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Transverse momentum dependence of charmonium production in heavy ion collisions

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The J/ψ production shows an anomalous suppression discovered in Pb-Pb by NA50 collaboration and confirmed by NA60 Collaboration in In-In at 158 GeV per nucleon at the CERN SPS. The suppression is centrality dependent and anomalous suppression sets in at number of participant near 80 in In-In and near 125 in Pb-Pb. None of the available theoretical models trying to reproduce the medium effects for J/ψ production is able to describe the observed pattern simultaneously in Pb-Pb and In-In.

The recent PHENIX experiment at RHIC measured J/ψ suppression in Au-Au and Cu-Cu collisions at 200 GeV energy for the nucleon-nucleon centre of mass system. The results show that the J/ψ suppression at these energies is of the same order as the suppression at SPS energies for Pb-Pb. The theoretical models that could reproduce SPS Pb-Pb results produce overestimation of the J/ψ suppression.

The observed transverse momentum dependences of J/ψ suppression in Pb-Pb collisions at SPS and Au-Au collisions at RHIC are qualitatively similar. The study of the transverse momentum distributions of J/ψ as a function of the centrality of the collision shows that the observed J/ψ suppression in ion-ion interactions at all energies is particularly significant mainly at low transverse momentum where the suppression strongly increases with centrality and is of the same order for Pb-Pb and Au-Au collisions. For peripheral Pb-Pb collisions, the transverse momentum dependence of the J/ψ suppression is similar to the dependence observed in p-A and S-U collisions and shows some Cronin enhancement in the high p_{T} region. For central Pb-Pb and Au-Au collisions, the data show a suppression which extends over the whole measured p_{T} range.

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1. Charmonium production at the CERN SPS

The dissociation of heavy quark resonances by colour screening in a deconfined medium [1] is one of the possible signature of Quark Gluon Plasma formation in high energy heavy ion collisions. Indeed at the CERN SPS the NA50 experiment measured the charmonium production in Pb-Pb collisions at 158 GeV per nucleon [2, 3] and in proton-nucleus collisions at 400 and 450 GeV [4 – 6] and observed the normal nucleus suppression of J/ψ in proton-nucleus reactions and anomalous suppression in central lead-lead collisions. The NA60 experiment continuied the measurement of J/ψ production at the CERN SPS in In-In collisions at 158 GeV per nucleon and confirmed the anomalous suppression for central events [7, 8].

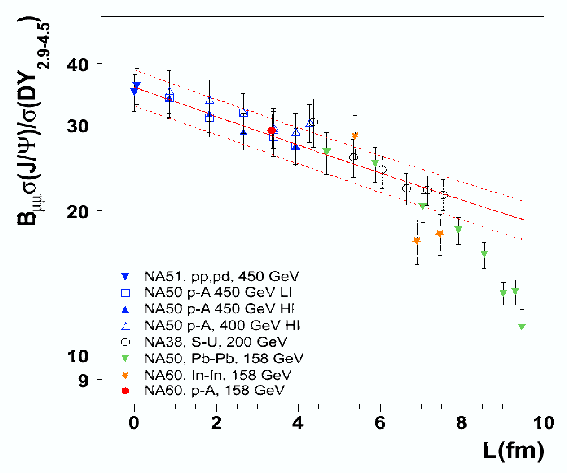

Figure 1: The J/ψ over Drell-Yan ratio versus the mean pass length in the matter, L. All data samples are rescaled to 158 GeV.

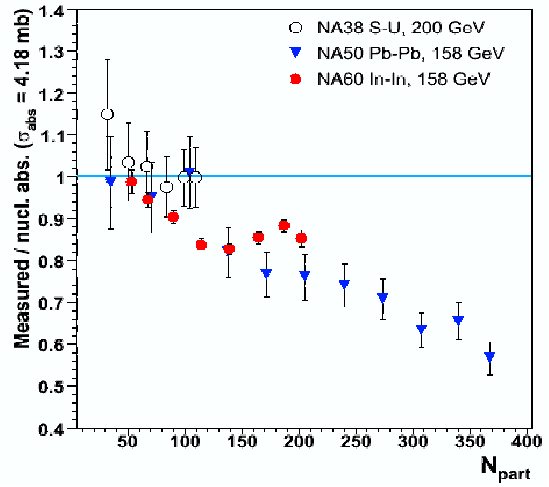

Figure 2: The J/ψ over Drell-Yan ratio, normalized to normal nuclear absorption, versus number of participants.

The results of J/ψ over Drell-Yan analysis including proton-nucleus data as a function of mean path length in the matter, L, are shown on Fig.1. The resuts, normalized to the normal nuclear

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absorption values, could be presented also as a function of $N_{\rm part}$ for nucleus-nucleus collisions. The value of $N_{\rm part}$ in collision is connected with the centrality of interaction. The available statistics for Drell-Yan events in NA60 was rather low, so analysis of the J/ψ sample alone in comparison with the theoretical distribution expected in the case of pure nuclear absorption was also performed. The ratio of measured J/ψ versus expected in the case of pure nuclear absorption was calculated and normalized to the standard J/ψ over Drell-Yan analysis. The anomalous suppression in the range 50 $< N_{\rm part} <$ 100 and some saturation at large $N_{\rm part}$ were observed [7, 8]. The results for In-In NA60 data in comparison with Pb-Pb NA50 and S-U NA38 data versus $N_{\rm part}$ are shown in the Fig.2.

There are several theoretical models trying to reproduce the medium effects for J/ψ production and to describe observed suppression pattern. They include a model where anomalous suppression is due to interaction of preresonance $c\bar{c}$ pair or the J/ψ itself with a dence system of produced hadrons ((mainly pions), the comovers. The comover model [9], which describes well the NA50 Pb-Pb data could not reproduce NA60 In-In results. Another is charmonia suppression plus regeneration model, where charmonia production is investigated within a kinetic theory framework simultaneously accounting for dissociation and regeneration processes in both quark-gluon plasma and hadron gas phases of the reaction [10]. This model agrees NA50 data quite well, but there is no agreement with the NA60 In-In data for J/ψ suppression pattern.

The next model describes suppression due to a percolation phase transition, where percolation is a geometric, pre-equilibrium form of deconfinement [11]. The model predicts sharp onset (due to the disappearance of the χ_c meson) at $N_{\rm part} \sim 125$ for Pb-Pb and at $N_{\rm part} \sim 140$ for In-In. For Pb-Pb second step (due to the disappearance of the J/ψ itself) is predicted at $N_{\rm part} \sim 320$. The agreement with the NA50 Pb-Pb data is rather good. But for NA60 the measured data show a similar pattern but the anomalous suppression sets at $N_{\rm part} \sim 80$.

There is also model that study effects of thermalized hadronic gaz on the J/ψ production [12]. But none of these models could reproduce simultaneously Pb-Pb and In-In data [7, 8].

2. PHENIX results

The resent PHENIX experiment at RHIC measured J/ψ suppression suppression in Au-Au and Cu-Cu collisions at $\sqrt{s}$ = 200 GeV in nucleon-nucleon centre of mass system [13]. The preliminary results show that the J/ψ suppression at these energies is of the same order as the suppression at SPS energies for Pb-Pb and is the same for different systems at RHIC. The R_{AA} ratio (so called nuclear modification factor) versus $N_{\rm part}$, where $R_{AA} = dN_{AA}/dy/(dN_{pp}/dy* < N_{coll} >)$, is plotted in Fig.3 and Fig.4 in comparison with theoretical predictions.

The theoretical models that could reproduce SPS results produce overestimation of the J/ψ suppression [9 – 11]. The models that include regeneration or detailed J/ψ transport agree with the experimental results better [10, 14 – 17].

3. Transverse momentum distribution of charmonium

To investigate in more detail the features of the reaction mechanism, NA50 experiment study the transverse momentum and transverse mass distributions of the J/ψ yield. In particular, the dependence, as a function of the centrality of the collision, of the mean square transverse momentum

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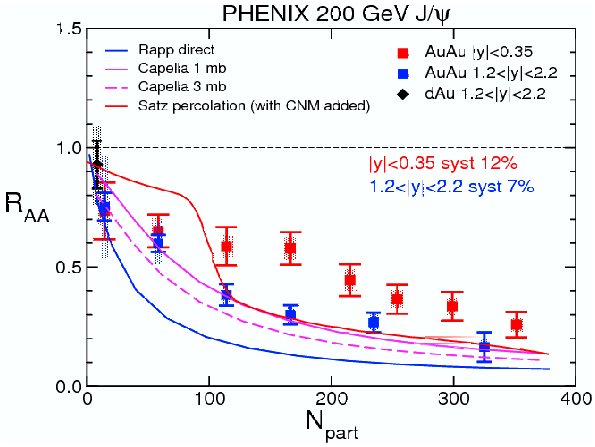

Figure 3: The comparison of J/ψ suppression, measured at PHENIX experiment with theoretical models that could reproduce Pb-Pb SPS data. Models calcultions were made for y=0.

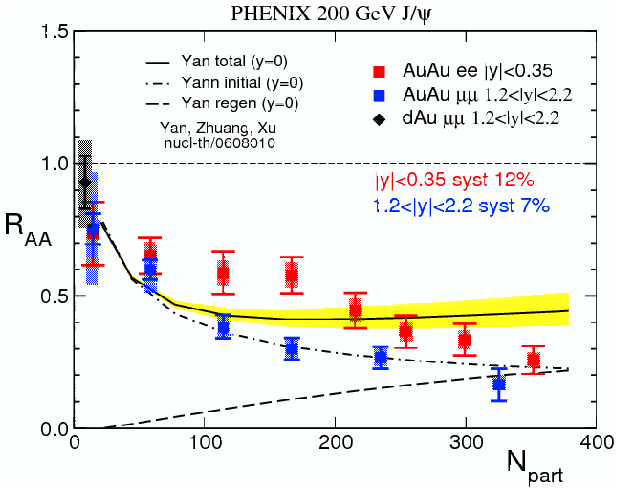

Figure 4: The comparison of J/ψ suppression, measured at PHENIX experiment with theoretical model [15] with J/ψ regeneration. Model calculations were made for y=0.

and of the slope of the M_T spectra for Pb-Pb 1996 year data were obtained and can be found in [18]. When rescaled to the same energy and as a function of the mean length path of J/ψ in nuclear matter, the mean square transverse momentum of J/ψ exhibits the same behaviour for p-A, S-U and Pb-Pb collisions [19], which could be related to initial parton scattering. The data also show a change of the slope of the T dependence on the energy density near the value where the J/ψ production cross section starts to deviate from the normal absorption curve [20, 21].

The data collected in year 2000 are of the high quality what allows a more detailed study of the J/ψ suppression as a function of the transverse momentum [22]. The ratio of the J/ψ cross section to the Drell-Yan cross section, which is proportional to the J/ψ yield per nucleon-nucleon collision was investigated. Events are binned according to the neutral transverse energy E_T which is experimentally measured by an electromagnetic calorimeter with laboratory pseudorapidity coverage in the range [1.1-2.3]. E_T is connected with the centrality of the collision in which dimuons

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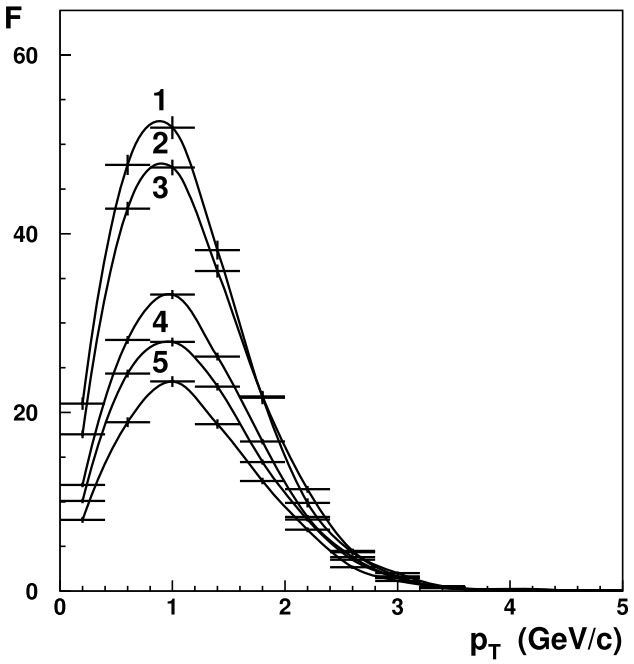

Figure 5: Ratio F of the J/ψ production cross section for Pb-Pb collisions at 158 GeV/c per nucleon as a function of the transverse momentum in GeV/c to the DY cross section for 5 E_T bins from the most peripheral (1) to central (5) bin.

are produced.

We plot on Fig.5 and Fig.6 the ratio F of the J/ψ to the DY cross section in the corresponding E_T bin as a function of transverse momentum p_T for 5 transverse energy bins (Fig.5) and as a function of the transverse energy E_T for 11 transverse momentum bins up to p_T = 5.0 GeV/c (Fig.6). The figures show that, whereas for low values of p_T there is a significant J/ψ suppression which strongly increases with centrality, when p_T increases, the dependence of the J/ψ normalized yield on centrality becomes weaker and weaker. In other words, the suppression observed on the integrated p_T yield from peripheral to central collisions originates mainly from the suppression of J/ψ with low p_T values.

Ratios R_i= (J/ψ_i / DY_i) / (J/ψ_1 / DY_1) of the J/ψ transverse momentum distribution normalized to the DY cross section in the E_i bin (i=2,3,4,5) to the first and most peripheral E_1 bin as a function of p_T are shown in Fig.7. For the peripheral collisions it shows some enhancement for p_T above 2 GeV/c. Then with respect to the most peripheral collisions, J/ψ becomes more and more suppressed with increasing centrality mainly at low p_T values. We compare Pb-Pb collisions with p-A reactions at 400 GeV on 6 different target nuclei: Be, Al, Cu, Ag, W and Pb, where the J/ψ survival probability is affected by normal nuclear absorption only. In this case, when the J/ψ yield is parametrized according to A^α, nuclear absorption leads to a value of α lower than unity reflecting the absorption of the $c\bar{c}$ pair within the target. The results of the J/ψ production study in p-A reactions are illustrated in Fig.8. For low values of p_T J/ψ production as a function of the atomic mass number A increases less than proportionally to A leading to a value of α lower than unity. For high p_T values J/ψ production increases faster than A so that the corresponding value of α is higher than 1. There is a kind of normal nuclear absorption for the lower p_T values but the

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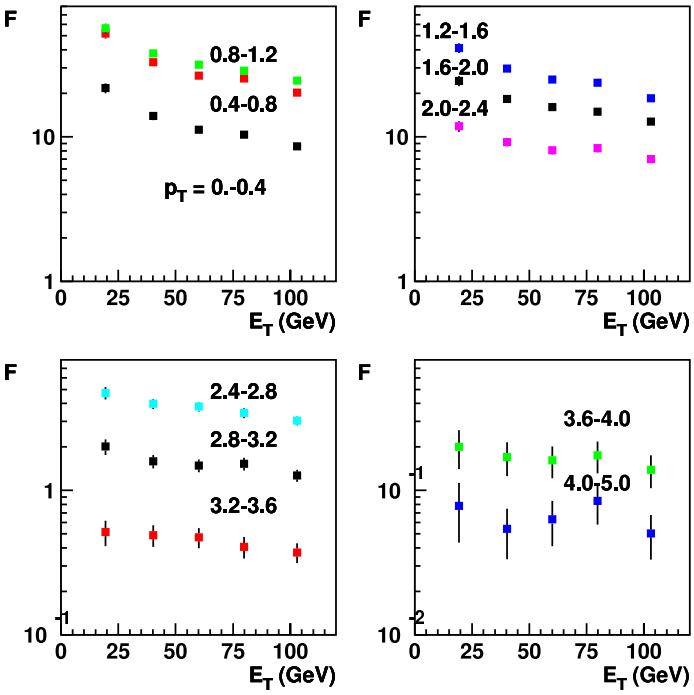

Figure 6: Ratio F of the J/ψ production cross section for Pb-Pb collisions at 158 GeV/c per nucleon in the p_T bins shown on the plots (in GeV/c) to the DY cross section, as a function of the measured neutral transverse energy in GeV.

magnitude of this absorption decreases with increasing p_T then vanishes and turns to overproduction for high p_T already above 2 GeV/c. This is, in fact, a wellknown behaviour observed since long in the production of hadrons and known as the Cronin effect.

The data for S-U collisions obtained at NA38 experiment, show the effect of absorption for low p_T (R<1), together with some hints of enhancement for high p_T (R>1) suggesting, within errors, a behaviour similar to the most peripheral Pb-Pb collisions and to the Cronin effect observed in p-A collisions. The enhancement for p_T above 2 GeV/c is also seen in transverse momentum dependence of nuclear modification factor R_{AA} for In-In collisions measured by NA60 experiment [23]. The Pb-Pb data can be rebinned using only 3 bins of transverse energy in order to minimize statistical fluctuations. Fig.9 shows that for the most central Pb-Pb collisions and with respect to the most peripheral bin, the suppression exists for all values of p_T. The centrality dependence decreases with increasing p_T. For the highest p_T values, no overproduction is observed, there is always an absorption. For central Au-Au and Cu-Cu collisions measured by PHENIX experiment suppression for the whole measured p_T range is observed. Fig.10 shows the R_{AA} ratio versus p_T for central In-In collisions measured by NA60 experiment in comparison with central Au-Au and Cu-Cu collisions measured by PHENIX experiment [23]. The J/ψ suppression for low p_T is of the same order at SPS and at RHIC energies.

4. Conclusions

In Pb-Pb collisions the anomalous J/ψ suppression was found for central events. The anoma-

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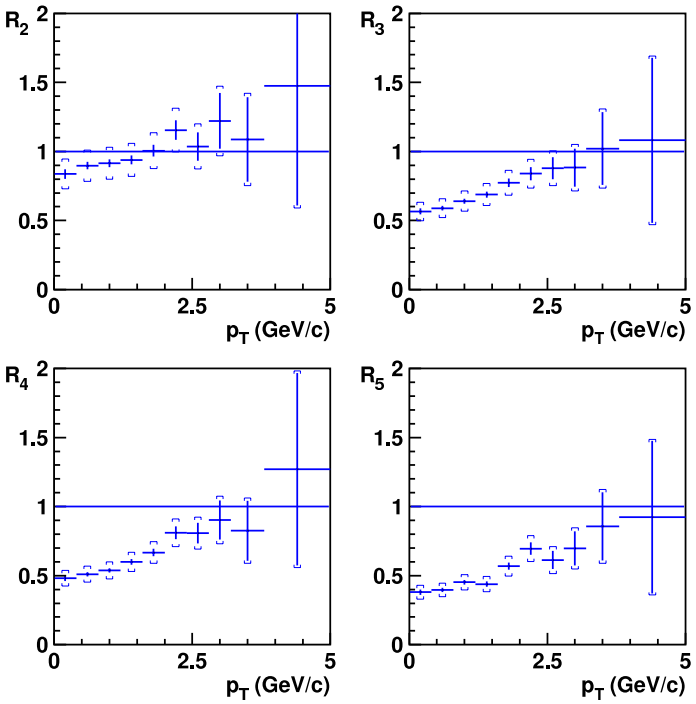

Figure 7: Ratios R_i of the J/ψ transverse momentum distribution normalized to the DY cross section in the E_i bin (i=2,3,4,5) to the first E_1 bin. The solid error bars on each data point are the statistical errors of the J/ψ yield ratios. The error bars with systematic errors from the DY cross section ratios are given as brackets.

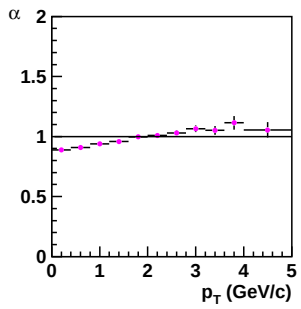

Figure 8: Parameter α obtained from the fit of the proton-nucleus J/ψ production cross sections as a function of the transverse momentum.

lous J/ψ suppression was experimentally confirmed by the NA60 in In-In collisions, but the theoretical models could not reproduce simultaneously Pb-Pb and In-In data.

The dependence of the J/ψ suppression pattern on p_T for Pb-Pb collisions is somewhat different from what is observed in the case of normal nuclear J/ψ absorption from p-induced reactions. In the latter case we see the change from absorption to enhancement with the increase of transverse momentum. For Pb-Pb collisions and for the whole p_T range, only absorption is observed with increasing centrality. Moreover, the data show that absorption is significantly stronger for low p_T and almost p_T independent for the most central collisions. The results at RHIC show that the J/ψ sup-

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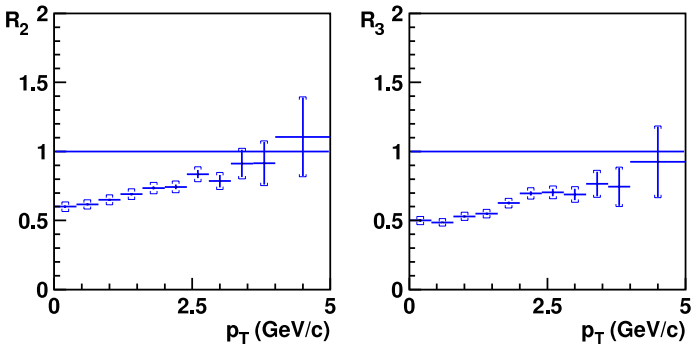

Figure 9: Ratios R_2 and R_3 of the J/ψ transverse momentum distribution normalized to the DY cross section for the second and third centrality bins with respect to the first and most peripheral one, in the case of three E_T intervals, for Pb-Pb collisions. The error bars have the same meaning as on Fig.7.

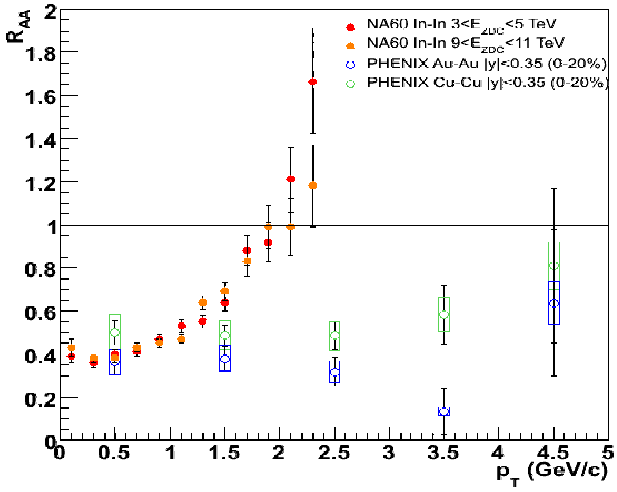

Figure 10: Ratio R_{AA} for In-In collisions at SPS in comparison with PHENIX data as a function of transverse momentum in GeV/c.

pression at these energies is of the same order as the suppression at SPS energies and is the same for different systems at RHIC. The observed transverse momentum dependences of J/ψ suppression in Pb-Pb collisions at SPS and Au-Au collisions at RHIC are qualitatively similar. The study of the transverse momentum distributions of J/ψ as a function of the centrality of the collision shows that the observed J/ψ suppression in ion-ion interactions at all energies is particularly significant mainly at low transverse momentum where the suppression strongly increases with centrality and is of the same order for Pb-Pb, In-In, Au-Au and Cu-Cu collisions. For peripheral Pb-Pb collisions, the transverse momentum dependence of the J/ψ suppression is similar to the dependence observed in p-A and S-U collisions and shows some Cronin enhancement in the high p_T region. For central Pb-Pb and Au-Au collisions, the data show a suppression which extends over the whole measured p_T range.

For the much higher energies of nuclear collisions at the LHC with possibility to measure very high p_T region, the quarkonium states, the charmonium and bottomonium families will be produced and possible suppression or enhancement pattern and p_T dependence of production could be

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studied. In fact, since the Υ dissolves only significantly above the critical temperature, the spectroscopy of the bottomonium family at LHC energies should reveal an unique set of information on the characteristics of the QGP.

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