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Particle production mechanisms from RHIC to LHC

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Recent RHIC data show evidence of multiple hadron production mechanisms, depending on the momentum of the produced particle. I will review the measurements of collective flow, high momentum quenching, and two particle angular correlations to show that neither thermal production nor string fragmentation can describe the abundances, the angular distributions or the kinematic properties of all hadrons produced at RHIC. The proposed new hadronization mechanisms not only serve as evidence for a deconfined partonic phase of matter, but also for strong coupling of the degrees of freedom in the deconfined phase. I will speculate that these properties of the QGP are likely to change with the increase in collision energy at the LHC, and that these differences in the phase properties are potentially measurable through identified particle properties in heavy ion collisions at the LHC. I will point out a surprising lack of flavor dependence in these properties at RHIC, though, which might have to lead to further revisions of our understanding of the relevant degrees of freedom in the partonic phase and during the hadronization process.

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1. Introduction

High energy elementary collisions indicated that the hadronization process in vacuum can be described by jet formation through string fragmentation [1]. Although no explicit hadronization mechanism is given in this picture the hadronic particle distribution 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 in such a model generally requires the formation of a di-quark structure, as a remnant of the initial hard scattering in a proton-proton collision.

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) [2, 3]. In addition, the intermediate p_T range shows features of a recombination mechanism, using either thermal [4] or non-thermal [5] 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 results go beyond the initial ISR [6] and even the recent FNAL [7] studies, 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.1a [8]. 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 discernible differences in the particle vs. anti-particle production over the kinematic

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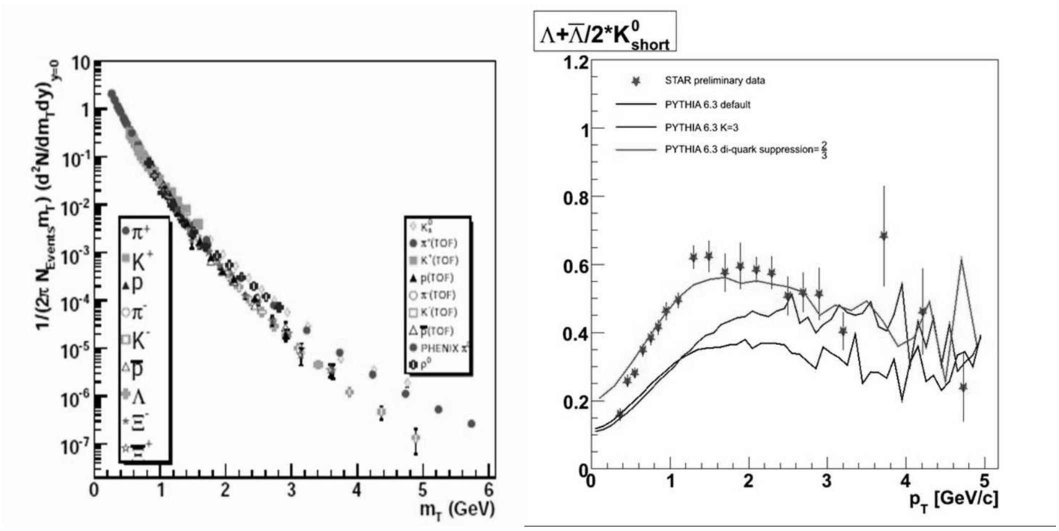

Figure 1: a.) Scaled transverse mass mid-rapidity (y = +-0.5) spectra measured in 200 GeV proton proton collisions in STAR and PHENIX [8]. b.)Λ/K_s^0 ratio compared to various PYTHIA fits with and without enhanced next-to-leading order corrections (described through enhanced K-factor) and di-quark suppression factor.

range measured at RHIC, and the enhanced gluon fragmentation contribution in PYTHIA and fragmentation function fits [9], necessary to describe RHIC data [8, 10], shows that at these collision energies the parton interactions are indeed dominated by low x gluons. Gluon dominance and subsequent di-quark suppression factors are also necessary to describe the measured baryon over meson ratios as shown in Fig.1b [11].

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. [9], Bourelly and Soffer [12], and DeFlorian et al. [13].

3. Hadronization in medium

The debate over a different hadronization mechanism from a deconfined partonic phase compared to the vacuum has been fueled by detailed measurements of dynamic effects in identified particle production at RHIC. Two of the most apparent effects are the strong elliptic flow in semi-central collisions, v2, which is defined as the second moment of the Fourier decomposition of the measured particle momentum spectrum, and the nuclear suppression factor, R_{AA}, which is defined as the ratio of the measured transverse momentum spectra in AA and pp collisions scaled with the appropriate number of binary collisions. Experiments often substitute R_{AA} with R_{CP}, where the ratio is formed between spectra from different centrality classes in AA and therefore does not rely on a separate pp measurement. The results for collective elliptic flow and nuclear suppression in the intermediate p_T range can both be parametrized with the number of constituent or valence quarks (n_q) in baryons and mesons. The scaled measurements are shown in Figs. 2 and 3, respectively.

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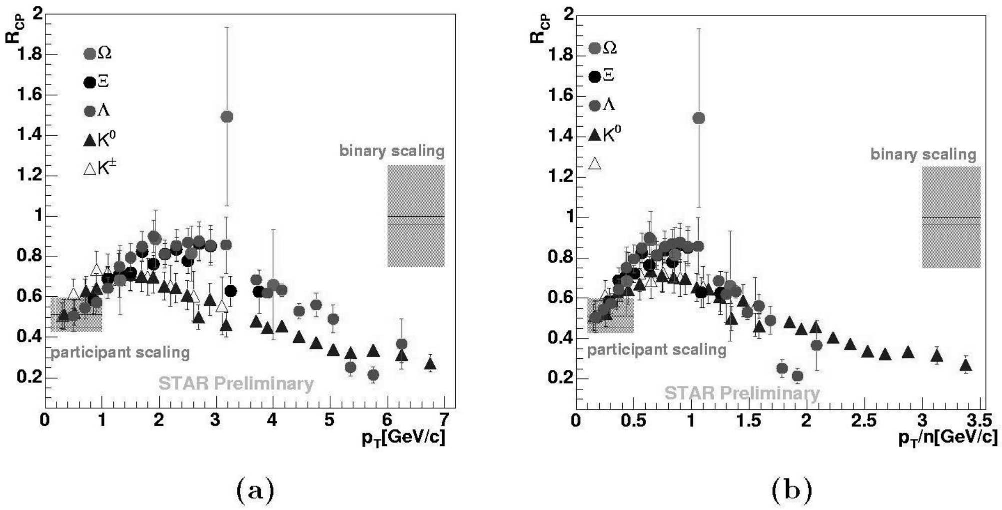

Figure 2: STAR data on (a) R_{CP} vs p_T in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV. (b) R_{CP} vs p_T/n in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV using n=3 for baryons and n=2 for mesons. R_{CP} is calculated from 0-5% and 40-60% central Au+Au collisions.

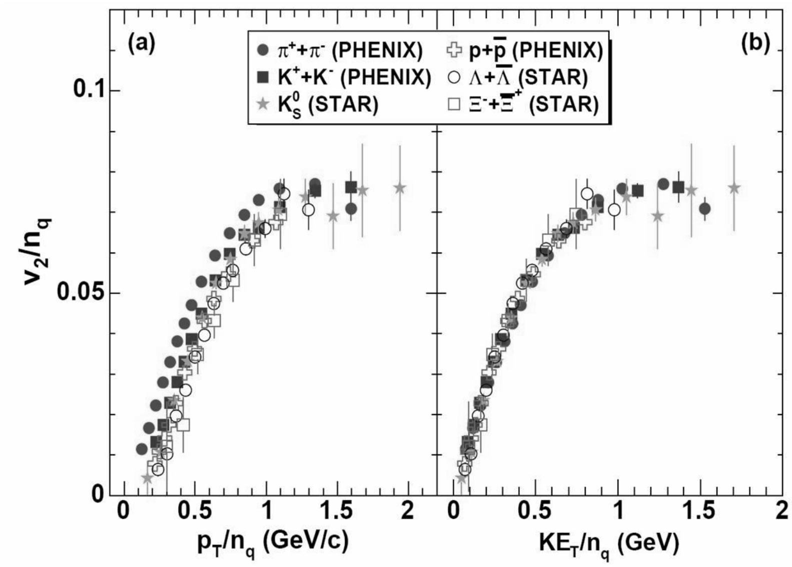

Figure 3: v2/n_q vs. p_T/n_q and KE_T/n_q for several particle species measured by STAR and PHENIX as indicated in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [14].

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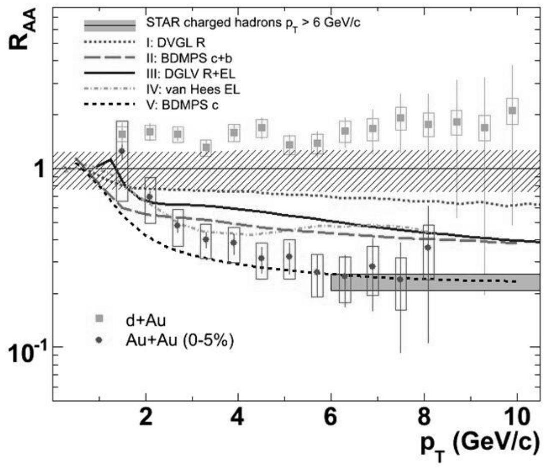

Figure 4: Nuclear suppression factor for non-photonic single electron spectra in semi-central Au+Au collisions at RHIC compared to the R_{AA} for charged hadrons (i.e. light quark suppression) and various models [19].

This gave rise to a whole series of theory papers describing the process of partonic recombination as an additional production mechanism for hadrons from the medium [4, 15] at intermediate p_T. The low momentum bulk matter 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 light constituent quarks is negligible, we can 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 v2. 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 of the v2 and R_{AA} measurements. Early results, though, seem to indicate that this is not the case. Both, the R_{AA} and the v2 measurements, can only be explained if one assumes identical p_T-dependencies for the flow and the quenching of light and heavy quarks as is shown in Fig.4 for R_{AA} [19] and in Fig.5 for v2 [20].

Many models, as shown in Fig.4, 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 v2. The most successful of these models try to give the heavy quark a special status, by postulating either the survival of heavy quark resonant states above T_c [21, 22] or the reduced formation time of heavy quark hadrons from the partonic phase [23]. Fig.6 shows a comparison of the data to the heavy quark bound state model.

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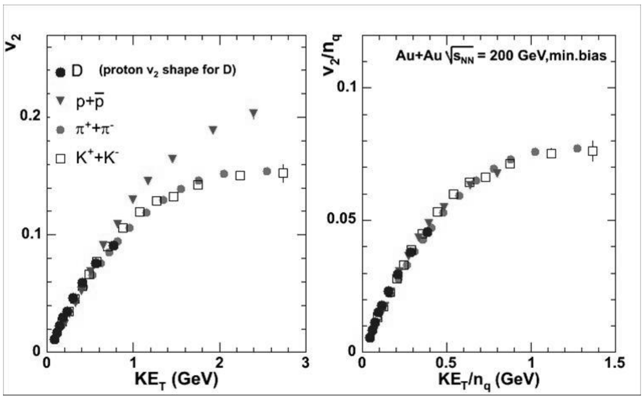

Figure 5: Elliptic flow (non-scaled and n_q scaled) for non-photonic single electron spectra in semi-central Au+Au collisions at RHIC compared to light quark hadrons [20].

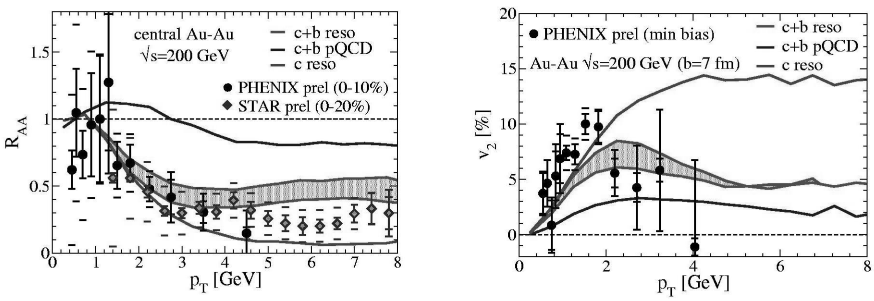

Figure 6: Nuclear suppression factor (left panel) and elliptic flow (right panel) for non-photonic single electron spectra in semi-central Au+Au collisions at RHIC. Data [16, 17, 18] are compared to theory predictions [22] using Langevin simulations with elastic c- and b-quark interactions in an expanding QGP fireball and heavy-light quark coalescence at hadronization [21].

The near identical p_T-dependence of the v2 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 v2 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

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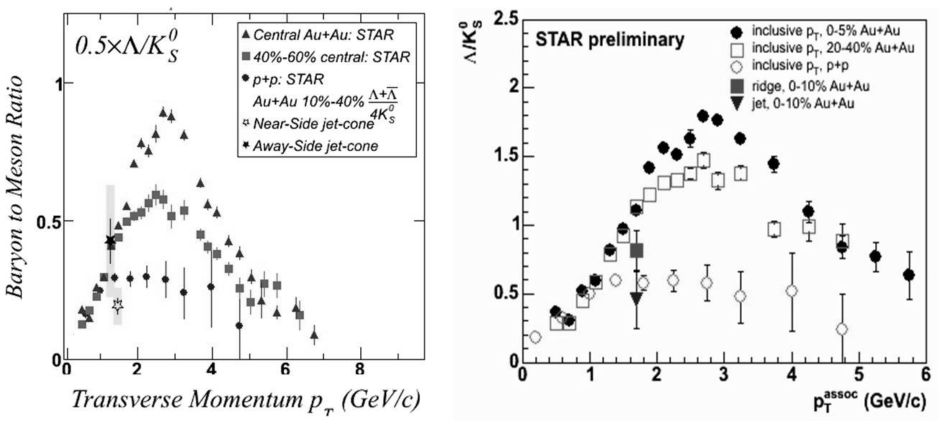

Figure 7: Inclusive Λ/K_s^0 ratio as a function of centrality and transverse momentum, a.) compared to ratios measured in the same-side and away-side jet region from triggered two-particle correlations [28], b.) compared to ratios measured in the same-side jet and same-side ridge region from triggered two-particle correlations [27].

shown deviations from simple recombination predictions [24]. 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 [25]. In this 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 η and ϕ [26]. Early studies of the particle composition in the ridge [27] and in the cone [28] 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 as is shown in Fig.7.

4. From RHIC to LHC

Recent lattice QCD calculations [29] show convincingly that finer lattice grids and recent improvements in the staggering algorithms lead to a quantitatively different picture than previous calculations [30].

In particular, the strong coupling strength reaches the weak limit at around 3 T_c. This fact is nicely documented by a quantitative agreement between lattice QCD, hard thermal loop, and resummed perturbation calculations above 3 T_c [31]. 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

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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. [32] 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 [33]. 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 [34]. 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) [35]. Clearly, although the intermediate momentum range is populated much stronger at the LHC than at RHIC, it will be challenging to disentangle all these different contributions to hadron production. On the other hand the large statistics at high momentum will allow us to study the transition from bulk matter production to non-thermal contributions at higher momentum in a systematic way at the LHC. In particular ALICE is well suited for hadronization studies through its superior particle identification capabilities, as has been shown in many contributions to this workshop.

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