Constraints induced by finite plasma formation time on some physical observables at RHIC

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(Dated: December 7, 2018)

Abstract

We discuss consequences of finite plasma formation time at RHIC. Nuclear modification factor, azimuthal asymmetry, di-jet correlations can quantitatively be described by particle production in the early stage of the nuclear collision. A possible impact on interpretation of the non-photonic electrons and \(J/\psi\) data is also considered.

PACS numbers: 25.75.Nq
The existence of a long Quark Gluon Plasma (QGP) formation time \([1]\), \(T=2-3 \text{ fm/c}\), may have a strong impact on some physical observables in the experiment. Direct physical interpretation of these observables could be misleading. If jets or other hard scattering processes do not suffer from strong energy loss or absorption during formation time, there should be a significant corona effect. All processes in the corona region will not be influenced by the produced dense medium. The relative contribution of corona decreases with centrality, but could account for at least 20% of hard processes in the most central collisions. It means, for example, that at each centrality class, the nuclear modification factor \(R_{AA}\) for a particle produced in a hard scattering process can’t be smaller than the corona contribution. Of course, this is valid if an additional absorption, like normal nuclear absorption, does not take place during these first 2-3 fm/c. Many physical observables will be influenced by contribution from the corona region. A list of possible consequences follows. We used a simple Monte Carlo simulation of nucleus-nucleus collisions based on Glauber approach with a Woods-Saxon nuclear density distribution \([1]\).

1. The PHENIX collaboration at Relativistic Heavy Ion Collider, RHIC, showed a preliminary result for the \(R_{AA}\) dependence on azimuthal angle relative to the reaction plane in \(\text{Au+Au}\) collisions at \(\sqrt{s_{NN}}=200\ \text{GeV}\) at RHIC \([2, 3]\), Fig. \(\text{[1]}\). As expected, \(R_{AA}\) is larger in the reaction plane and smaller out of the plane. The most interesting feature of this result is that in the event centrality class 50-60%, the in-plane \(R_{AA}\) becomes close to one. That is, no absorption at all is seen for high \(p_t\) pions. At the same time a significant particle absorption is seen in the out-of-plane \(R_{AA}\). Here \(R_{AA}\) is a nuclear modification factor which is defined as

\[
R_{AA}(p_T) = \frac{(1/N_{\text{evt}}) \int d^2N^{A+A}/dp_Td\eta}{(\langle N_{\text{binary}} \rangle/din\sigma^{N+N}/dp_Td\eta)}
\]

where \(\langle N_{\text{binary}} \rangle\) is a number of binary nucleon-nucleon collisions at a particular centrality class. In the 50-60% event centrality class, the amount of nuclear matter is still significant in all directions. It’s puzzling that a high momentum pion can “punch through” the interaction zone in the in-plane direction but may be stopped when traveling in the other direction. In the paper \([1]\) we attempted to explain numerically this feature by a QGP formation time of \(T = 2.3\ \text{fm/c}\). During this time, for centrality class 50-60%, in-plane produced jets can freely leave the interaction zone. From other side, jets produced out-plane, where the size of
interaction region is larger, have not enough time to escape and will be partially absorbed by the formed dense medium.

2. Obvious consequences of such a scenario are: a) all pions above 5-6 GeV/c are produced by parton fragmentation from the corona region, which is formed between 2 to 3 fm/c after the beginning of the collision; b) combining this with the experimental fact that the hadron to pion ratio, enhanced at low momenta, returns back to its vacuum value at \( p_t \) above 5 GeV/c [4], we can conclude that all high \( p_t \) hadrons are produced from corona region; c) \( R_{AA} \) versus \( p_t \) for pions and hadrons at high transverse momenta will be flat [4].

3. The model parameter \( T = 2.3 \text{ fm/c} \) was adjusted to describe a small subset of Au+Au data at centrality 50-60%. However, with this value of \( T \) we can nicely explain the \( R_{AA} \) behaviour not only for all centrality classes of Au+Au collisions, but for Cu+Cu interactions too, Fig. 2.

4. We also estimate another experimental variable, \( v_2 \). It describes the elliptic shape of the nucleus-nucleus collision in azimuthal angle as \( \frac{dN}{d\phi} = N(1 + 2v_2 \cos(2\phi)) \). The long formation time naturally brings the result of non-zero \( v_2 \) for high \( p_t \) pions [1], Fig. 3. The value of \( v_2 \) reaches 11-12% in mid-central collisions of gold nuclei with Woods-Saxon density distributions. At each centrality class \( v_2 \) will be constant at high transverse momenta.

5. Two-particle angular correlations of hadrons close to the high \( p_t \) “trigger” particle or opposite to the “trigger” particle directions allow to investigate of the near-side and the away-side jets properties, respectively. Following the argumentation that all particles at high \( p_t \) are produced from corona region, we can explain the weak dependence of properties of the near-side jets [7] with centrality in Au+Au collisions. In the cited paper, some increase was observed in the near-side particle yield only for low momentum associated particles.

6. STAR collaboration published the results on \( I_{AA} \) in Au+Au collisions - the ratio of away-side yield per trigger particle to the similar value from p+p collisions [8]. We calculate \( I_{AA} \) within our model with \( T = 2.3 \text{ fm/c} \) for different centralities. The increase of corona thickness by 2.3 fm keeps the value of \( I_{AA} \) at the level close to \( R_{AA} \), Fig. 4. We want to emphasize that these are two different variables, \( I_{AA} \) is related to the yield per trigger particle. The trigger particle should “survive” from absorption in a first place. In this calculation we assume that away-side jet distribution has a Gaussian shape with the width parameter of 0.35 radians.

7. At Quark Matter 2005 conference, August 4-9, in Budapest, Hungary, STAR col-
laboration claims that away-side jet re−appears at high trigger and associated particles momenta [9]. While changing the momentum range of the associated particle, the jet width will change too - for higher momentum particles the jet width should be smaller. We check the STAR result by changing the width of simulated away-side jet, Fig. 5. For all values of width, \( I_{AA} \) is still significant even for most central events. We argue that in previous analysis at lower momentum range, the away-side jet was wider and it was not easy to reconstruct its remnants on the level of 20-25%. Besides this, at low associated particle momentum, the response of the high density medium on the absorbed away-side jet changes dramatically in shape and in yield [10].

8. Discussions in the previous parts 2, 6 and 7 lead to the conclusion that, probably, even at particle momenta 5-10 GeV/c, we don’t see “punch-through” jets, these are di-jets from corona region. This is why width of the away-side jet does not change with centrality and is the same as in p+p collisions [9]. We investigate the away-side jet shape in our model. Di-jet forms kind of a tangential emission from the surface of interaction region. If in experiment the trigger particle radiates at particular direction, di-jets can survive along the two tangents, from the edges of the collision zone. If the collision zone is small and away-jet is wide we may see jet splitting too. In Fig. 6 we plot the results of the simulation of di-jets in mid-central 30-35% Au+Au events. The away-side jet originally had a Gaussian shape with the width of 0.75 radians. The dashed histograms represent jets survived at the two tangential directions. We see slight shifts from the original direction on the order of 25% of the original width. The solid line histogram represents the sum of these two subsets and its fit by the Gaussian function. The width parameter sigma of this fit, 0.77 radians, is very close to the original width. The observed features do not change significantly with centrality. We can conclude that, indeed, the shape and the width of away-side jet are not changed much. There is no visible back jet splitting produced in the corona region, thus it can not be an explanation of the two peak structures seen in the experiment [10] at low momentum of the associate particle.

9. In Fig. 7 we present PHENIX preliminary results on non-photonic electrons at high momenta shown at Quark Matter 2005 [11]. We also plot the lower limit of \( R_{AA} \) determined by particle production from the corona region during the formation time, solid line. Experimental points sit exactly on the line. These electrons originated from D-mesons, charmed baryons and, probably, from bottom quark decays. The conclusion of Fig. 7 would be that
at high $p_t$ the charm quarks are completely absorbed by dense medium, similar to the light quarks.

10. In the case of a strong charm quark absorption, following the argument in our previous part 4, one can expect a significant $v_2$ for non-photonic electrons. Experiments indeed found non-zero $v_2$. Qualitatively, it is possible to describe also the momentum dependence of $v_2$. Leptonic modes of D-meson decay are mostly with 3- and 4-particles in the final state. The low momentum electrons should be produced isotropically from the low energy D-mesons. With increasing energy of the meson, decay products will start to follow the direction of decaying meson, so electron $v_2$ will increase too (this argument was also stressed in the reference [12]), and finally will saturate for high $p_t$ at the values presented in Fig. 3. It would be mistaken to say naively “charm flows”. This statement needs clarification and an additional experimental investigation.

11. We expect many interesting features from $J/\psi$ production in nucleus-nucleus collisions. $J/\psi$ is a closed system of two heavy charm quarks. In particular interest is the interaction of such a system with the surrounding medium. Previously, a very strong $J/\psi$ suppression was observed at lower energy nucleus-nucleus collisions [14, 15]. New PHENIX preliminary data show the suppression at about similar strength [13], Fig. 8. In our consideration we divide nucleus-nucleus collision into two stages: before plasma formation and after. As it was already demonstrated, hard scattering processes, like jet production, do not suffer from energy loss or absorption during plasma formation time. The matter is transparent for them at this stage. In contrast, during the actual “plasma time”, the medium looks completely “black” for jets.

Part of $J/\psi$s could be absorbed during early stage of the collision. In this case the medium will be “grey” for them. At the same time, other models predict incomplete suppression of $J/\psi$ in QGP phase, which means also that plasma is “grey”. We try to demonstrate how the distinction of plasma formation time, QGP itself and different suppression processes lead to a few major scenarios, Fig. 8. Scenario (a), white and black: no absorption at the early stage, total absorption in the QGP - solid line in Fig. 8. In this case everything is similar to the jet absorption. Scenario (b), grey and black: during the plasma formation time $J/\psi$ has normal nuclear absorption but suffers from total absorption in the QGP, lower dashed line. This line goes obviously below the solid curve and was obtained by applying the results of R.Vogt calculations to the corona region only. In other words, it is the solid line result from
the case (a) times the original curve from R. Vogt. This would be an overestimation of the normal nuclear absorption because we did not take into account that the initial stage lasts 2.3 fm/c only. Scenario (c), *white and grey*: top dotted line, where we assume that there is no absorption during the initial stage and some suppression in the QGP stage. Here we take just one model with QGP absorption by Kostyuk et al. [17] and applied to the second, QGP, phase only.

It is worthwhile to mention that the original calculations [16, 17] for $J/\psi$ we used in cases (b) and (c) significantly overestimate and underestimate $R_{AA}$, respectively [13].

By listing such naive speculations we want to stress the importance of the different stages of the nuclear collision, including plasma formation time, for $J/\psi$ production.

In conclusion, we want to emphasize that we propose not “yet another” simple model with just one parameter, which actually, may increase a little bit if the longitudinal expansion will be taken into account. We do not pretend to describe in many details all features of the nucleus-nucleus collision at RHIC. We present an *orthogonal* point of view on some experimental data. This view could be useful for better understanding of properties of a new matter produced at RHIC. Perhaps, it will bring clear vision or some new ideas on formation process and properties of a quark-gluon phase.

We tried to explain some of the features seen in the experiment, but also bring two major questions: where this formation time comes from, why models with fractional parton energy loss do not work well or why energy loss is very strong? The answers may come soon: interesting new approaches such as the complex plasma model [18] or the radically new picture of QCD with polymer chains have been proposed [19] recently.

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Figures
FIG. 1: PHENIX preliminary $R_{AA}$ results for $\pi^0$ at momenta 5-6 GeV/c versus angle $\phi$ relative to the reaction plane for different centralities in Au+Au collisions at RHIC [3]. Points are experimental data, thin lines show systematic errors from the reaction plane resolution and vertical bars in the middle show the reaction plane averaged $R_{AA}$ value and its error. Black horizontal bars are predictions of our model.
FIG. 2: Calculated $R_{AA}$ for Au+Au, dashed curve, and Cu+Cu, solid curve, collisions versus the number of participant nucleons, $N_{\text{part}}$. The circles are experimental data for $\pi^0$ yield for Au+Au integrated for $p_t \geq 4$ GeV/c [4]. The triangles are data for Cu+Cu integrated for $p_t \geq 7$ GeV/c [5].
FIG. 3: Calculated ellipticity parameter \( v_2 \) for Au+Au collisions, solid line, versus the number of participant nucleons, \( N_{\text{part}} \). Data for \( \pi^0 \) with error bars are: squares for 5-7 GeV/c, circles for 4.59 GeV/c. PHENIX preliminary data [3, 6].
FIG. 4: Calculated $I_{AA}$ for Au+Au, the curve, versus the number of participant nucleons, $N_{\text{part}}$. The width (sigma) of away-side jet is 0.35 radians. The circles are experimental data from [8].
FIG. 5: Calculated $I_{AA}$ for Au+Au versus the number of participant nucleons, $N_{\text{part}}$, for different width of away-side jet - the numbers in radians next to the lines. Results for Cu+Cu at 200 GeV and Au+Au collisions at 62.4 GeV are also shown.
FIG. 6: Angular distributions within the away-side jet in the case of jet production from the corona region with strong jet absorption in QGP core. The original away-side jet had a Gaussian shape with the width parameter of 0.75 radians. Dashed histograms represent the jet distribution from two different sides of the collision zone. The solid line histogram is the sum of these two subsets. Numbers in the box represent the result of the solid line histogram fit by the Gaussian function.
FIG. 7: $R_{AA}$ for non-photonic electrons in Au+Au versus the number of participant nucleons, $N_{part}$. The PHENIX preliminary experimental data are from [11]: circles and squares are for $p_t=4.25$ GeV/c and 4.75 GeV/c, respectively. Shown are statistical errors only. Solid line - the result of our calculation which puts the geometrical limit in case of strong charm quark absorption.
FIG. 8: $R_{AA}$ for $J/\psi$ in Au+Au versus the number of participant nucleons, $N_{\text{part}}$. The PHENIX preliminary experimental data are from [13]: circles - at midrapidity, squares - at rapidity $y = 1.2 - 2.2$. Shown are statistical errors only. For explanations of the different lines, see discussion in the text.