

Formation of charmonium states in heavy-ion collisions and thermalization of charm

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Abstract. We examine the possibility to utilize in-medium charmonium formation in heavy-ion interactions at collider energy as a probe of the properties of the medium. This is possible because the formation process involves recombination of charm quarks which imprints a signal on the resulting normalized transverse momentum distribution containing information about the momentum distribution of the quarks. We have contrasted the transverse momentum spectra of J/ψ , characterized by $\langle p_T^2 \rangle$, which result from the formation process in which the charm quark distributions are taken at opposite limits with regard to thermalization in the medium. The first uses charm quark distributions unchanged from their initial production in a pQCD process, appropriate if their interaction with the medium is negligible. The second uses charm quark distributions which are in complete thermal equilibrium with the transversely expanding medium, appropriate if a very strong interaction between charm quarks and medium exists. We find that the resulting $\langle p_T^2 \rangle$ of the formed J/ψ should allow one to differentiate between these extremes, and that this differentiation is not sensitive to variations in the detailed dynamics of in-medium formation. We include a comparison of predictions of this model with preliminary PHENIX measurements, which indicates compatibility with a substantial fraction of in-medium formation.

PACS. 25.75.Nq Quark deconfinement, quark-gluon plasma production, and phase transitions – 12.38.-t Quantum chromodynamics

1 Introduction

The in-medium formation picture we consider here [1] uses competing formation and dissociation reactions in a Boltzmann equation to calculate the final J/ψ population. The absolute value of this formation was found to be very sensitive to the underlying charm quark momentum distributions [2]. There is also quite strong variation of the results which depend on largely unconstrained model parameters involving details of the size and expansion profile of the deconfinement region. The initial PHENIX data [3] suffered from low statistics, and was compatible with a fairly large region of model parameter space [4].

Recent work in this area concentrated on finding a signature for in-medium J/ψ formation which is independent of the detailed dynamics and magnitude of the formation. We found that the p_T spectrum of the formed J/ψ may provide such a signature [5].

The calculations which used initial charm quark momentum distributions from NLO pQCD amplitudes to generate a sample of $c\bar{c}$ pairs, were then supplemented by an initial-state transverse momentum kick to simulate

confinement and nuclear effects. In the evolution of the interacting system size from pp to pA to AA collisions, the p_T will be in general increased due to initial-state effects of interaction of constituents in the nuclei.

$$\langle p_T^2 \rangle_{AB} - \langle p_T^2 \rangle_{pp} = \lambda^2 [\bar{n}_A + \bar{n}_B - 2], \quad (1)$$

where \bar{n}_A is the impact-averaged number of inelastic interactions of the projectile nucleons in nucleus A, and λ^2 is the square of the transverse momentum transfer per collision. The PHENIX measurements of J/ψ p_T spectra in pp and minimum-bias d-Au interactions [6] allow us to determine the amount of initial state k_T needed to supplement our collinear pQCD events. (This is equivalent to using a hadronization model similar to a color evaporation scheme, except that we assume that the resulting p_T of the resulting J/ψ is determined by the pair p_T for all invariant mass of the combinations. One can then extrapolate to Au-Au and predict the spectrum of J/ψ which are produced from hadronization of the initial “diagonal” $c\bar{c}$ pairs, again for minimum bias interactions. (We use diagonal to distinguish these pairs from the “off-diagonal” combinations which contribute to in-medium J/ψ formation.) One finds $\bar{n}_A = 5.4$ from minimum bias d-Au interactions at RHIC energy (using $\sigma_{pp} = 42$ mb), which leads

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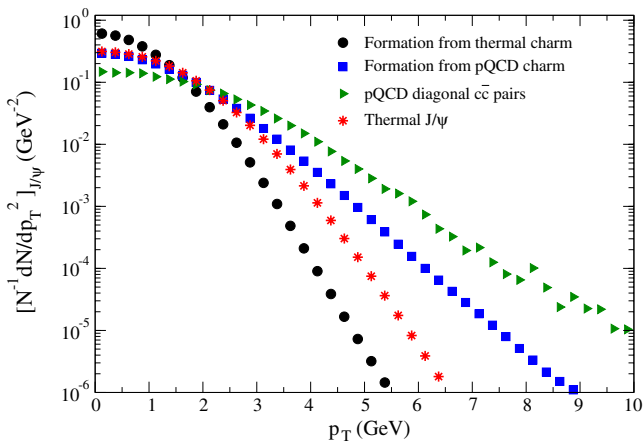


Fig. 1. Comparison of in-medium J/ψ transverse momentum spectra predictions from various scenarios.

to $\lambda^2 = 0.35 \pm 0.14 \text{ GeV}^2$. We note that the relatively large uncertainty comes entirely from the difference in p_T broadening in d-Au between positive and negative rapidity.

Our prediction for the “normal” evolution of the p_T spectrum in Au-Au interactions is shown by the triangular points in fig. 1.

The properties of the normalized p_T spectrum for the formation process follow from two separate effects: First, the fact that the process is dominated by the off-diagonal pairs introduces a modified initial p_T distribution. Next, one weights these pairs by a formation probability for J/ψ . We use the operator-product-motivated cross-section for $c\bar{c}$ forming J/ψ with emission of a final-state gluon, which of course is just the inverse of the dissociation process. However, any cross-section which has the same general properties as this one gives essentially the same result [5]. We show by the square points in fig. 1 the prediction for the formed J/ψ . One sees that this spectrum is substantially narrower than the one with no in-medium formation.

The same procedure was employed when using quark momentum distributions which follow for charm in thermal equilibrium with the expanding region of deconfinement. The parameters of temperature and maximum transverse expansion rapidity are determined by a fit to this thermal behavior of the produced light hadrons. The application to charm quarks was originally motivated in ref. [7], who showed that the low- p_T spectrum of decay leptons from charmed hadron decays would not be able to differentiate between the thermal and a purely pQCD distribution. We show here, however, that the p_T spectrum of in-medium formed J/ψ is very sensitive to this distribution. The circles in fig. 1 result from formation calculations using $T = 170 \text{ MeV}$ and $y_{Tmax} = 0.5$ for the thermal charm quarks. One sees that this p_T spectrum is narrower yet than in-medium formation from pQCD quarks. Finally, we show by the stars the p_T spectrum of J/ψ which themselves obey this thermal distribution. The resulting spectrum falls between the in-medium formation spectra for either pQCD or thermal charm quark momentum distributions.

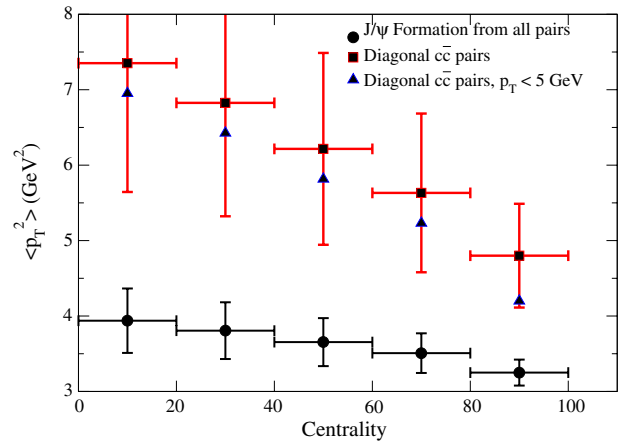


Fig. 2. Centrality dependence of $J/\psi \langle p_T^2 \rangle$ contrasting predictions assuming either 100% production from initial $c\bar{c}$ pairs or 100% in-medium formation.

2 Centrality behavior

We now proceed to investigate the variation of the pQCD-based results with respect to the collision centrality in Au-Au interactions. First, we use the value of λ^2 extracted from pp and pA data, together with values of \bar{n}_A calculated as a function of collision centrality, to recalculate the $\langle p_T^2 \rangle$ values for either the initial production or the in-medium formation separately. This provides the centrality behavior of the J/ψ spectrum in the case that one or the other of these mechanisms is solely responsible for the total J/ψ population. We show these results together in fig. 2.

One sees as expected that $\langle p_T^2 \rangle$ is maximum for the most central collisions, but the absolute magnitudes are widely separated for initial production and in-medium formation at each centrality. One should note that the uncertainties are dominated by the difference between the p_T -broadening measurements at positive and negative rapidities in the d-Au interactions. Thus the point-to-point uncertainties are much smaller for the centrality behavior. We have also included separate values for $\langle p_T^2 \rangle$ in the region limited by a maximum p_T of 5 GeV, to facilitate comparison with experiment in this same range.

There exist preliminary results from PHENIX for $\langle p_T^2 \rangle$ of J/ψ produced in Au-Au collisions [8]. These are reported as a function of the number of nucleon-nucleon collisions N_{coll} . In order to compare with our predictions, we transform centrality to N_{coll} using a Glauber model. The resulting predictions are shown in fig. 3. Although there is substantial uncertainty in the absolute values, one can infer a clear preference for in-medium formation over the initial production prediction.

In order to provide a meaningful prediction for the overall J/ψ spectrum, one should of course include both initial production and in-medium formation together as sources. This requires some estimate of the relative magnitudes of these processes, and is subject to considerable model uncertainties. What we can say, however, is that in-medium formation will be most dominant for central

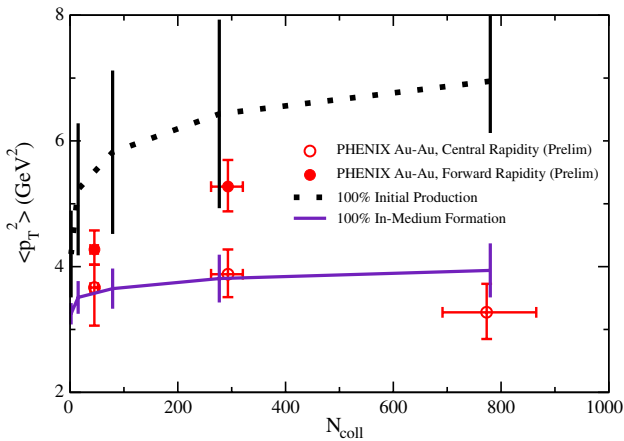


Fig. 3. Comparison of $\langle p_T^2 \rangle$ predictions for initially produced J/ψ and in-medium formation with preliminary PHENIX measurements. The collision centrality is parameterized by the number of nucleon-nucleon collisions N_{coll} . The theory curves and uncertainties are taken from fig. 2.

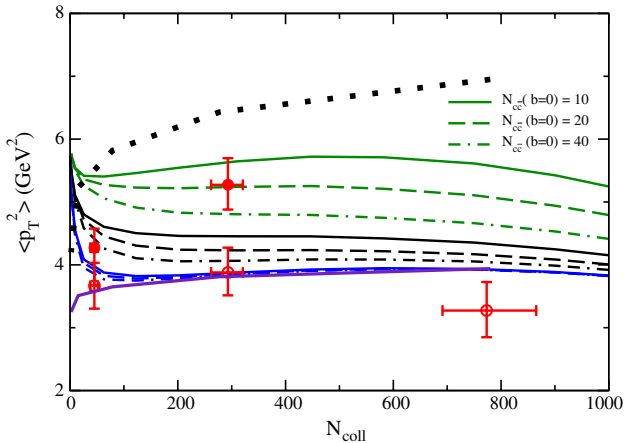


Fig. 4. Variation of predictions in fig. 3 resulting from a model calculation of the relative fraction of J/ψ which originates from initial production or in-medium formation.

collisions, where the quadratic dependence on $N_{c\bar{c}}$ is enhanced. Conversely, one expects that initial production will increase in relative importance for very peripheral collisions. To get an approximate idea of how this effect will appear, we revert to our original model calculations which included the absolute magnitude results [2]. One relevant parameter is the number of initial pairs, $N_{c\bar{c}}$, parameterized by its value at zero impact parameter. These results are shown in fig. 4 for three representative values of $N_{c\bar{c}} = 10, 20, \text{ and } 40$, which span the range of values extracted from STAR [9] and PHENIX [10] measurements of charm inferred from semileptonic decays and direct reconstruction of D-mesons.

The 100% curves for initial production and in-medium formation remain as in fig. 3. Between these two extremes are shown the calculations including centrality-dependent fractions of each, as described above. Each $N_{c\bar{c}}$ value is shown by the solid, dashed, and dot-dashed lines, respec-

tively. The duplication of these lines results from different initial temperature values of 300, 400, and 500 MeV, which provides variation in the gluonic dissociation rates and the deconfinement lifetime in the model calculations. One sees that, with the exception of extremely peripheral collisions, all of the predictions remain substantially below that for initial production alone. It would require a substantial reduction of experimental uncertainty in the measured $\langle p_T^2 \rangle$, however, to pin down the preferred model parameters appropriate for in-medium formation.

3 Hadronization contribution

In addition to in-medium formation of J/ψ , one needs to consider the possibility of subsequent production at the hadronization transition. This contribution must be significant, as can be confirmed by an examination of the absolute values of in-medium formation in the model calculations. For central collisions, our calculated values of the ratio $N_{J/\psi}/N_{c\bar{c}}$ typically range from 0.004 to 0.01 as the model parameters are varied. This means that essentially all of the initial $c\bar{c}$ pairs will survive through the deconfined phase and some fraction of these must hadronize into additional J/ψ . For an estimate of this fraction, we utilize the statistical hadronization model [11]. The most recent applications of this model to RHIC Au-Au collisions [12,13] predict values for $N_{J/\psi}/N_{c\bar{c}} \approx 0.005$, comparable to that for our in-medium formation. Thus we need to consider contributions to the final J/ψ population which originate in approximately equal amounts from each mechanism. Fortunately, one can make this combination for central collisions alone, since both in-medium formation and statistical hadronization predict the same centrality behavior [2]. The results of such a calculation are shown in fig. 5.

Shown are the p_T spectra for the in-medium formation utilizing pQCD charm distributions (diamonds) and thermal plus flow charm distributions (squares). They are at the extremes of $\langle p_T^2 \rangle$, as previously noted. Also shown is

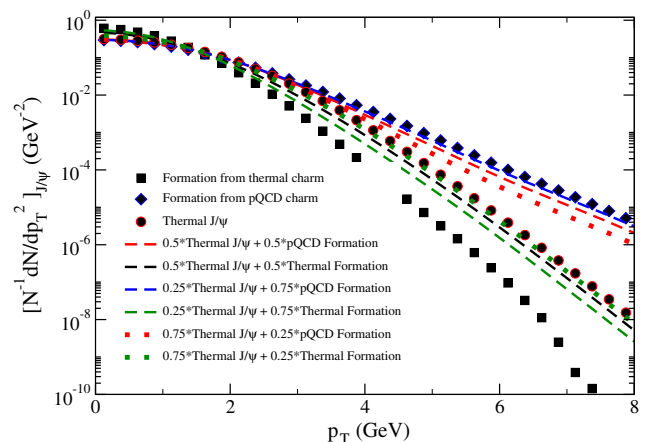


Fig. 5. Comparison of p_T spectra for J/ψ resulting from variable fractions of in-medium formation and subsequent hadronization of residual charm.

the thermal plus flow distribution for a direct J/ψ , which we take as our expectation if statistical hadronization is the dominant source of J/ψ . The distributions which fall between the extremes are the result of various (but comparable) contributions of in-medium formation and hadronization. One sees that these combinations predict the spectra to evolve toward that for the thermal J/ψ as its fraction increases. However, the rate of this evolution is substantially greater for in-medium formation from thermal charm quarks than the corresponding behavior for in-medium formation from pQCD charm quarks. Thus, the possibility to utilize the p_T spectra as a probe of charm thermalization in the medium remains a viable option.

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