Particle correlations at RHIC from parton coalescence dynamics – first results

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Abstract. A new dynamical approach that combines covariant parton transport theory with hadronization channels via parton coalescence and fragmentation is applied to Au+Au at RHIC. Basic consequences of the simple coalescence formulas, such as elliptic flow scaling and enhanced $p/\pi$ ratio, turn out to be rather sensitive to the spacetime aspects of coalescence dynamics.

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1. Introduction

Two exciting recent discoveries in Au + Au reactions at $\sqrt{s_{NN}} = 200$ GeV at RHIC were the lack of baryon suppression[1, 2, 3, 4] in the region $2 < p_{\perp} < 5$ GeV and the quark number scaling of elliptic flow[5, 6, 7, 8]. Parton coalescence[9, 10, 11, 12] is currently the most promising proposal to explain both phenomena.

In the coalescence model, mesons(baryons) form via a fusion of two(three) quarks/antiquarks. The simplest forms of the model based on (1), or minor variations of it, were fairly successful in reproducing particle spectra at RHIC[9, 10] in terms of a common set of “reasonable” constituent phasespace distributions over a “reasonable” hadronization hypersurface. These parameters were consistent with the assumption of a deconfined quark-gluon plasma. The scaling of elliptic flow $v_2(p_{\perp})$ with constituent number is also understood based on these simple formulas[11, 12].

Nevertheless, these earlier studies left several important questions open. For example, it is known[11, 12] that (1) violates unitarity. The yield in a given coalescence channel scales quadratically/cubically with constituent number, moreover, the same constituent contributes to several channels. It is also unclear whether the extracted hadronization parameters are consistent with any dynamical scenario. In addition, the simplified form of constituent phasespace distributions assumed ignores several types of phasespace correlations that would be generated in a dynamical approach.

The goal of this study is to improve upon the above deficiencies and study how the dynamics of parton coalescence affects correlation observables at RHIC, such as elliptic flow.

2. Dynamical coalescence approach

Most of the parton coalescence formalism is based on studies of deuteron formation[13, 14, 15, 16]. In the framework of nonrelativistic (equal-time) N-body quantum mechanics, the number of deuterons (of given momentum) at time $t$ is $N_d(t) =$
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when several coalescence final states were possible for a given constituent, one was chosen randomly in an unbiased fashion. Meson channels to

$N_{\text{pairs}} \ln \left[ \Delta_{d} \dot{\rho}^{(2)} \left( t \right) \right]$, where $\dot{\rho}_{d} \equiv |\Phi_{d}| \langle \Phi_{d} |$ is the deuteron density matrix, $\dot{\rho}^{(2)} \left( t \right)$ is the projection of the density matrix $|\Psi^{(N)} \left( t \right) \rangle |\Psi^{(N)} \left( t \right) \rangle$ of the system onto the deuteron (two-particle) subspace, there are $N_{\text{pairs}}$ possible $n-p$ pairs, while $\Phi_{d}$ and $\Psi^{(N)} \left( t \right)$ are the wave function of the deuteron and the system. One is interested in the observed deuteron number $N_{d}(t \rightarrow \infty)$ but unfortunately cannot solve the full $N$-body problem.

One approximation is to postulate that interactions cease suddenly at some time $t_{f}$, and approximate $\dot{\rho}^{(2)} \left( t \right)$ in the Wigner representation as the product of classical phase space densities $f_{n} \times f_{p}$ on the $t = t_{f}$ hypersurface. The approximation, at best, is valid for weak bound states and ignores genuine two-particle correlations. Applied to meson formation $q\bar{q}$ to $M$, one obtains the “simple coalescence formula”

$$\frac{dN_{M}(\vec{p})}{d^{3}p} = g_{M} \int d^{3}x_{1} d^{3}p_{1} d^{3}x_{2} d^{3}p_{2} W_{M}(\Delta \vec{x}, \Delta \vec{p}) f_{q}(\vec{p}_{1}, \vec{x}_{1}) f_{\bar{q}}(\vec{p}_{2}, \vec{x}_{2}) \delta^{3}(\vec{p}_{1} + \vec{p}_{2})$$

with $\Delta \vec{x} \equiv \vec{x}_{1} - \vec{x}_{2}$, $\Delta \vec{p} \equiv \vec{p}_{1} - \vec{p}_{2}$, and the meson Wigner function $W_{M}(\vec{x}, \vec{p}) = \int d^{3}b \exp[-i\vec{p} \cdot \hat{\Phi}_{M}(\vec{x} - \vec{b}/2)\hat{\Phi}_{M}(\vec{x} + \vec{b}/2)]$. The degeneracy factor $g_{M}$ takes care of quantum numbers (flavor, spin, color). The formula for baryons involves a triple phase space integral and the baryon Wigner function. The generalization to arbitrary 3D hadronization hypersurfaces is straightforward.

One difficulty with (1) is the proper choice of the hypersurface. While quantum mechanics gives a constant deuteron number at any time after freezeout, (1) decreases with $t_{f}$ for a free streaming distribution. Also, transport approaches (i.e., self-consistent freezeout) yield diffuse freezeout distributions in full 4D spacetime. These problems have been addressed by Gyułass, Frankel and Remler (GFR), where they derived a way to interface transport models and the coalescence formalism (in the weak binding limit).

The GFR result is essentially the same as (1), except that the weight $W_{M}$ is evaluated using the freezeout spacetime points $(t_{1}, \vec{x}_{1})$, $(t_{2}, \vec{x}_{2})$ of each constituent pair. When taking $\Delta \vec{x}$, the earlier particle needs to be propagated to the time of the later one, resulting in an extra term, e.g., $\Delta \vec{x} = \vec{x}_{1} - \vec{x}_{2} + (t_{2} - t_{1}) \vec{v}_{1}$ if $t_{1} < t_{2}$. The origin of this correction is that a weak bound state can only survive if none of its constituents have any further interactions. The generalization to baryons involves propagation to the latest of the three freezeout times.

To investigate coalescence dynamics at RHIC, we implanted GFR into covariant parton transport theory. First the parton ($g, u, d, s, \bar{u}, \bar{d}, \bar{s}$) evolution was computed until freezeout using Molnar’s Parton Cascade (MPC) 1.6.7. For simplicity, only $2 \rightarrow 2$ processes were considered, with Debye-screened parton cross sections $\sigma_{\text{total}} \propto 1/(t - \mu_{D}^{2})$, $\mu_{D} \approx 0.7$ GeV. The calculation was driven by the total $gg$ cross section taking $\sigma_{gg} = (9/4)\sigma_{q\bar{q}} = (9/4)^{2}\sigma_{q\bar{q}} = 3$ and 10 mb.

At parton freezeout, GFR was applied using, as common in transport approaches, box Wigner functions $W = \prod_{i,j} \Theta(x_{m} - |\vec{x}_{i} - \vec{x}_{j}|)\Theta(p_{m} - |\vec{p}_{i} - \vec{p}_{j}|)$, with $x_{m} = 1$ fm. This way (1) has a simple probabilistic interpretation: if $W = 1$ (and the quantum numbers match) the hadron is formed, otherwise it is not ($W = 0$).

When several coalescence final states were possible for a given constituent, one was chosen randomly in an unbiased fashion. Meson channels to $\pi, K, \eta, \eta'$, $p, K^{*}, \omega, \Phi$; and baryon channels to $p, n, \Sigma, \Lambda, \Xi, \Delta, \Omega$ were considered. Gluons were split to a $q-\bar{q}$ pair, with asymmetric momentum fractions $x = 0$ and $x = 1$, effectively corresponding to $1g \rightarrow 1$ quark (or antiquark). Easy color neutralization was also assumed. Partons that did not find a coalescence partner were fragmented using JETSET 7.4.10. JETSET was also used to decay unstable hadrons.
The parton initial conditions in [18] were utilized but with LO pQCD minijet three-momentum distributions for $p_\perp > 2$ GeV ($K = 2$, GRV98LO, $Q^2 = p_T^2$), smoothly extrapolated spectra below $p_\perp < 2$ GeV to yield a total parton $dN(b=0)/dy = 2000$ at midrapidity (motivated by the observed $dN_{ch}/dy \sim 600$ and the expectation that coalescence dominates the production), and perfect $\eta = y$ correlation.

3. Key results‡

Figure 1 shows the relative enhancement of pion and proton production due to the coalescence process for $Au + Au$ at $b = 8$ fm. The ratio of the spectra from a calculation with both coalescence and fragmentation hadronization channels to that from a calculation with fragmentation only is plotted, for $\sigma_{gg} = 3$ mb (solid curve), 10 mb (dotted), and a scenario with immediate freezeout (IFS) on the formation hypersurface (dashed-dotted). In all three cases coalescence gives a large enhancement for both species in the intermediate $2 < p_\perp < 4 − 5$ GeV window, in agreement with earlier expectations[10, 9, 11] based on (1). However, unlike the earlier results, for realistic $\sigma_{gg} = 3 − 10$ mb, the dynamical approach gives roughly the same enhancement for both $\pi$ and $p$, i.e., no additional enhancement for baryons. The reason for this is that, in the weak-binding case assumed, baryons are more fragile: they have three constituents and therefore less chance to escape without further interactions. On the other hand, IFS, which ignores this dynamical effect, enhances baryons over mesons.

Figure 1. Pion and proton enhancement from parton coalescence as a function of $p_\perp$ and parton cross section.

Figure 2 shows pion and proton elliptic flow $v_2(p_\perp)$ for $\sigma_{gg} = 10$ mb. The left panel show that if all partons are hadronized via fragmentation, the final hadron elliptic flow is less than that of partons (solid line) because fragmentation quenches the spectra and also smears out the flow (jet width $\langle |j_\perp| \rangle > 0$). The middle panel shows the influence of dynamical correlations on the flow hadrons coming from coalescence. Pion(proton) $v_2$ is reduced by 20(40)% relative to the simple flow scaling expectations[8] (dotted lines). Therefore, parton $v_2(p_\perp)$ curves extracted from the hadron flows would underpredict the real parton flow, and also differ from each other by 20%. The right panel shows that when both hadronization channels are included, flow scaling is further violated because the fragmentation contribution reduces elliptic flow.

The above findings demonstrate that coalescence is an important hadronization channel. However, the results also show that dynamical effects are potentially large. Further studies are needed to reveal what it takes to preserve the basic features of the simple coalescence formulas.

‡ Due to page limitations, only a few key results are shown here. See [24] for the rest of the results.
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