What is the matter created in heavy ion collisions?

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1 Foreword

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 summarized in 2005 by its four experiments, BRAHMS, PHENIX, PHOBOS and STAR, in their so-called *white papers* [1, 2, 3, 4] that will be referenced thereafter. Beyond and after this, a wealth of data has been collected and analyzed, and provided additional elements for an answer to the question raised by my title. It is categorically impossible to give a comprehensive review of these results in a 30 minutes talk or a 10 pages report. I have made the choice to focus on the so-called *hard probes* : jet quenching in sections 2 and 3, quarkonia in section 4 and photons in section 5. Emphasis is put on latest results (some of them being very preliminary) and on the new tools recently made available. A more comprehensive (and slightly older) review can be found in Ref. [5].

One of the 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 [6]: $\varepsilon = dE_T/dy|_{y=0}/\tau_0 A_T$, 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. The question of the time to be considered is not trivial, but 1 fm/c is a maximum if one cares about the earliest as possible *thermalized* medium. Indeed, hydrodynamical analyses of collective phenomena provide thermalization times between 0.6 and 1 fm/c, while the formation time is estimated to be 0.35 fm/c and the nucleus-nucleus crossing time is 0.13 fm/c. For a detailed discussion of energy density and time scale estimates, see section 2 of Ref. [2]. What matters here is that 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 [7]: $\varepsilon_c \sim 1$ 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 High Transverse Momentum Suppression

Fig. 1 is an illustration of the first and most striking QGP signature seen at RHIC, namely the quenching of jets [8, 9]. Displayed is the nuclear modification factor R_{AA} defined as the yield of particles seen in A+A collisions, normalized by the same yield from p+p collisions scaled by the average number of binary collisions corresponding to the considered centrality: $R_{AA} = dN_{AA}/\langle N_{coll}\rangle \times dN_{pp}$. 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] [12] (purple squares) up to 13 GeV/c, while the corresponding π^0 (orange triangles) and η up to 10 GeV/c (red circles) are suppressed by a factor of five. 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. The medium is so dense that it cannot be made of individual hadrons, but rather of quarks and gluons. In [13], PHENIX has released π^0 modification factors up to 20 GeV/c, and performed a quantitative estimate of the constraints they put 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 Ref. [14].

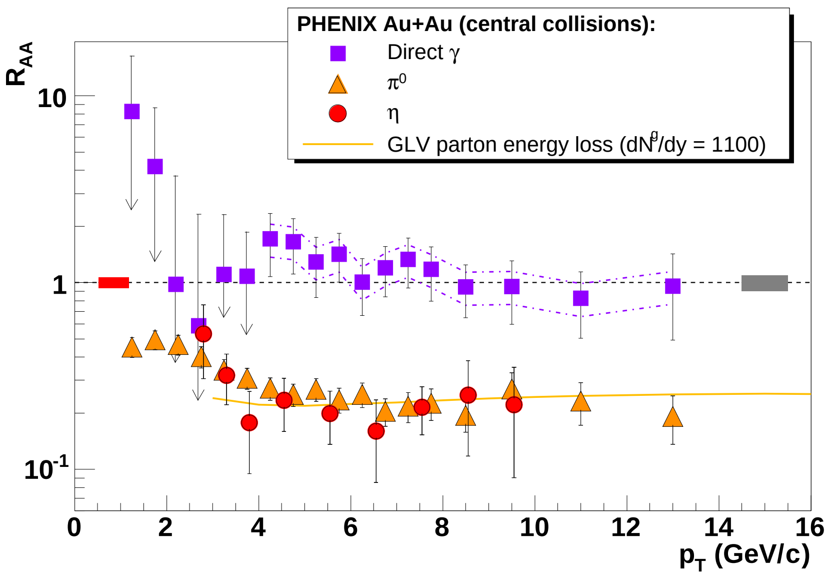

Figure 1: Nuclear modification factors for photon, η and π^0 for central collisions, from the PHENIX experiment.

[1]PHENIX has released preliminary photons up to 18 GeV/c [10], which start to deviate below unity. As discussed in [11], 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 QGP.

High p_T suppression is 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. It is not observed in d+Au collisions (in particular for neutral pions [15] to be compared to the ones on Fig. 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).

In addition, quenching of electrons coming from semi-leptonic decays of heavy flavors (charm and beauty) was also observed [16, 17]. The low p_T dominant yield scale with the number of collisions ($R_{AA} \simeq 1$) as expected and seen on Fig. 2 (full green circles) but higher p_T electrons (blue open circles) are quenched by an amount not far from the one of light quarks (red squares). This was a surprise, since energy loss in a gluon medium was expected to be reduced for heavy quarks. In order to reproduce the data, one needs a much higher gluon density than the one required for light flavors ($dN_g/dy \sim 3500$ [18]). Various hypotheses are made to reinforce the heavy quark quenching (adjunction of elastic energy loss, change in the charm/beauty ratio, modification of the strong coupling constant…).

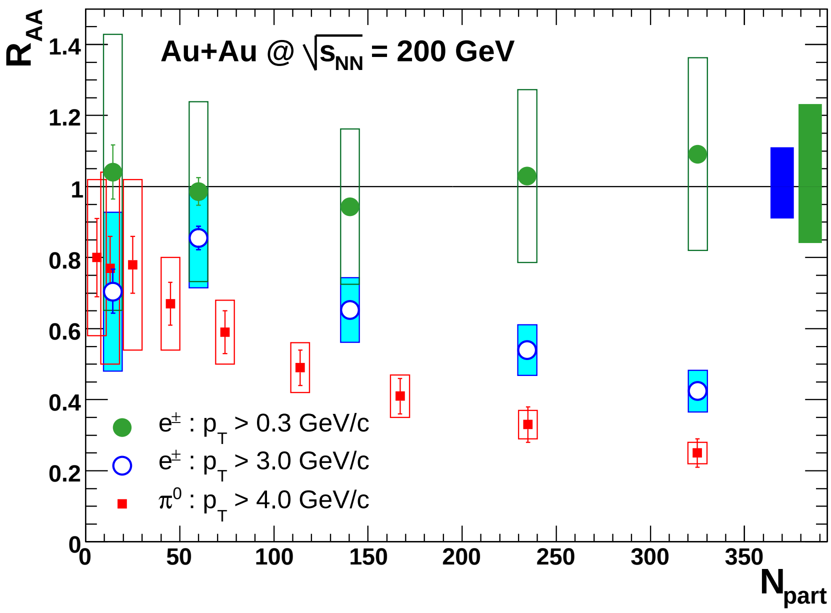

Figure 2: Heavy flavor decay electrons nuclear modification factor, for various p_T as a function of centrality [16].

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

3 Back to Back Jets

Another way to look at jets is to consider back to back high transverse momentum hadron correlations. Fig. 3 shows the measurements of such correlations for various collision types performed by the STAR experiment and reported in section 4.2 of Ref. [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 [19]. 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) where away-side hadrons are clearly distinguishable [20].

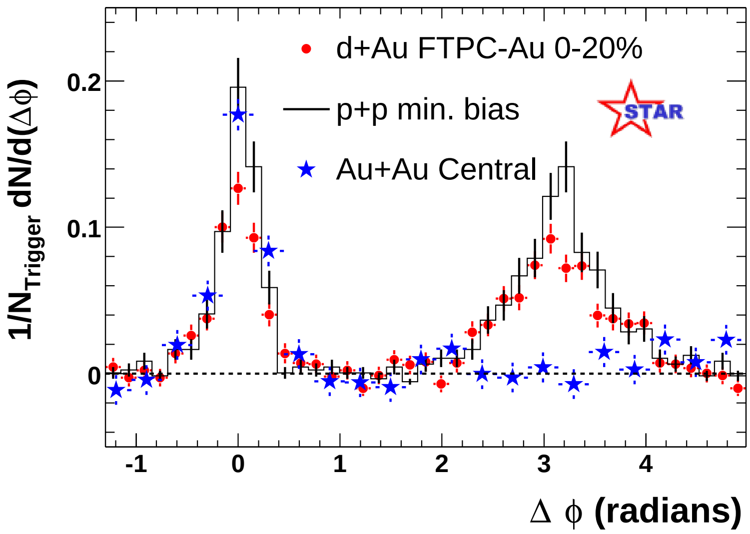

Figure 3: Dihadron azimuthal correlations in p+p, d+Au and Au+Au central collisions, from the STAR experiment.

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 [21]. 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 [22].
- These weakened away-side jets are depleted at $\Delta\phi = \pi$ and exhibit two displaced maxima around $\Delta\phi = \pi \pm 1.1$ radians [23, 24]. 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 [25], Čerenkov-like or Mach-cone emissions [26]. 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 [27].
- 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 [22, 24, 28].

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. In addition to this, two 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 should be unmodified by the medium and thus balancing its initial transverse momentum. Both STAR [29] and PHENIX [30] 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 a similar suppression as R_{AA}.
- Another long awaited tool was the full reconstruction of jets in a heavy ion collision environment. It has been shown very recently by the STAR experiment [31]. A very preliminary fragmentation function is derived and show no sizeable modification.

4 Quarkonia Suppression

We saw on Fig. 2 that the bulk (low p_T) charm production scales to first order with the number of binary collisions. This forms a good baseline for the study of bound states made of charm-anticharm quarks, the more stable of which being the J/ψ particle. In fact, charmonia were predicted to melt in the QGP, due to Debye screening of the color charge [32]. Furthermore, J/ψ suppression was indeed observed at lower energy ($\sqrt{s_{NN}} = 17.3$ GeV) by the NA50 experiment [33] and is the main signature that led CERN to claim for the discovery of QGP. It was thus very awaited at RHIC energies. Fig. 4 shows J/ψ nuclear modification factors as measured by the PHENIX experiment [34], 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.

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 [33, 35]. In order to compare 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, summarized in [35], can nevertheless be used to estimate them. The most data-driven one, inspired by [36] is used to obtain the right part of Fig. 4. 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 is clearly needed 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 [37, 38, 39, 40, 41, 42, 43] exists). This beautiful idea of *reconfinement*, and thus of *deconfinement*, unfortunately do 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 to conclude.

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 do melt beyond

[2] For a complete recent review on the subject, see Ref. [44].

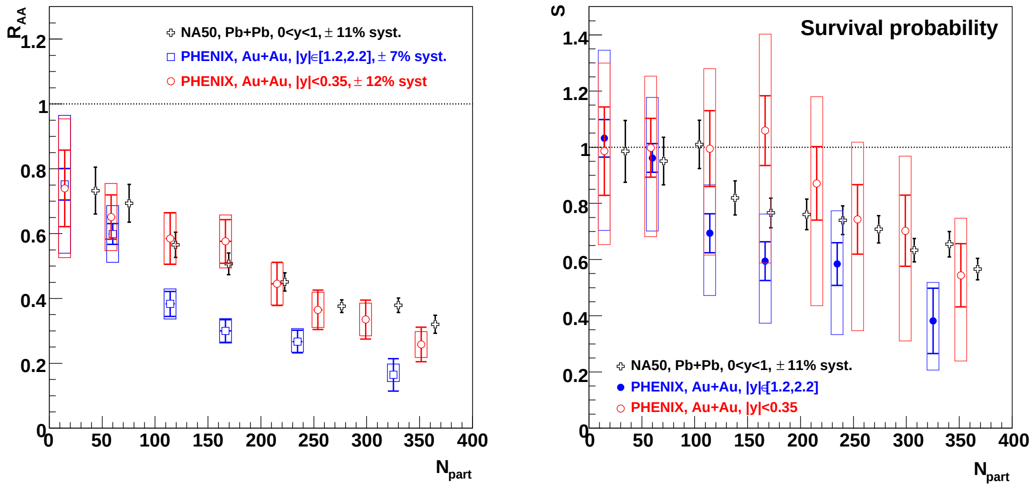

Figure 4: J/ψ suppression measured by the PHENIX and NA50 experiments, as a function of centrality, given by the number of participants. Left: nuclear modification factor. Right: J/ψ survival probabilities after normal nuclear effects subtraction.

normal nuclear effects, at least in the most central collisions. This is a sign that **the matter is deconfining**.

5 Thermal Radiation

A thermalized matter should emit its own thermal radiation. We saw on Fig. 1 that photons are unmodified by the medium and the nuclear modification factor is compatible with unity. This holds for $p_T > 2$ GeV/c, but lower p_T photons exhibit an *enhancement*. The bottom of Fig. 5 shows the p+p photon spectrum (as stars bur from PHENIX) compared to NLO pQCD calculation. The upper spectra are from various centrality selection 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 an internal conversion method [45]) clearly exhibit an enhancement. Various hydrodynamical models (for a review, see [46]) 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 $T_c = 190$ MeV provided by lattice QCD [7] as the phase transition boundary to a quark-gluon plasma.

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

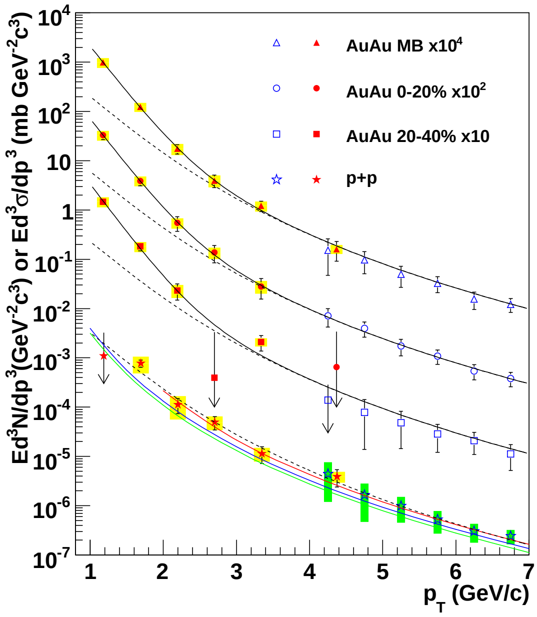

Figure 5: Thermal + perturbative QCD fits to the photon yield in Au+Au collisions, as seen by the PHENIX experiment [45]. The lower points are from p+p collisions and are matched to perturbative QCD only.

6 Conclusions

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

References

[1] I. Arsene et al. Nucl. Phys. A757 (2005) 1, nucl-ex/0410020.

[2] K. Adcox et al. Nucl. Phys. A757 (2005) 184, nucl-ex/0410003.

[3] B. B. Back et al. Nucl. Phys. A757 (2005) 28, nucl-ex/0410022.

[4] J. Adams et al. Nucl. Phys. A757 (2005) 102, nucl-ex/0501009.

[5] R. Granier de Cassagnac. Int. J. Mod. Phys. A22 (2008) 6043, arXiv:0707.0328.

[6] J.D. Bjorken. Phys. Rev. D27 (1983) 140.

[7] F. Karsch. Lect. Notes Phys. 583 (2002) 209.

[8] S. S. Adler et al. Phys. Rev. Lett. 91 (2003) 072301, nucl-ex/0304022.

[9] S. S. Adler et al. Phys. Rev. C75 (2007) 024909, nucl-ex/0611006.

[10] T. Isobe. J. Phys. G34 (2007) S1015, nucl-ex/0701040.

[11] F. Arleo. JHEP 09 (2006) 015, hep-ph/0601075.

[12] S. S. Adler et al. Phys. Rev. Lett. 94 (2005) 232301, nucl-ex/0503003.

[13] A. Adare et al. Phys. Rev. C77 (2008) 064907, arXiv:0801.4020.

[14] I. Vitev and M. Gyulassy. Phys. Rev. Lett. 89 (2002) 252301, hep-ph/0209161.

[15] S. S. Adler et al. Phys. Rev. Lett. 91 (2003) 072303, nucl-ex/0306021.

[16] A. Adare et al. Phys. Rev. Lett. 98 (2007) 172301, nucl-ex/0611018.

[17] B. I. Abelev et al. Phys. Rev. Lett. 98 (2007) 192301, nucl-ex/0607012.

[18] M. Djordjevic et al. Phys. Lett. B632 (2006) 81, nucl-th/0507019.

[19] C. Adler et al. Phys. Rev. Lett. 90 (2003) 082302, nucl-ex/0210033.

[20] J. Adams et al. Phys. Rev. Lett. 91 (2003) 072304, nucl-ex/0306024.

[21] J. Adams et al. Phys. Rev. Lett. 93 (2004) 252301, nucl-ex/0407007.

[22] J. Adams et al. Phys. Rev. Lett. 95 (2005) 152301, nucl-ex/0501016.

[23] S. S. Adler et al. Phys. Rev. Lett. 97 (2006) 052301, nucl-ex/0507004.

[24] A. Adare et al. Phys. Rev. C78 (2008) 014901, arXiv:0801.4545.

[25] A. D. Polosa and C. A. Salgado. Phys. Rev. C75 (2007) 041901, hep-ph/0607295.

[26] J. Ruppert and B. Muller. Phys. Lett. B618 (2005) 123, hep-ph/0503158.

[27] B. I. Abelev et al. arXiv:0805.0622.

[28] J. Adams et al. Phys. Rev. C73 (2006) 064907, nucl-ex/0411003.

[29] A. M. Hamed. Hard probes 2008 conference, arXiv:0809.1462.

[30] M. Nguyen. J. Phys. G35 (2008) 104121, arXiv:0805.1225.

[31] S. Salur. Hard probes 2008 conference, arXiv:0809.1609.

[32] T. Matsui and H. Satz. Phys. Lett. B178 (1986) 416.

[33] B. Alessandro et al. Eur. Phys. J. C39 (2005) 335, hep-ex/0412036.

[34] A. Adare et al. Phys. Rev. Lett. 98 (2007) 232201, nucl-ex/0611020.

[35] A. Adare et al. Phys. Rev. C77 (2008) 024912, arXiv:0711.3917.

[36] R. Granier de Cassagnac. J. Phys. G34 (2007) S955, hep-ph/0701222.

[37] A. Andronic et al. Nucl.Phys. A789 (2007) 334, nucl-th/0611023.

[38] R. L. Thews. Eur. Phys. J. C43 (2005) 97, hep-ph/0504226.

[39] L. Ravagli and R. Rapp. Phys. Lett. B655 (2007) 126, arXiv:0705.0021.

[40] X. Zhao and R. Rapp. Phys. Lett. B664 (2008) 253, arXiv:0712.2407.

[41] L. Yan et al. Phys. Rev. Lett. 97 (2006) 232301, nucl-th/0608010.

[42] O. Linnyk et al. Nucl. Phys. A807 (2008) 79, 0801.4282.

[43] K. Tywoniuk et al. J. Phys. G35 (2008) 104156, arXiv:0804.4320.

[44] R. Granier de Cassagnac. J. Phys. G35 (2008) 104023, arXiv:0806.0046.

[45] A. Adare et al. submitted to Phys. Rev. Lett., arXiv:0804.4168.

[46] D. d'Enterria and D. Peressounko. Eur. Phys. J. C46 (2006) 451, nucl-th/0503054.

Discussion

Question: When will we have a single simple signature of the quark gluon plasma creation?

Answer: In this complicated field, I think that the picture of what the created matter really is can only emerge from a variety of “signatures”, each of which being individually challenged by models, given the very wide phase space offered to theories. I think this variety of signatures is indeed observed at RHIC.