QCD and Heavy Ions: RHIC Overview

Raphael Granier de Cassagnac
Laboratoire Leprince-Ringuet, École polytechnique, CNRS-IN2P3, Palaiseau, France

Nowadays, the most violent heavy ion collisions available to experimental study occur at the Relativistic Heavy Ion Collider (RHIC) of the Brookhaven National Laboratory. There, gold ions collide at $\sqrt{s_{NN}} = 200$ GeV. The early and most striking RHIC results were summarised in 2005 by its four experiments, BRAHMS, PHENIX, PHOBOS and STAR, in their so-called *white papers* [1, 2, 3, 4] that will be largely referenced thereafter. Beyond and after this, a wealth of data has been collected and analysed, providing additional information about the properties of the matter created at RHIC. It is categorically impossible to give a comprehensive review of these results in a 20 minutes talk or a 7 pages report. Here, I have made a selection of some of the most striking or intriguing signatures: jet quenching in Section 2, quarkonia suppressions in Section 3 and thermal photons in Section 4. A slightly longer and older version of this review can be found in [5]. Some updates are given here, as well as emphasis on new probes recently made available.

1 Multiplicities and Densities

The first obvious *things* that come out of heavy ion collisions are *a lot* of particles. The number of charged particles was measured for various collision energies and centralities by the four RHIC experiments, and in particular by the dedicated PHOBOS collaboration over a broad range of 10.8 units of pseudorapidity [6]. At midrapidity, the number of charged particle reaches $dN_{ch}/d\eta|_{\eta=0} \simeq 670$ in the most violent Au+Au collisions and they sum up to about 6000 particles (of any charge) over the full rapidity range. These huge numbers were in fact *lower* than expected from various simple models, extrapolating lower energy results (for more details and complete references, see Section 2.1 in Ref. [3]). This moderation of the produced particles is an indication that the gluon density in the initial state starts to saturate, or similarly to be shadowed. In other words, low momentum gluons from neighbour nucleons overlap and recombine. In short, these results show that **the (initial) matter is gluon saturated**.

The second obvious manifestation of the collision violence is the transverse (i.e. unboosted by the initial parton longitudinal momenta) energy liberated. Measuring it allows one to estimate the energy density ε of the medium after a given time τ_0, through the Bjorken formula [7]: $\varepsilon = dE_T/dy|_{y=0}/\tau_0 A_T$, where A_T is the transverse area of the collision. The four RHIC experiments measure consistent values of $dE_T/dy|_{y=0}$ that correspond to an energy density of at least 5 GeV/fm^3 at $\tau_0 = 1$ fm/c, and for the most central collisions. The time to be considered is certainly lower than 1 fm/c (see Section 2 of Ref. [2]) and thus the *lower* energy density estimate is much higher than the threshold for the transition to a quark gluon plasma, as predicted by QCD on the lattice [8]: $\varepsilon_c \sim 1$ GeV/fm^3.

This tells us that **the matter should be deconfined**, i.e. made of free quarks and gluons. The following sections review some of the measurements that indicate that it is indeed the case.

2 Jet Quenching

2.1 High Transverse Momentum Suppression

Figure 1 is an illustration of the first and most striking QGP signature seen at RHIC, namely the quenching of jets [9, 10]. Displayed is, for various particles, the nuclear modification factor R_{AA} defined as the yield of particles seen in A+A collisions, normalised by the same yield from p+p collisions scaled by the average number of binary collisions $\langle N_{coll} \rangle$ corresponding to the considered centrality: $R_{AA} = dN_{AA}/\langle N_{coll} \rangle dN_{pp}$. Hard processes (high p_T particles in particular) are expected to respect such a scaling ($R_{AA} = 1$). This is indeed the case of the direct photon[1] [13] (grey squares), while the corresponding π^0 (blue circles) and η (red triangles) are suppressed by a factor of five at large p_T. This is understood as an energy loss of the scattered partons going through a very dense matter, and producing softened jets and leading (high p_T) particles. This medium is so dense that it cannot be made of individual hadrons, but rather of quarks and gluons. In [14], PHENIX has released data on π^0 modification factors up to 20 GeV/c, and performed a quantitative estimate of the constraints on theoretical models. As an example, gluon densities of $dN_g/dy = 1400^{+270}_{-150}$ are needed to produce such a strong quenching in the model depicted in [15].

High p_T suppressions are seen for various particles with various p_T reaches and by the four experiments [1, 2, 3, 4]. It gets stronger for more central collisions. Checking that *normal* nuclear matter cannot induce what is seen in heavy ion collisions is a crucial test for *any* QGP signature and property. It is usually done through p+A like collisions. And indeed, high p_T suppression is not observed in d+Au collisions (in particular for neutral pions [16] to be compared to the ones in Figure 1) where a moderate enhancement is even seen as a function of p_T, probably due to multiple scattering of the incoming partons providing additional transverse momentum (the so-called Cronin effect).

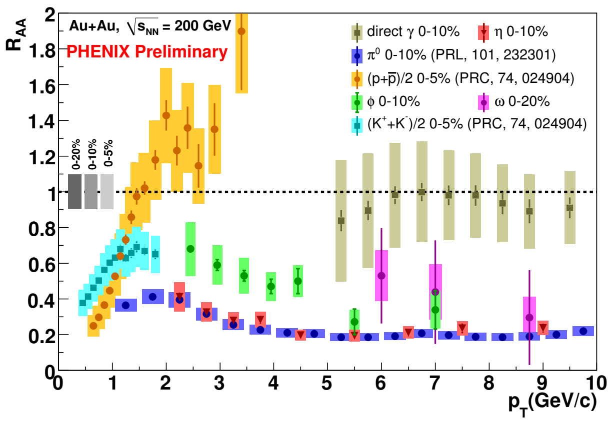

Figure 1: Nuclear modification factors for photons, π^0, η, protons, ϕ, ω and kaons for central collisions, from the PHENIX experiment.

In any case, the quenching of high p_T particles shows that **the matter they traverse is dense**.

[1] PHENIX has released preliminary photons up to 18 GeV/c [11], which start to deviate below unity. As discussed for instance in [12], this can be explained by several phenomena (nucleus to proton isospin difference, EMC effect, or quark energy loss prior to photon emission) which have nothing to do with a QGP.

2.2 Azimuthal Correlations

Another way to look at jets is to consider back to back high transverse momentum hadron correlations. Figure 2 shows the measurements of such correlations for various collision types performed by the STAR experiment and reported in Section 4.2 of reference [4].

Displayed are the azimuthal distributions of hadrons around a *trigger* particle of high enough p_T to reflect the main direction of jets (4 GeV/c for the trigger particle and 2 GeV/c for the others in this example). In p+p collisions (black histogram), one clearly sees particles belonging to both the narrower same ($\Delta\phi = 0$) and broader opposite ($\Delta\phi = \pi$) jets, while in central Au+Au collisions (blue stars) the away-side jet disappears [17]. This is also attributed to jet quenching, the away-side jet being absorbed by the dense matter produced at RHIC. As for the high p_T suppression we saw in the previous section, this effect is not observed in d+Au collisions (red circles) in which away-side hadrons are clearly distinguishable [18].

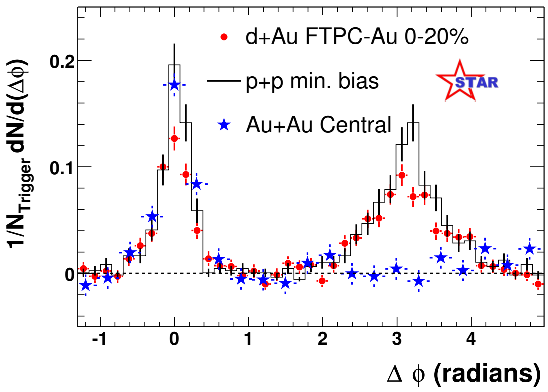

Figure 2: Dihadron azimuthal correlations in p+p, d+Au and Au+Au central collisions, from the STAR experiment.

Jet-induced hadron production has been further and extensively investigated at RHIC and various effects corroborate the jet quenching hypothesis, among which:

- In Au+Au collisions, the away-side disappearance grows with centrality. In fact, the most peripheral collisions exhibit a very similar away-side pattern as in p+p and d+Au collisions.

- The jets emitted in the reaction plane are less suppressed than in the perpendicular direction, where they have more matter to traverse [19, 20]. In fact, the high p_T (near-side) particles we see in central Au+Au collisions are likely to come from the periphery, the *corona*, of the collision.

- By lowering the p_T requirements (down to $\sim$1 GeV/c), one can find back the away-side jets [21].

- These weakened away-side jets are depleted at $\Delta\phi = \pi$ and exhibit two displaced maxima around $\Delta\phi = \pi \pm 1.1$ radians [22, 23]. This camel-back or conical-like shape provides insight in the quenched parton interactions with the medium. Various scenarios are proposed, such as radiative loss [24], Čerenkov-like or Mach-cone emissions [25]. The later allows one to compute an average speed of sound in the medium of $c_S \sim 0.45$.

- Analyses of three particles correlations also exhibit the conical pattern [26].

- The near-side jet exhibits a *ridge* along pseudorapidity (thus perpendicular to the azimuthal structure) that suggests the jets are indeed flowing with the expanding matter [21, 23, 27].

In brief, these high p_T dihadron correlation studies show that **the matter is opaque** to jets to a first approximation, and clearly modifying their remaining structure.

2.3 New Tools

In addition to all the above, new tools were recently made available, thanks to the statistics accumulation at RHIC:

- The correlation of a jet (or leading hadron) with a high energy photon helps calibrating the jet, since the photon, essentially unmodified by the medium, should balance its initial transverse momentum. Both PHENIX [28] and STAR [29] have seen away side jets and released preliminary analyses of the so called I_{AA} (or I_{CP}), which is the jet particle yield per photon seen in central A+A collisions with respect to p+p (or peripheral A+A). Though limited by statistics, I_{AA} exhibit similar suppressions as R_{AA}.
- Another long awaited tool was the full reconstruction of jets in a heavy ion collision environment. Reconstructed jets have been shown recently by the STAR [30] and PHENIX [31] experiments, in Au+Au and Cu+Cu collisions respectively. The STAR preliminary result exhibits jet broadening with R_{AA} going from close to unity to much lower values ($R_{AA} < 0.1$) when varying the radius of the jet reconstruction cone (from $R = 0.4$ to 0.2).

Both these novel methods should allow, in the near future, to derive medium-modified fragmentation functions.

3 Quarkonia Suppression

The bulk (low p_T) charm production scales to first order with the number of binary collisions ($R_{AA} \sim 1$), as shown in [32]. This forms a good baseline for the study of bound states made of charm-anticharm quarks, the more stable among them being the J/ψ particle. In fact, charmonia were predicted to melt in the QGP, due to Debye screening of the colour charge in the medium [33]. Furthermore, J/ψ suppression was indeed observed at lower energy ($\sqrt{s_{NN}} =$ 17.3 GeV) by the NA50 experiment [34] and is the main signature that led CERN to claim for the discovery of QGP. It was thus an awaited measurement at RHIC energies. Figure 3 shows J/ψ nuclear modification factors as measured by the PHENIX experiment [35], for both mid (red circles, $|y| < 0.35$) and forward rapidity (blue squares, $1.2 < |y| < 2.2$), as a function of centrality (given by the number of participants N_{part}). These results brought two surprises:

- First, the midrapidity result is surprisingly similar to the one observed by the NA50 experiment which also lies close to midrapidity (black crosses, $0 < y < 1$). There is no fundamental reason for this to happen since the energy density for a given N_{part} is higher at RHIC and should further melt quarkonia.
- Even more surprising is the fact that, at forward rapidity, J/ψ are further suppressed (by $\sim 40\%$), while any density induced suppression scenario, such as the Debye screening mentioned above would predict the opposite trend.

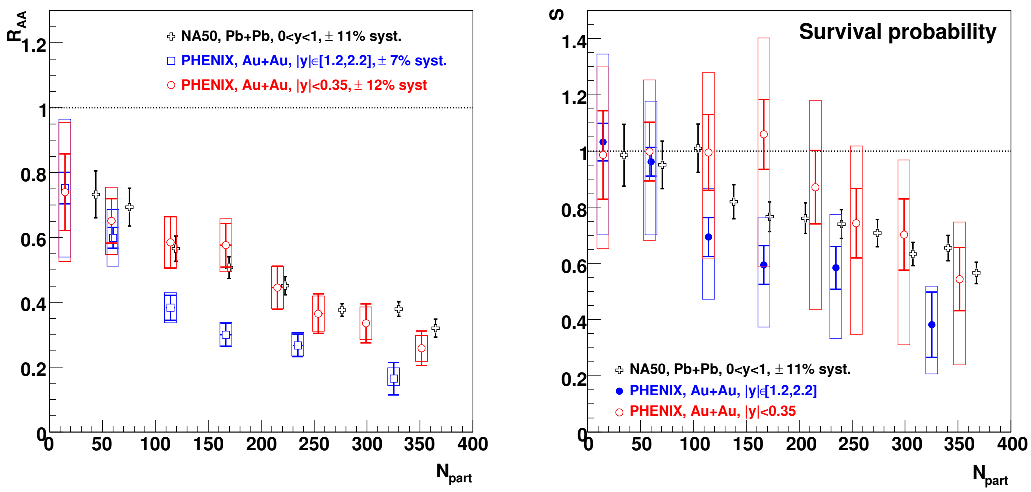

Figure 3: J/ψ suppression measured by the PHENIX and NA50 experiments, as a function of centrality, given by the number of participants. Left: nuclear modification factor. Right: J/ψ survival probabilities after normal nuclear effects subtraction.

But one needs to be careful in interpreting these results since J/ψ are known to be suppressed by regular nuclear matter as it is seen in p+A or d+A collisions [34, 36]. In order to compare the two regimes, one thus first needs to subtract these *normal* nuclear matter effects. At RHIC, they are poorly constrained by a relatively low statistics d+Au data set. Several methods, summarised in [36], can nevertheless be used to estimate them. The most data-driven one, inspired by [37] is used to obtain the right part of Figure 3. The very large error bar displayed as a box is essentially reflecting the large normal suppression uncertainties. It illustrates that the two surprises mentioned above may be caused by normal effects: anomalous suppression could be different at SPS and RHIC, and similar at forward and rapidity at RHIC. More RHIC d+Au data were very recently released [38] that will help to reduce the normal suppression uncertainty. However, we clearly see that J/ψ are suppressed beyond normal nuclear effects, both at SPS and RHIC (especially at forward rapidity).

An alternate scenario was (prematurely) proposed to explain the RHIC rapidity difference. J/ψ could indeed be recreated in the plasma by recombination of independent charm and anticharm quarks (a large variety of recombination or coalescence models exists, see references in [39]). This beautiful idea of *reconfinement*, and thus of *deconfinement*, unfortunately does not provide very quantitative predictions of the nuclear modification factors (recombination models suffering from the lack of input charm quark distributions). Other observables (p_T dependence, elliptic flow, feed-down contributions...) start to be available[2] but so far, they do not allow any firm conclusion.

However, even if the details of the mechanisms responsible for the exact J/ψ yield at RHIC are not known, we do not need them to reckon that J/ψ seem to melt beyond normal nuclear effects, at least in the most central collisions. This is a sign that **the matter is deconfining**. It is to be noted that the era of Υ studies ($b\bar{b}$ bound states) was recently opened and should

[2] For a comprehensive review on the subject, see [39].

provide new insights in quarkonia suppression. At present, preliminary result gives $R_{AA} < 0.64$ with a confidence level of 90% for minimum-bias upsilon-mass dielectrons [40], while $R_{dA} = 0.98 \pm 0.32 \pm 0.28$ [41]. These do not yet allow one to derive strong conclusions.

4 Thermal Radiation

Any equilibrated and hot system should emit thermal radiation. We saw in Figure 1 that photons are unmodified by the medium and the nuclear modification factor is compatible with unity. This holds for large p_T (typically larger than 4 GeV/c), but lower p_T photons exhibit an *enhancement*.

In Figure 4, the bottom curves and points show the p+p photon spectrum (stars) from PHENIX compared to NLO pQCD calculation. The upper spectra are from various centrality selections of Au+Au collisions. The dashed lines are derived from the p+p collisions and scaled up by the number of collisions. The lowest p_T photons (obtained through the "internal conversion" method [42]) clearly exhibit an enhancement. Various hydrodynamical models (for a review, see [43]) fairly reproduce the data assuming early (typically at a time of the order of 0.15 to 0.6 fm/c) temperature of 300 to 600 MeV, well above the critical temperature of $T_c \simeq 190$ MeV predicted by lattice QCD [8] as the phase transition boundary to a quark-gluon plasma.

We thus see thermal photons that demonstrate that **the matter is hot**.

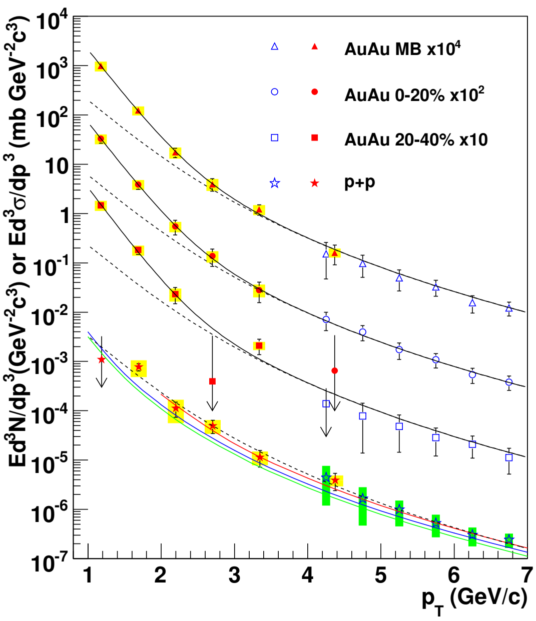

Figure 4: Thermal + perturbative QCD fits to the photon yield in Au+Au collisions, as seen by the PHENIX experiment. The lower points are from p+p collisions and are matched to perturbative QCD only.

5 Conclusions

Even if we have not (yet) observed any sharp change in the behaviour of the Au+Au observables related to the predicted phase transition, nor numbered the degrees of freedom of the system, it is clear that the matter produced at RHIC behaves very differently than ordinary hadronic matter. Indeed, we saw that the matter is gluon saturated, dense, opaque, deconfining and hot. Other observables [5] show that it is also strongly interacting and liquid-like, as well as of partonic nature. It is thus very likely to be formed by deconfined quarks and gluons.

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