Particle production mechanisms from RHIC to LHC

Rene Bellwied

Wayne State University, Physics Department
666 West Hancock, Detroit, MI 48201, U.S.A.
e-mail: bellwied@physics.wayne.edu

Abstract. I will review RHIC data with respect to the intriguing possibility that the hadron production mechanism in the produced partonic medium might be different than in vacuum. I will use the measurements of collective features, such as flow and quenching of identified particles, to show that different regions of the particle momentum spectrum are likely populated through different mechanisms, and that the medium seems to play an important role in hadronization. Finally I will address the question whether the different initial conditions achievable in heavy ion collisions at LHC energies, compared to RHIC, might affect the properties of the deconfined quark-gluon phase and its hadronization to baryonic matter.

Keywords: list of keywords, relevant to the article
PACS: specifications see, e.g. http://www.aip.org/pacs/

1. Introduction

It has long been assumed that the hadronization or fragmentation process in vacuum can be described by string models, which distinguish between longitudinal string fragmentation to explain the soft underlying event and transverse parton fragmentation to explain the hard scattering jet formation mechanism [1]. Although no explicit hadronization mechanism is given in this picture the particle formation can be parametrized through the fragmentation function \( D_q^h \), which yields the probability that a certain parton ’q’ fragments into a certain hadron ’h’. Baryon formation is especially difficult to visualize in such a model and requires in most approaches the formation of a di-quark structure, as a remnant of the initial hard scattering in a proton-proton collision. Recent results from RHIC have actually contributed significantly to the more detailed understanding of hadronization in vacuum. I will discuss these results briefly in the next chapter.

Hadronization in medium should be different simply because the majority of
partons which contribute to the hadron formation are likely to equilibrate to a thermal state before hadronization occurs. In that sense we do not expect to see features of a.) jet formation and b.) string fragmentation at least in the low momentum part of the particle emission spectra. Early RHIC measurements have shown though that we can expect to see the characteristics of modified (due to quenching) jet formation at sufficiently high transverse momenta ($p_T$). In addition, the intermediate $p_T$ range shows features of a recombination mechanism, using either thermal [2] or non-thermal [3] partons in an additional hadronization process. Differential measurements of the flavor dependence of collective phenomena such as elliptic flow and jet quenching should allow us to better understand hadron formation. I will review the details of the first five years of identified particle measurements at RHIC and show that the measured flavor dependencies are not well understood and lead to new questions about hadron production in medium.

In the final chapter I will briefly review the anticipated changes in the initial conditions of the partonic phase when the collision energy is increased from RHIC to LHC. In particular I will argue that the strong coupling seen in the Quark Gluon Liquid at RHIC is likely to reduce to a point where the early phase is a weakly interacting plasma. I will comment on the effects that this drastic change in conditions might have on the hadronization and the collective phenomena measured at RHIC.

2. Hadronization in vacuum

Over the past five years the RHIC experiments have studied particle formation in proton-proton collisions in great detail. These studies go beyond the initial ISR studies [4] and even the recent FNAL studies [5], in terms of particle identification capabilities and the application of modern analysis methods, which are largely based on the analysis of heavy ion reactions. The most relevant results regarding hadronization out of the vacuum are:

a.) breakdown of the so-called $m_T$-scaling at intermediate $p_T$ as shown in Fig.1 [6]. Instead of a common scaling for all identified $m_T$ spectra, STAR has found a baryon/meson scaling at sufficiently high transverse momentum. This can be explained by the requirement of di-quark formation for baryon production, which leads to a di-quark suppression factor which needs to be applied to the baryon spectra in order to find a common hadron scaling. This effect is well described by the gluon fragmentation model in PYTHIA. It is the first experimental evidence for di-quark formation at RHIC though.

b.) gluon dominance in the fragmentation process at RHIC energies. Besides the $m_T$ scaling, the lack of discernable differences in the particle vs. anti-particle production over the kinematic range measured at RHIC, and the enhanced gluon fragmentation contribution in PYTHIA and fragmentation function fits [7], necessary to describe RHIC data [6,8], shows that at these collision energies the parton interactions are indeed dominated by low x gluons.
Fig. 1. Scaled transverse mass mid-rapidity ($y = \pm 0.5$) spectra measured in 200 GeV proton proton collisions in STAR and PHENIX \[6\].

c.) contributions of non-valence quark fragmentation to, in particular, baryon production at RHIC. This effect is best documented by several new parametrizations of the baryon fragmentation functions by Albino et al. \[7\], Bourelly and Soffer \[9\], and DeFlorian et al. \[10\].

Two particle correlation measurements of unidentified charged particles in pp and AA collisions have also contributed significantly to the understanding of the hadronization process in vacuum and in medium. In vacuum the non-triggered correlation functions can be separated into a soft longitudinal string fragmentation which generates the 'underlying event', and a hard transverse parton fragmentation process which generates the jet structures \[11\]. This differential measure develops into a medium dependent pattern as a function of centrality in AA collisions. A complementary triggered analysis based on the leading particle momentum in pp and AA collisions shows that the jet structure itself, as determined by its charge ordering, shows very little centrality dependence as long as the jets are emitted near the surface of the fireball \[12, 13\]. This has been confirmed recently in identified particle correlations measurements \[14\].

3. Hadronization in medium

The debate about a different hadronization mechanism from a deconfined partonic phase compared to the vacuum has been fueled by detailed measurements of dy-
Fig. 2. STAR data on $R_{CP}$ vs $p_T/n$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using $n=3$ for baryons and $n=2$ for mesons. $R_{CP}$ is calculated from 0-5% and 40-60% central Au+Au collisions.

Dynamic effects in identified particle production at RHIC. The results for collective elliptic flow ($v_2$) and nuclear suppression ($R_{AA}$) in the intermediate $p_T$ range can both be parametrized with the number of constituent quarks in baryons and mesons, respectively. The scaled measurements are shown in Figs. 2 and 3, respectively.

This gave rise to a whole series of theory papers describing the process of partonic recombination as the main production mechanism for hadrons from the medium. The bulk matter, which takes on the role of the underlying event in heavy ion collisions exhibits features of thermal emission, but unfortunately the possible contribution of an interacting hadronic phase to the thermal properties (radial flow, mass scaling etc.) make the interpretation of the hadronization mechanism for low momentum particles quite ambiguous. In the intermediate to high momentum range, where the mass of the relevant degrees of freedom is negligible, we should be able to probe the mechanism in a more detailed way.

In that context it is interesting to note that there is a total lack of constituent quark mass dependence in the scaling of $v_2$. In recombination approaches this is largely attributed to the fact that the constituent quark mass of the up, down and strange quarks is quite similar (300 and 460 MeV, respectively) and that all identified particles measured until recently did not include heavier flavors. The recent measurement of the nuclear suppression factor and the elliptic flow for D-mesons, based on electrons from the semi-leptonic decay of the heavy mesons [16, 17, 18], should allow us to determine the applicability of partonic recombination a little better. In other words a heavy constituent quark should change the pattern
Fig. 3. $v_2/n_q$ vs. $p_T/n_q$ and $KE_T/n_q$ for several particle species measured by STAR and PHENIX as indicated in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [15].

of the $v_2$ and $R_{AA}$ measurements. Early results, though, seem to indicate that this is not the case. Both, the $R_{AA}$ and the $v_2$ measurements, can only be explained if one assumes identical $p_T$-dependencies for the flow and the quenching of light and heavy quarks.

Many models have been proposed to address these measurements and in particular the apparent lack of a dead cone effect for induced gluon radiation, as well as the lack of a heavy quark mass dependence in the $v_2$. All these models try to give the heavy quark a special status, by postulating either the survival of heavy quark resonant states above $T_c$ [19, 20] or the reduced formation time of heavy quark hadrons from the partonic phase [21]. Fig. 4 shows a comparison of the data to the heavy quark bound state model.

The near identical $p_T$-dependence of the $v_2$ and the quark energy loss between light and heavy quarks is very striking, though, and might require a much more fundamental explanation.

One possibility is that the quasi-particle state formed near $T_c$ is really not depending on the constituent or even bare quark mass concept, but rather simply the number of partons, which could be mostly gluons, until close to hadronization. Still, for a dynamic evolution measure such as the $v_2$ as a function of $p_T$, the dynamics of the degree of freedom has to play a role, and at least the effect of the bare quark mass should be measurable if we indeed probe the fragmentation or recombination of quarks. A detailed measurement of reconstructed D-mesons and B-mesons is sorely needed to remove the ambiguities in the semi-leptonic measurements, and a future measurement of high momentum heavy flavor mesons and baryons should answer the question of the applicability of recombination as a hadronization mechanism.

Detailed measurements of strange particle production and correlations in jets have already shown deviations from simple recombination predictions [22]. On the
other hand medium response effects, such as the formation of emission structures (ridge, cone) in the wake of a traversing jet seem to again point at different particle production mechanisms in the jet and in the medium response structure. In the context it is interesting to note the emission pattern differences between the medium response to the triggered jet (same-side) and the non-triggered jet (away-side). Although the same-side jet is expected to show a large surface bias (hard scattering occurs near the surface of the fireball, so that the same-side jet can escape without being quenched), the medium traversed must be finite because the ensuing ridge structure in $\Delta \eta$ is always correlated with a jet. On the away side the medium response apparently leads to a cone structure in $\eta$ and $\phi$ [23]. Early studies of the particle composition in the ridge [14] and in the cone [24] were shown at this conferences, and show distinct differences to jet fragmentation in vacuum. Within the measured $p_T$ range the baryon to meson ratios in the cone and the ridge actually agree with each other and with predictions from recombination models.

4. From RHIC to LHC

Recent lattice QCD calculations, which were summarized by Peter Petreczky at this conference [25] show convincingly that the finer lattice grid and recent improvements in the staggering algorithms lead to a quantitatively different picture than previous calculations [26].

In particular, the hadronization temperature ($T_{crit}$ in lattice QCD) is now about 20 MeV higher (190 MeV) than previously, which leads to a de-coupling of the hadronization and chemical equilibration (170 MeV) surfaces. Even more
importantly the strong coupling strength reaches the weak limit at around $3 \, T_c$. This fact is nicely documented by the quantitative agreement between lattice QCD, hard thermal loop, and resummed perturbation calculations above $3 \, T_c$ \cite{27}. So it is very likely that at LHC energies we will indeed reach the plasma, rather than liquid, phase which was originally anticipated for RHIC energies. This phase will only exist for a very short time (a few fm/c) and then has to de-excite through the strong coupling phase to the hadronization surface, but the question arises whether the weak coupling in the early phase might lead to any measurable features. It is likely that the hadronization mechanism is not affected, but collective phenomena which are supposed to develop early, such as collective elliptic flow, might be reduced by the weak coupling phase. One can also speculate that the system might be more dilute when it enters the strong coupling regime, and therefore exhibits less of a collectivity.

On the other hand, the partonic system is expected to live longer, and estimates by Eskola et al. \cite{28} show that the applicability of hydrodynamics might extend to higher $p_T$ which means that the thermal bulk particle formation mechanism will start to populate the intermediate $p_T$ range. At the same time it is likely that recombination will push out to higher $p_T$ simply because the thermal partons will carry more energy at LHC energies \cite{29}. Finally the increase in jet cross section at LHC energies will also affect the single particle spectra in a measurable way. Jet quenching is expected to lead to enhanced particle production in the intermediate $p_T$ range \cite{30}. This effect is not different from quenching at the lower energies, but the enhanced jet cross section and the enhanced average jet energy at the LHC contributes close to 50% of the particle yield in the $p_T$ range between 1 and 6 GeV/c. In the model this enhancement is due to hadronization of gluon radiation, and it still needs to be shown whether recombination can be applied to describe soft gluon fragmentation. Certainly hybrid models which allow the recombination of thermal partons with hard fragmentation partons claim to predict the particle spectrum at the LHC over a wide momentum range (2-20 GeV/c) \cite{31}. It will be important to distinguish different parton hadronization mechanisms in the mid to high $p_T$ range at the LHC.
References

1. R.D. Field and R.P. Feynman, *Phys. Rev.* D15, 2590 (1977)
2. R.J. Fries et al., *Phys. Rev. Lett.* 90, 202303 (2003).
3. K.P. Das And R.C. Hwa, *Phys. Lett.* B68, 459 (1977)
4. J.P. Bocquet et al. (UA1 coll.), *Phys. Lett.* B366, 441 (1996)
5. D. Acosta et al. (CDF coll.), *Phys. Rev.* D72, 052001 (2005)
6. B. Abelev et al. (STAR coll.), *Phys. Rev.* C75, 064901 (2007)
7. S. Albino et al., [hep-ph/0502188](https://arxiv.org/abs/hep-ph/0502188)
8. B. Abelev et al. (STAR coll.), *Phys. Lett.* B637, 161 (2006)
9. C. Bourrely and J. Soffer, *Phys. Rev.* D68, 014003 (2003)
10. D. de Florian et al., [arXiv:0707.1506](https://arxiv.org/abs/0707.1506)
11. M. Daugherity for STAR collaboration, [nucl-ex/0611032](https://arxiv.org/abs/nucl-ex/0611032)
12. R. Longacre for STAR collaboration, [nucl-ex/0702008](https://arxiv.org/abs/nucl-ex/0702008)
13. J. Putschke for STAR collaboration, [nucl-ex/0701074](https://arxiv.org/abs/nucl-ex/0701074)
14. J. Bielcikova, contribution to this workshop
15. see e.g. A. Taranenko for PHENIX collaboration, [nucl-ex/0703025](https://arxiv.org/abs/nucl-ex/0703025)
16. S.S. Adler et al., PHENIX coll., *Phys. Rev. Lett.* 94, 082301 (2005)
17. J. Bielcik for STAR collaboration, *Nucl. Phys.* A774, 697 (2006)
18. S.S. Adler et al., PHENIX collaboration, *Phys. Rev. C72*, 024901 (2005)
19. R. Rapp and H. Van Hees, *J. Phys.* G32, S351 (2006)
20. H. van Hees et al., *Phys. Rev.* C73, 034913 (2006)
21. A. Adil and I. Vitev, *Phys. Lett.* B649, 139 (2007)
22. B. Abelev, contribution to this workshop
23. J. Jia, contribution to this workshop
24. J. Zuo, contribution to this workshop
25. P. Petreczky, contribution to this workshop
26. F. Karsch, *Nucl. Phys.* A698, 199 (2002)
27. J.P. Blaizot et al., [hep-ph/0611393](https://arxiv.org/abs/hep-ph/0611393)
28. K.J. Eskola et al., [hep-ph/0510009](https://arxiv.org/abs/hep-ph/0510009)
29. R.J. Fries and B. Mueller, *EPJ C34*, S279 (2004)
30. N. Borghini and U. Wiedemann, *Nucl. Phys.* A774, 549 (2006)
31. R.C. Hwa and C.B. Yang, *Phys. Rev. Lett.* 97, 042301 (2006)