Exploring the initial state in relativistic heavy ion collisions

Gabor David
Brookhaven National Laboratory, Upton, NY 11973, USA
E-mail: david@bnl.gov

Abstract. While the most spectacular effects seen in relativistic heavy ion collisions are attributed to the formation of a strongly interacting, hot and dense medium (final state), there is a rapidly growing consensus that the initial state of the incoming relativistic nuclei is in part responsible for the observed phenomena. The initial state is best studied in d+Au collisions where only cold nuclear matter is present and probed by a single proton or neutron. Based on the latest results from the PHENIX experiment at RHIC (BNL) from the high statistics d+Au data at $\sqrt{s_{NN}}=200$ GeV (2008) we will review the nuclear modification factors at forward rapidities as well as the status of central-forward and forward-forward correlations which provide an important test of gluon saturation in the Au nucleus at low momentum fraction $x$.

1. Introduction

Experimental data from heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) suggest the formation of a novel form of matter with partonic degrees of freedom, the strongly coupled Quark Gluon Plasma (sQGP) [1, 2, 3, 4]. The three most striking early observations indicating the presence of such medium and all made at zero rapidity were

- the suppression of high transverse momentum ($p_T$) hadrons in Au+Au collisions along with the lack of hadron suppression in d+Au collisions [5, 6];
- the lack of suppression for direct photons [7] validating both the concept of “suppression” and supporting the strongly interacting nature of the medium; finally in the soft region
- the strong azimuthal asymmetries (elliptic flow) that for various particles scale with the number of constituent quarks rather than the mass of the particles.

In fact, the effects of the medium observed at mid-rapidity (or final state effects) were so overwhelming that for a while possible changes in the initial state (the parton distribution functions of the incoming nuclei themselves) didn’t get equal attention. Not that the experimental evidence was lacking: the very first published RHIC paper [8] found total multiplicities at mid-rapidity in $\sqrt{s_{NN}}=56$ GeV and 130GeV Au+Au collisions that were smaller than expected from extrapolations based on SPS data (a blessing to the experiments). High $p_T$ observables at mid-rapidity sample relatively large $x$ values, but the bulk behavior (like total multiplicity) or spectra at large rapidities are low $x$ phenomena. Shadowing of low $x$ partons, particularly those of gluons, in nuclei - a par excellence initial state effect - has been established experimentally quite some while ago and the idea of gluon saturation was present in the literature since the early 1980s [9]. Remarkably, only models incorporating some form
of low $x$ gluon suppression were able to describe the RHIC multiplicity results. While the first $d+Au$ collisions at RHIC confirmed the dominance of medium effects in mid-rapidity hadron suppression in $Au+Au$ (since no such suppression was observed in $d+Au$ where the medium is absent) it was also found that at forward rapidities hadrons are suppressed even in $d+Au$ [10, 11] - a strong indication of the relative depletion of gluon distributions at very low $x$. Other, more recent results, like hints of the Cronin-effect at mid-rapidity in $d+Au$ or even low energy ($\sqrt{s_{NN}} = 22$GeV) $Cu+Cu$ collisions, or $J/\Psi$ production at forward and backward rapidities in $d+Au$ confirm that the initial state (“cold nuclear matter”) has rich physics on its own which must be understood if we want to have a good quantitative description of the A+A data. While initial state effects play some role even in A+A collisions at mid-rapidity and high $p_T$ [12], most information is extracted from $d+Au$ collisions, particularly at high (pseudo)rapidities. The main issue when interpreting the results is how well the momentum fraction $x$ of the contributing partons can be constrained by the experiments.

2. Cold nuclear matter

2.1. Charged hadrons at high $|\eta|$
2.2. Rapidity separated (forward-central) correlations

![Figure 2](image)

**Figure 2.** Trigger energy and centrality dependence of the ratio of $\eta \approx 0$ yields when triggered of $\pi^0$ going forward ($d$ going side) vs. backward (Au going side)

Correlations, particularly large rapidity gap correlations help to better constrain the sampled $x$ region of the colliding partons. On Fig. 2 preliminary results are shown from the $\sqrt{s_{NN}}=200$ GeV $d+$Au run (2008) on the conditional yields of moderate $p_T$ hadrons ($1.0 < p_T < 3.0$ GeV/$c$) observed at mid-rapidity when a high energy $\pi^0$ is found in the forward or backward MPC. Apart of the most peripheral collisions ("Centrality D") a clear suppression is observed when the trigger particle is in the $d$-going direction, i.e. when we sample predominantly the low $x$ gluon distribution of the Au nucleus. While not conclusive, this result is certainly in agreement with the gluon saturation picture.

The result on Fig. 3 is more or less complementary insofar that the trigger particle is now at mid-rapidity and the nuclear modification factor $I_{dA}$ (the ratio of conditional yields in $d+$Au and $p+p$ collisions) is shown against centrality, expressed in terms of binary collisions ($N_{coll}$). The suppression increases with centrality, once again in accordance with the gluon saturation prediction. It should be noted, however, that the same model also predicts the broadening of the correlation width which so far has not been observed (within large experimental errors).

2.3. Forward-forward correlations

Azimuthal correlations of hadrons when both hadrons are detected in the forward direction have the advantage that the sampled $x$ region is well constrained in the nucleus; it is restricted to very small $x$ values where saturation effects should be manifest. In $p+p$ collisions one expects a similar shape of the back-to-back correlations as at central rapidity: a narrow peak around the trigger particle and a wider one at $\pi$. In $d+$Au collisions, however, the saturation model predicts the disappearance of the away-side jet ("monojets") because the high-$x$ probe parton of the $d$ tends to scatter coherently off the dense low-$x$ gluon field of the Au nucleus, instead of scattering off just one gluon, thus there is no clean jet on the opposite side. This prediction is
Figure 3. $I_{dA}$ vs. centrality (expressed in terms of $N_{coll}$) for mid-rapidity hadron - forward $\pi^0$ correlations. 

Certainly consistent with the results shown on Fig. 4 where uncorrected, per-trigger conditional yields are plotted as a function of azimuthal angle $\Delta\Phi$ for two $\pi^0$s, both at forward rapidity ($d$ going direction): the away-side peak is clearly visible in $p+p$ collisions but broadens and disappears almost completely in the most central $d+Au$ collisions. Qualitatively this is in agreement with the broadening (virtual disappearance) of the away-side peak observed by the STAR experiment [13]. It should be noted that while the result is consistent with the saturation model, pQCD calculations adding contributions from quarks scattering off multiple nucleons [14] make similar predictions at such low transverse momenta. Therefore, increasing the transverse momentum range accessible experimentally would be highly desirable. Detectors already under construction in PHENIX and others still in the design stage will certainly help in solving these tantalizing questions.

3. Summary

While the formation and properties of the sQGP in relativistic heavy ion collisions are of utmost interest, a full, quantitative, *dynamic* picture of the entire collision cannot be established without understanding the very real changes in the initial state. In some sense one might say that the high $p_T$ phenomena - spectacular as they are - are mostly *probes* of effects, for which much of the *cause* is hiding at low $p_T$. The exploration of the initial state has only begun and so far the results are more qualitative than quantitative; for a better understanding we need both improved analyses and upgraded detectors. Looking *forward* - both figuratively and in the very
Figure 4. Conditional yield vs azimuthal angle $\Delta \phi$ for two $\pi^0$, both at forward rapidity, in $p+p$ (blue) and $d+Au$ (red) collisions, as measured in the PHENIX MPC detector. Points for $\Delta \phi > \pi$ are mirrored.

real sense of pseudorapidity - is a key to understanding the dynamics of relativistic heavy ion collisions.

References
[1] Arsene I et al. 2005 Nucl. Phys. A 757 1
[2] Back B B et al. 2005 Nucl. Phys. A 757 28
[3] Adams J et al. 2005 Nucl. Phys. A 757 102
[4] Adcox K et al. 2005 Nucl. Phys. A 757 184
[5] Adler S S et al. 2002 Phys. Rev. Lett 88 022301
[6] Adcox K et al. 2003 Phys. Rev. Lett 91 072303
[7] Adler S S et al. 2005 Phys. Rev. Lett 94 232301
[8] Back B B et al. 2000 Phys. Rev. Lett 85 3100
[9] Gribov L V, Levin E M, Ryskin M G 1981 Nucl. Phys. B 188 555
[10] Arsene I et al. 2004 Phys. Rev. Lett 93 242303
[11] Adler S S et al. 2004 Phys. Rev. Lett 94 082302
[12] Kopeliovich B Z, Nemchik J 2010 Preprint arXiv:1009.1162 [hep-ph]
[13] Braidot E 2010 Preprint arXiv:1005.2378 [hep-ph]
[14] Qiu J and Vitev I 2004 Phys. Rev. Lett 93 262301