.

| Condition                                    | Number of events |
|----------------------------------------------|------------------|
| 40 GeV di-jets                               | 120,000          |
| \( \gamma \)-jets with \( E_\gamma = 10 \) GeV and proton above 5 GeV/c | 2,000,000        |
| \( \gamma \)-jets with \( E_\gamma = 15 \) GeV and proton above 5 GeV/c | 200,000          |
| \( \gamma \)-jets with \( E_\gamma = 20 \) GeV and proton above 5 GeV/c | 19,000           |

These measurements are statistics limited because one requires a coincidence between an identified high pt hadron on the hadron jet side and the direct photon on the \( \gamma \)-jet side. In order to make an unambiguous fragmentation measurement we also need to consider that the intermediate pt range might be ’contaminated’ by recombination processes. Therefore the range above 6 GeV/c for the identified hadron would be ideal. In order to push the fractional momentum coverage to low z, this requires to measure \( >15 \) GeV/c direct photons.

4. What can AA measurements tell us about degrees of freedom above \( T_c \)?

One key question that arises from the RHIC-I experimental results is the origin of the rather strong coupling that allows hydrodynamics to describe the collective properties of the phase. Indirect measurements of the initial energy density through transverse energy measurements under the assumption of early thermalization show that the initial temperature achievable at RHIC is about 2 \( T_c \) [30]. Is the sQGP between 1-2 \( T_c \) really a surprise? Lattice QCD calculations show us that the Stefan Boltzmann limit of an ideal gas is not reached at these temperatures [31]. The lattice properties at 2 \( T_c \) undershoot the ideal gas limit by about 15%. If one believes that these 15% can cause the strong coupling we see at RHIC, then the question is justified whether the ideal gas limit can be reached at higher initial
temperature, which could cause a difference in the properties of the QGP measured at RHIC-II and LHC. Theoretical guidance on this topic is mixed with certain theories showing a large difference between the coupling at 1.5 $T_c$ (RHIC) and 4 $T_c$ (LHC) [32], [33], whereas most lattice calculation show almost no difference [31]. The same lattice calculations, though, show that the strong coupling constant is running as a function of temperature and distance, and it seems even in these calculations that the coupling strength picks up considerably below 2 $T_c$ [34]. We therefore might have a detailed difference in plasma behavior at the LHC and RHIC. Any measurement that could proof such a difference will require sensitivity to the very early time of the system evolution. One can speculate that the elliptic flow which is due to the original eccentricity of the system at time zero might be reduced if the system has time to get back to a more spherical shape in a weakly interacting system before the thermalized sQGP phase is reached. Therefore the $v_2$ would decrease from RHIC to LHC energies.

In a lattice QCD calculation [34], as well as in other calculations such as a quasi-particle picture above $T_c$ [32], the interaction strength picks up when one approaches $T_c$ from above, simply by having an interaction mass or thermal mass produced through gluonic fields. There is no explicit mass term attached to the partonic degree of freedom, which is different from the constituent quark picture [35]. In other words, simple lattice or quasi-particle pictures do not yield constituent quarks above $T_c$, but simply lead to a one to one duality between initial parton and final hadron. Therefore they should not support a constituent quark scaling law for properties developed above $T_c$. Another picture of degrees of freedom, causing strong coupling above $T_c$, is the model of gluonic bound states, according to Shuryak et al. [36]. In the model these states will be melted at the initial $T$ achievable at LHC, but they could exist in the RHIC environment. They are mostly colored but the few color neutral combinations could potentially be measured as high mass resonance states. Again it is not clear how these degrees of freedom can be reconciled with constituent quarks. In summary there is no consistent dynamic picture of mass generation, which evolves from an initial state (potentially the Color Glass Condensate (CGC) [37]) through a thermalized massless parton state through a constituent quark state to the final hadronic state. Parts of this evolution could be tested at RHIC-II by measuring probes such as energy loss and $v_2$ which are sensitive to the degrees of freedom above $T_c$. In particular, particle identification will allow us to determine flavor and coupling strength dependencies above $T_c$.

Another interesting question is whether constituent quarks explicitly break chiral symmetry, because in recombination models the valence quarks simply are assigned their actual constituent mass, e.g. 300 MeV/$c^2$ for the light quarks, in order to calculate the baryon/meson differences. The question of chiral symmetry restoration in general has not yet been successfully addressed in the RHIC-I program. The main measurement tools are based on results from lower energies at SIS and the SPS [38], [39]. Here it is shown that masses at or below production threshold are medium modified at relativistic energies, but this seems an effect purely caused by a large hadronic medium with finite baryochemical potential. Measurements in the
Kaon system at SIS and the vector meson spectrum at lower SPS energies have been repeated at RHIC, but there are as of yet no results that hint at chiral symmetry restoration in the partonic medium. The PHENIX $\phi$ to KK measurement is probably the best resolution measurement of this channel and it shows neither width nor mass shifts of the vector meson \cite{40}. The complementary $\phi$ to $e^+e^-$ is still under investigation by PHENIX in order to determine any modification to the branching ratio. In order to better address the issue of chirality in the partonic phase, measurements of chiral partners might have to be obtained. The shifting of chiral partners to the same mass or the melting of chiral partners at the same $T_c$ would be indications of chiral symmetry restoration \cite{41}. Unfortunately most chiral partner systems are difficult to measure. The main candidate systems are the $\sigma$ and the $\pi$ or the $\rho$ and the $a_1$. In particular the latter is experimentally interesting \cite{42}. Early measurements by STAR on the $\rho$ have proven to be successful in establishing the signal above the hadronic cocktail background \cite{43}. The question for RHIC-II will be whether the $a_1$ can be measured. The main problem is the large width of this resonances, but its $\pi+\gamma$ decay channel is quite unique assuming a good photon measurement in the intermediate pt range can be performed. A new detector at RHIC-II might enable us to do so.

5. Required detector capabilities of a new RHIC-II detector.

The discussion of the necessary physics measurements in the previous chapters leads to the following conclusions regarding a novel experimental setup for RHIC-II:

a.) the detector needs to be as hermetic as possible, i.e. the pseudo-rapidity needs to be $2\pi$ radially and extended to the largest pseudo-rapidity azimuthally. Existing high energy barrel detectors reach out to $\eta = \pm 3.5$ and are used as a basis for the proposed detector concepts. A specific forward program which requires to extend the coverage out to about $\eta = \pm 5$ is not discussed here but could be accommodated via a dedicated forward spectrometer with its own magnetic field as described in the R2D Expression of Interest \cite{44}.

b.) particle identification over the same hermetic coverage needs to extend out to 20-30 GeV/c in order to enable our measurements of fragmentation properties in pp and AA.

c.) the direct photon measurements in AA require a very high resolution electromagnetic calorimeter (ideally a crystal calorimeter), plus potentially hadronic calorimetry for the neutral hadron energy component in the jet and in order to suppress fragmentation photons via isolation cuts. A crystal calorimeter will also potentially allow the measurement of decay photons from the $a_1$ resonance.

d.) all detector components including the tracking, vertexing and muon detectors need to be fast in order to serve as triggering devices for rare processes and in order to obtain large statistics minimum bias samples for the bulk processes.

e.) finally the detector requires a high magnetic field over the central seven units of pseudo-rapidity in order to acquire the necessary resolution of high pt tracks and
in order to sweep a considerable part of the bulk matter out of the mid-rapidity range where most of the jet reconstruction analysis will be performed.

These five major points led to the design of R2D. Presently two options for such a detector are being discussed, a large L-R2D based on the SLD magnet dimensions, and a compact S-R2D based on the CDF magnet dimensions. The CDF magnet is near identical in inner radius and field strength to the CLEO and BABAR magnets and thus components of all three of these detectors might be re-used upon their decommissioning. L-R2D is shown in John Harris’ contribution to this workshop [29]. One possible variant of S-R2D is shown in Fig.4.

![ Possible CDF/CLEO set-up for R2D ("main" tracker + Si strip Detectors & CEM Detectors) ](image)

**Fig. 4.** A variant of the compact layout for a new RHIC-II detector (S-R2D) based on a solid state tracking device and RICH-type particle identification detectors.

The L-R2D option is preferred because it features a sufficiently large volume inside the magnet to allow for radially deep particle identification detectors based on RICH technology. Unfortunately L-R2D might require the construction of an additional experimental area at RHIC, which will increase the total cost. The S-R2D is less expensive (by about 40%), but it is not yet determined how much the restrictions in the particle identification capabilities compromise the physics program. The variant of S-R2D shown in Fig.5 features a compact RICH detector. Presently both options are being developed for review by the DoE and the BNL-PAC. An additional forward spectrometer is being considered for either option. A layout for the forward components can be found in the Expression of Interest [44].

In the present cost estimate about 40% of the final cost is offset by using existing high energy physics components. Negotiations with the existing high energy physics collaborations have begun in order to transition the necessary components after decommissioning.
6. Summary

The surprising discovery of a liquid-like phase of matter above the critical parameters for a phase transition to a quark-gluon plasma needs to be investigated in detail in order to understand hadronization and chirality in QCD. This is a program which will enable us to experimentally test the theory of asymptotic freedom [45]. The question of how matter generates its mass is fundamental to our understanding of the universe. The properties of the created partonic phase have recently been compared to quantum black holes [46] and I think it is interesting to note, that these properties are distinctly non-hadronic, which for the first time enables us to probe the transition from partons to hadrons from an initially thermalized partonic phase. Detailed measurements of the degrees of freedom near $T_c$, the running of the strong coupling constant above $T_c$, the quark separation of fragmentation contributions to final hadrons and the determination of chiral symmetry restoration make for an exciting new program at RHIC-II.

Acknowledgements

I thank John Harris, Andre Peshier, Rob Pisarski, Derek Teaney and Simon Albino for useful discussions.

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