Heavy-quark and Quarkonia production in high-energy heavy-ion collisions

André Mischke†
ERC Starting Independent Research Group, Institute for Subatomic Physics, Utrecht University, Princetonplein 5, 3584 CC Utrecht, the Netherlands.

Abstract
Relativistic heavy-ion collisions provide the unique opportunity to produce and study a novel state of QCD matter, the Quark-Gluon Plasma, in the laboratory. Heavy-quarks are a powerful probe for the detailed investigation of the QGP properties. In this paper we review recent results from RHIC on open and hidden heavy-flavor hadron production and their interaction with the QCD matter on the partonic level.

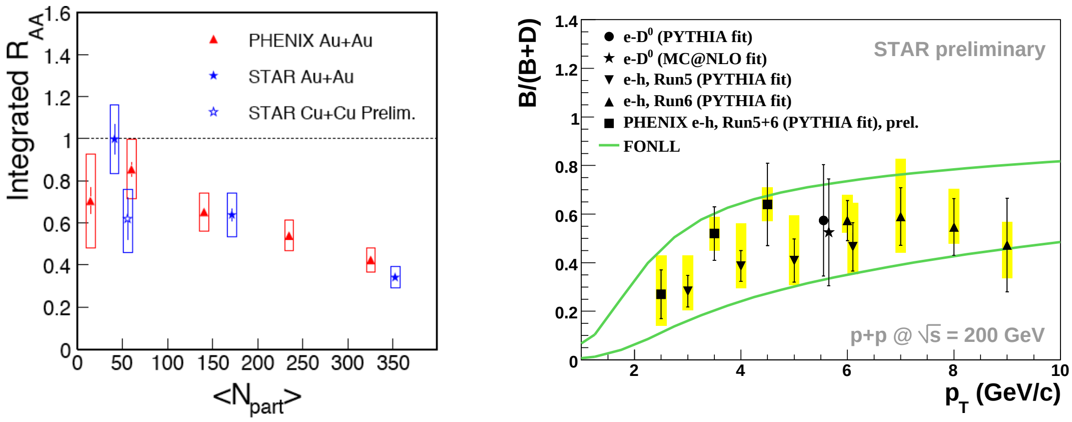
1 Introduction

High-energy nucleus-nucleus collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory allow exploring strongly interacting matter at very high temperatures and energy density. QCD matter at these conditions is expected to form a system of deconfined quarks and gluons, the so-called Quark-Gluon Plasma (QGP), if the critical energy density ($\epsilon_c \sim$ 0.7 GeV/fm^3) is exceeded. The goal of relativistic heavy-ion physics is to study the properties of the QGP under laboratory controlled conditions [1, 2].

The results from RHIC have given evidence that the nuclear matter created in such collisions exhibits properties consistent with the QGP formation [3]. In particular, measurements of the momentum distribution of emitted particles and comparison with hydro-dynamic model calculations have shown that the outwards steaming particles move collectively, with the patterns arising from variations of pressure gradients early after the collision. This phenomenon, called elliptic flow, is analogous to the properties of fluid motion. The flow results suggest that color degrees of freedom carried by quarks and gluons are present in the produced medium, which flow with negligible shear viscosity. Thus, the QCD matter produced at RHIC behaves like a perfect liquid. Moreover, it has been found that the matter remaining in the collision zone is extremely opaque to the passage of partons from hard scattering processes in the initial state of the collisions. These traversing partons are believed to lose energy via gluon Bremsstrahlung in the medium before fragmenting into hadrons.

A detailed and quantitative understanding of the parton energy loss in the medium is one of the intriguing issues which currently needs to be addressed. The study of heavy-flavor (charm, bottom) production in heavy-ion collisions provides key tests of the parton energy loss mechanisms and offers important information on the properties of the produced medium [4]. Due to their large mass ($m > 1$ GeV/c^2), heavy quarks are expected to be primarily produced in the initial stage of the collision and, therefore, probe the complete space-time evolution of the medium.

† E-mail: a.mischke@uu.nl



(a) (b)

Fig. 1: (a) Nuclear modification factor $R_{\rm AA}$ (averaged above $p_{\rm T} > 3$ GeV/c) of heavy-flavor decay electrons as a function of collision centrality (quantified in $N_{\rm part}$) in Au+Au and minimum bias Cu+Cu collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV. (b) Relative bottom contribution to the total yield of heavy-flavor decay electrons derived from e$-D^0$ and e$-$hadron azimuthal angular correlations, compared to the uncertainty band from a FONLL calculation.

Theoretical models predicted that heavy quarks should experience smaller energy loss than light quarks while propagating through the QCD medium due to the suppression of small angle gluon radiation, the so-called *dead-cone effect* [5, 6].

2 Probing the QCD medium with heavy quarks

Nuclear effects are typically quantified using the nuclear modification factor $R_{\rm AA}$ where the particle yield in Au+Au collisions is divided by the yield in pp reactions scaled by the number of binary collisions. $R_{\rm AA}$ = 1 would indicate that no nuclear effects, such as Cronin effect, shadowing or gluon saturation, are present and that nucleus-nucleus collisions can be considered as a incoherent superposition of nucleon-nucleon interactions. Charm and bottom quarks can be identified by assuming that isolated electrons in the event stem from semi-leptonic decays of heavy-quark mesons. At high transverse momentum ($p_{\rm T}$), this mechanism of electron production is dominant enough to reliably subtract other sources of electrons like conversions from photons and π^0 Dalitz decays. Fig. 1(a) shows the average $R_{\rm AA}$ for heavy-flavor decay electrons in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV as a function of participating nucleons ($N_{\rm part}$) measured by the STAR and PHENIX experiments [7, 8]. The data are consistent with each other, and the $R_{\rm AA}$ shows an increasing suppression from peripheral to central Au+Au collisions. The minimum bias Cu+Cu data fit into this systematics. The strong suppression for the most central Au+Au collisions indicates an unexpectedly large energy loss of heavy quarks in the medium in contradiction to expect ions from the dead-cone effect. Surprisingly, the measured $R_{\rm AA}$ of 0.2 is similar to the one observed for light-quark hadrons. Current models with reasonable model parameters overpredict the observed suppression [7,8]. The data is described reasonably well if the bottom contribution to the electrons is assumed to be small. Therefore, the observed discrepancy could indicate that the B dominance over D mesons starts at higher p_{T} than expected. A possible scenario for heavy-quark meson suppression invokes collisional dissociation in the medium [9].

The measurement of the relative charm and bottom contributions to the heavy-flavor decay electrons (also called non-photonic electrons) is essential for the interpretation of the electron spectra and nuclear modification factor. Azimuthal angular correlations between non-photonic electrons and hadrons allow to identify the underlying production process [10]. The relative bottom contribution $B/(B+D)$ to the non-photonic electrons is extracted from the e$-$hadron and e$-D^0$ azimuthal correlation distributions [11]. Figure 1(b) shows the $B/(B+D)$ ratio together with a prediction from calculations of heavy-flavor production in pp collisions at Fixed-Order plus Next-to-Leading Logarithm (FONLL) level [12]. These data provide convincing evidence that bottom contributes significantly ($\sim$50%) to the non-photonic electron yields above p_{T} = 5 GeV/c. Further studies have to show whether these results imply substantial suppression of bottom production at high p_{T} in the produced medium. An important step to answer this question will be the direct measurement of open charmed mesons and the identification of B mesons via displaced electrons using the detector upgrades of the STAR and PHENIX experiments.

3 Dissociation of quarkonium states in the hot and dense QCD medium

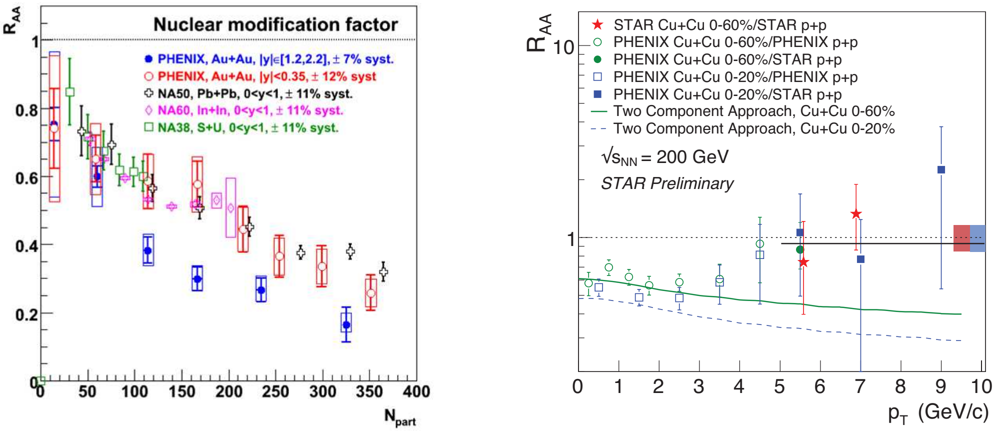
The dissociation of quarkonia due to color-screening in a QGP is a classic signature of deconfinement in relativistic heavy-ion collisions [13, 14], where the sequential suppression of the quarkonia states, such as Υ, Υ' and Υ'', depends on the temperature of the surrounding medium, thus providing a QCD thermometer.

3.1 J/ψ measurements

Results from the PHENIX experiment have shown that the centrality dependence of the suppression of the J/ψ yield in $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV Au+Au collisions is similar to that observed at the CERN-SPS accelerator ($\sqrt{s_{\mathrm{NN}}}$ = 17.3 GeV) [16], even though the energy density reached in collisions at RHIC is about a factor of 2-3 higher (cf. Fig. 2(a)). Moreover, it has be observed that the J/ψ yield in the forward rapidity region is more suppression than the one at mid-rapidity, which might be explained by cold nuclear absorption.

Theoretical prediction based on string theory application of AdS/CFT suggests that the effective J/ψ dissociation temperature is expected to decrease with p_{T} [15]. This conjecture is different from the predictions of more traditional screening models where the suppression due to screening vanishes towards higher p_{T}. Recent R_{AA} measurements for J/ψ in Cu+Cu collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV from the STAR [17] and PHENIX experiments [18] are compared in Fig. 2(b). The R_{AA} is suppressed at low p_{T} (around 1 GeV/c), and the data suggest that R_{AA} increases with increasing p_{T} and reaches unity around 5 GeV/c, although the large errors currently preclude strong conclusions. This result is in contradiction with expectations from AdS/CFT based models and the *Two-Component-Approach* model [19], which predicts a suppression at high p_{T}. These results could indicate that other J/ψ production mechanisms that counter the suppression such as recombination and formation-time effects might play a more dominant role at higher p_{T}.

The large signal-to-background ratio ($\sim$3) of the J/ψ in pp collisions (cf. Fig. 3(a)) makes



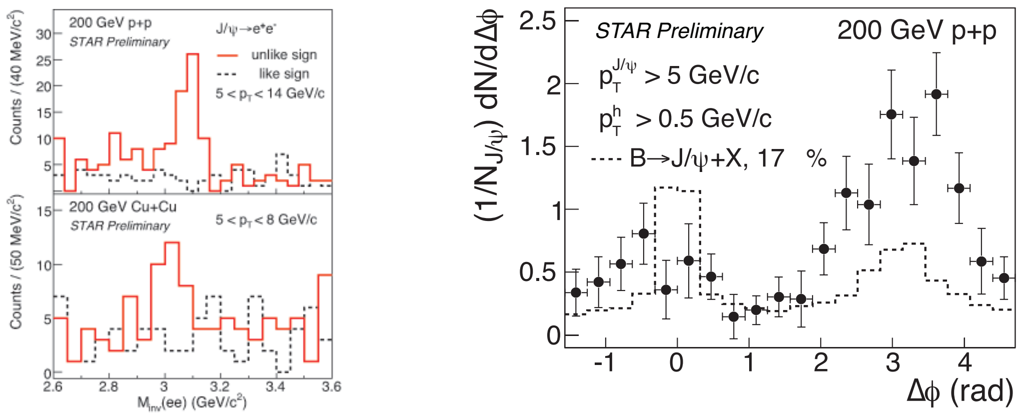
(a) (b)

Fig. 2: (Color online) (a) The centrality dependence of the nuclear modification factor $R_{\rm AA}$ of J/ψ, measured for different collisions energies and rapidity regions. For Au+Au collisions, the J/ψ yield in the forward rapidity region (full circles) shows more suppression than the one at mid-rapidity (open symbols). (b) $R_{\rm AA}$ of J/ψ in the 20 and 60% most central Cu+Cu collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV. The boxes in the right indicate the normalization uncertainty. The horizontal line represents a fit to the data in the $p_{\rm T}$ range 5-10 GeV/c. The curves are model predictions from the *Two-Component-Approach* model.

it possible studying J/ψ-hadron correlations at high trigger-$p_{\rm T}$, which provide important information on the underlying J/ψ production mechanisms. Figure 3(b) illustrates the azimuthal angular correlations between high-$p_{\rm T}$ J/ψ ($p_{\rm T} > 5$ GeV/c) and charged hadrons ($p_{\rm T} > 0.5$ GeV/c). Notably, no significant correlation yield is observed on the near-side ($\Delta\phi \sim 0$ rad), which is not in line with earlier results from di-hadron correlation measurements [3]. Since corresponding PYTHIA simulations (also depicted in Fig. 3(b) as the dashed histogram) show a strong near-side correlation peak from J/ψ from B decays ($B \to J/\psi + X$), the experimental results can be used to estimate the B feed-down contribution to the inclusive J/ψ yield at $p_{\rm T} > 5$ GeV/c. It was found to be 17$\pm$3$\%$ in the studied $p_{\rm T}$ range [17].

3.2 First Υ measurements in nuclear collisions

The golden decay channel for the Υ reconstruction is the decay into electron pairs $\Upsilon \to e^+e^-$. The STAR detector with its large acceptance ($|\eta| < 1$ and $0 < \phi < 2\pi$) and excellent trigger capabilities combined with a very good electron identification is very well suited for Υ measurements in nuclear collisions. The first preliminary measurements of the Υ invariant mass in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV are presented in [20] and shows a significant Υ signal. The Υ production cross-section in pp collisions is $BR_{ee} \times \frac{d\sigma}{dy}_{y=0} = 91 \pm 28(stat.) \pm 22(sys.)$pb. This measurement follows the world data trend and shows, within uncertainties, very good agreement with NLO calculations [21]. The analysis of the full pp and Au+Au data-sets will allow to extract the Υ nuclear modification factor in the near future.



(a) (b)

Fig. 3: (a) The e^+e^- invariant mass distribution in pp (upper panel) and Cu+Cu collisions (lower panel) at $\sqrt{s_{\rm NN}}$ = 200 GeV. The solid and dashed histograms represent the distribution of unlike and like-sign pair combinations, respectively. (b) J/ψ-hadron azimuthal angular correlations in pp collisions after background subtraction. The dashed histogram shows the J/ψ-hadron contribution from B decays obtained from PYTHIA simulations.

4 Summary

The observed strong suppression of the yield of heavy-flavor decay electrons at high $p_{\rm T}$ in central Au+Au collisions together with the measurement of the azimuthal angular correlation of electrons and hadrons in pp collisions imply that B production is stronger suppressed in nuclear collisions than expected. The nuclear modification factor ($R_{\rm AA}$) of J/ψ in Cu+Cu collisions increases from low to high $p_{\rm T}$ and reaches unity for $p_{\rm T} > 5$ GeV/c. This result is about 2σ above the $R_{\rm AA}$ at low $p_{\rm T}$ ($<$ 4 GeV/c) and is consistent with no J/ψ suppression. First RHIC results on the Υ production in nuclear collisions are promising and show that the suppression measurements will be possible in the near future.

Acknowledgments

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