

# Correlations in the Parton Recombination Model

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We describe how parton recombination can address the recent measurement of dynamical jet-like two particle correlations. In addition we discuss the possible effect realistic light-cone wave-functions including higher Fock-states may have on the well-known elliptic flow valence-quark number scaling law.

## 1. Introduction

Recent data from the Relativistic Heavy Ion Collider (RHIC) have shown a strong nuclear suppression of the pion yield at transverse momenta larger than 2 GeV/ $c$  in central Au + Au collisions, compared to  $p + p$  interactions [1]. This is widely seen as the experimental confirmation of jet quenching, the phenomenon that high energy partons lose energy when they travel through the hot medium created in a heavy ion collision [2–4], entailing a suppression of intermediate and high  $P_T$  hadrons.

However, the experiments at RHIC have provided new puzzles. The amount of suppression seems to depend on the hadron species. In fact, in the production of protons and antiprotons between 2 and 4 GeV/ $c$  the suppression seems to be completely absent. Generally, pions and kaons appear to suffer from a strong energy loss while baryons and antibaryons do not. Two stunning experimental facts exemplify this [5–8]. First, the ratio of protons over positively charged pions is equal or above one for  $P_T > 1.5$  GeV/ $c$  and is approximately constant up to 4 GeV/ $c$ . Second, the nuclear suppression factor  $R_{AA}$  below 4 GeV/ $c$  is close to one for protons and lambdas, while it is about 0.3 for pions.

There have been recent attempts to describe the different behavior of baryons and mesons through the existence of gluon junctions [9] or alternatively through recombination as the dominant mechanism of hadronization [10–12]. The recombination picture has attracted additional attention due to the observation that the elliptic flow pattern of different hadron species can be explained by a simple recombination mechanism [13–15]. The anisotropies  $v_2$  for the different hadrons are compatible with a universal value of  $v_2$  in the parton phase, related to the hadronic flow by factors of two and three depending on the number of valence quarks [16].

The competition between recombination and fragmentation delays the onset of the perturbative/fragmentation regime to relatively high transverse momentum of 4–6 GeV/ $c$ , depending on the hadron species, providing a natural explanation for the aforementioned

phenomena. To this date, parton recombination has developed into the most successful model for describing hadron production at RHIC in the intermediate transverse momentum domain.

## 2. Two-Particle Correlations

One of the biggest challenges for the recombination models to date has been the measurement of dynamic two-particle correlations. The picture of quarks recombining from a collectively flowing, deconfined thermal quark plasma appears to be at odds with the observation of “jet-like” correlations of hadrons observed in the same transverse momentum range of 2 to 5 GeV/c [17,18]. The experiments at RHIC measure the associated particle yield per trigger hadron  $A$ . After subtracting the uncorrelated background and using the notation  $\Delta\phi = |\phi_A - \phi_B|$ , the relevant observable is defined as

$$Y_{AB}(\Delta\phi) = N_A^{-1} \left( \frac{dN_{AB}}{d(\Delta\phi)} - \frac{d(N_A N_B)}{d(\Delta\phi)} \right). \quad (1)$$

Triggering on a hadron, e.g., with transverse momentum  $2.5 \text{ GeV}/c < p_T < 4 \text{ GeV}/c$ , the data shows an enhancement of hadron emission in a narrow angular cone around the direction of the trigger hadron in a momentum window below  $2.5 \text{ GeV}/c$ . Can such correlations be reconciled with the claim that hadrons in this momentum range are mostly created by recombination of quarks?

Obviously, the existence of such correlations is incompatible with any model assuming that no correlations exist among the quarks before recombination, since such correlations require deviations from a global thermal equilibrium in the quark phase. However, it can be shown that correlations among partons in a quark-gluon plasma naturally translate into correlations between hadrons formed by recombination of quarks [19]. Correlations are even enhanced by an amplification factor  $Q = n_A n_B$  similar to the scaling of elliptic flow. The interaction of hard partons with the medium has been discussed as one plausible mechanism for the existence of such parton correlations, even though other scenarios for the creation of parton-parton correlations in the deconfined phase are possible. A numerical example displayed in figure 1 shows that two-parton correlations of order  $\approx 10\%$  will be sufficient to explain hadron correlations as measured by the PHENIX collaboration. One may conclude that the existence of localized angular correlations among hadrons are not in contradiction with the recombination scenario but rather indicative for the existence of correlations among quarks prior to hadronization.

## 3. Beyond the Valence Quark Approximation

Recombination models usually are based on the concept of *constituent quark recombination*, which assumes that the probability for the emission of a hadron from a deconfined medium is proportional to the probability for finding the valence quarks of the hadron in the density matrix describing the source. The baryon enhancement, as well as the different momentum dependence of meson and baryon anisotropies, rely essentially on the different number of valence quarks in mesons (two) and baryons (three). The simplicity of this concept has been criticized, because it does not do justice to the complexity of the internal structure of hadrons in quantum chromodynamics (QCD). The question is

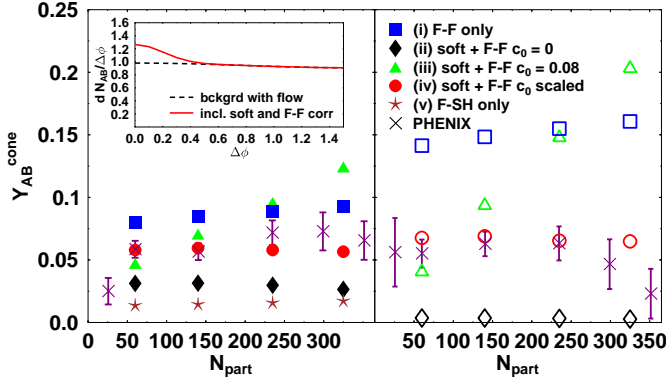


Figure 1.  $Y_{AB}^{\text{cone}}$  which is  $Y_{AB}$  integrated over  $0 \leq \Delta\phi \leq 0.94$ , for meson (left panel) and baryon triggers (right panel) as a function of centrality. The inset shows the associated yield as a function of  $\Delta\phi$  at an impact parameter  $b = 8$  fm.

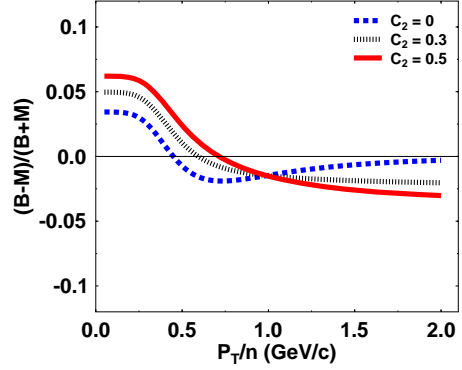


Figure 2. Relative difference  $(\tilde{v}_2^{(B)} - \tilde{v}_2^{(M)}) / (\tilde{v}_2^{(B)} + \tilde{v}_2^{(M)})$  between the scaled meson and baryon elliptic flow for three different sizes of the higher Fock state component.

how a more realistic treatment of the internal structure of hadrons in QCD affects these observables.

In the light-cone frame, where formally the hadron momentum  $P \rightarrow \infty$  and the momentum fractions of the partons are the only dynamic degrees of freedom, a meson  $M$  with valence quarks  $q_\alpha$  and  $\bar{q}_\beta$  can then be written as an expansion in terms of increasingly complex Fock states:

$$\begin{aligned}
 |M\rangle &= \int_0^1 dx_a dx_b \delta(x_a + x_b - 1) c_1(x_a, x_b) |q_\alpha(x_a) \bar{q}_\beta(x_b)\rangle \\
 &+ \int_0^1 dx_a dx_b dx_c \delta(x_a + x_b + x_c - 1) c_2(x_a, x_b, x_c) |q_\alpha(x_a) \bar{q}_\beta(x_b) g(x_c)\rangle \\
 &+ \int_0^1 dx_a dx_b dx_c dx_d \delta(x_a + x_b + x_c + x_d - 1) c_3(x_a, x_b, x_c, x_d) |q_\alpha(x_a) \bar{q}_\beta(x_b) q_\gamma(x_c) \bar{q}_\gamma(x_d)\rangle + \dots
 \end{aligned} \tag{2}$$

It has been shown [20] that the yield of relativistic parton clusters is independent of the number of partons in the cluster. Therefore, hadron spectra remain unaffected by the inclusion of a higher Fock state with an additional gluon. One important implication is that gluon degrees of freedom could be accommodated during hadronization. They simply become part of the quark-gluon wave functions of the produced hadrons, but remain hidden constituents because the commonly produced hadrons do not contain valence gluons.

However, higher Fock states introduce deviations from the scaling law for elliptic flow. Using a narrow wave function limit, one can easily generalize the well-known valence quark scaling law to higher Fock states:

$$v_2^{(H)}(P) \approx \sum_\nu |c_\nu|^2 n_\nu v_2(P/n_\nu) \tag{3}$$

Figure 2 shows the relative difference  $(\tilde{v}_2^{(B)} - \tilde{v}_2^{(M)})/(\tilde{v}_2^{(B)} + \tilde{v}_2^{(M)})$  between the scaled meson and baryon elliptic flow for three different sizes of the higher Fock state component (0%, 30%, 50%). In all cases, baryons have a slightly larger scaled  $\tilde{v}_2$  than mesons at small momenta. This effect is likely to be overwhelmed by the influence of mass differences, which have been neglected in the sudden recombination model. At larger momenta, the scaled meson  $\tilde{v}_2$  is slightly larger. In principle, these violations on the order of  $\sim 10\%$  should be visible in a scaling analysis and first observations along these lines have been reported at this meeting [21].

It should be emphasized that the interpretation of elliptic flow data from RHIC proving the existence of quark degrees of freedom in the bulk matter is still valid. However, the connection of the measured elliptic flow to the quark elliptic flow might be less straight forward than anticipated.

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