Heavy flavor physics at STAR

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In these proceedings, heavy flavor production as measured by STAR is discussed. This can be done directly by reconstruction of the hadronic decays or indirectly by the measurement of electrons from semileptonic decays of heavy quark mesons. The extracted charm production total cross-section per nucleon-nucleon collision in d+Au and Au+Au collisions shows binary scaling, supporting the idea that charm quarks are produced in hard scattering in the initial phase of the collision. The preliminary non-photonic electron spectra from $p+p$, $d+Au$ and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV at mid-rapidity are presented. The momentum range of reconstructed non-photonic electrons is $1.5 < p_T < 10$ GeV/c. The dominant contribution to the non-photonic electron spectrum is the semi-leptonic decay of D and B mesons. The electron nuclear modification factor ($R_{AA}$) shows a large suppression in central Au+Au collisions, indicating an unexpectedly large energy loss for heavy quarks in the hot and dense matter created at RHIC. Theoretical models tend to overpredict the data if the contributions from both charm and beauty decays are taken into account.

1 Introduction

The measurement of inclusive hadron yields in central Au+Au collisions at RHIC led to the discovery of the suppression of hadron production at large transverse momenta ($p_T$) compared to p+p collisions. This is generally attributed to the energy loss of light partons in the dense nuclear matter created at RHIC. The energy loss itself depends on the properties of the medium, such as size and gluon density, as well as on the properties of the probe, such as color charge and mass. Heavy quarks are believed to be mostly created through gluon fusion in the initial phase of the collision and thus are excellent probes of the hot and dense matter. Due to the large mass of heavy quarks, the suppression of small angle gluon radiation should reduce their energy loss and consequently, any suppression of heavy-quark mesons at high $p_T$ is expected to be smaller than that observed for hadrons consisting of light quarks.

Heavy quark mesons can be studied by the direct reconstruction of their hadronic decays, such as $D^0 \rightarrow K^-\pi^+$. This direct reconstruction becomes a challenge in Au+Au collisions,
because of the very large combinatorial background. Therefore, the current measurements by STAR are limited to $p_T < 3$ GeV/c. However, a combined fit, together with low $p_T$ electron spectra, allows the $c - \bar{c}$ cross section to be measured. The extracted values of the total charm cross-section are $1.33 \pm 0.06$ (stat.) $\pm 0.18$ (sys.) mb in 0-12% central Au+Au, $1.26 \pm 0.09 \pm 0.23$ mb in minimum bias Au+Au collisions and $1.4 \pm 0.2 \pm 0.2$ mb in minimum bias d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Within the systematic and statistical errors, the total charm production follows binary scaling from d+Au to Au+Au collisions, supporting the idea that heavy quarks are dominantly produced in the early stages of the collision in hard scatterings.

An alternative way to infer information about heavy quark production is the study of electrons from semi-leptonic decays of D and B mesons which is the focus of this paper. This method allows STAR to study charm and beauty production up to substantially larger $p_T$. There are several sources of electrons that contribute to the inclusive spectra. We divide them into two groups: non-photonic electrons (signal) and photonic electrons (background). The non-photonic electrons are mainly from semi-leptonic decays of heavy mesons with a small contribution from the Drell-Yan process. The background photonic electrons are from $\gamma$ conversions, and $\pi^0$, $\eta$ Dalitz and light vector-meson decays.

2 Electron identification in STAR

The results presented in this paper were obtained from an analysis of data recorded with the STAR detector in 2003 (p+p, d+Au) and 2004 (Au+Au). Electron identification is based on a combination of energy loss in the Time Projection Chamber, energy deposition in the Barrel Electro-Magnetic Calorimeter, and shower profile in the Shower Maximum Detector. Further details of the analysis can be found elsewhere. After all analysis cuts, a clean sample of electrons was obtained with a $p_T$ dependent residual hadron contamination that varies from 10 to 15%. The data sample for the Au+Au dataset was divided into 3 centrality bins (0-5%, 10-40%, and 40-80%). The electron reconstruction efficiency and acceptance were determined by embedding simulated electrons into real events. For the most central events, the electron reconstruction efficiency increases with $p_T$ up to 5 GeV/c and then remains constant at 40%. The photonic electrons have been statistically identified and subtracted from the inclusive electron spectrum. The efficiency of the photonic background rejection was determined by embedding $\pi^0$, with a realistic $p_T$ distribution, into real events and is about 60% for the most central Au+Au events, decreases slightly with $p_T$.

3 Non-photonic electron spectra and $R_{AA}$

In Figure 1a, the ratio of inclusive electrons to photonic background electrons is shown as a function of the $p_T$ of the electrons. For $p_T > 2.0$ GeV/c, there is a clear enhancement of electrons with respect to the background. This enhancement becomes more evident at higher momentum. Figure 1b shows the preliminary background subtracted non-photonic electron spectra for p+p, d+Au and Au+Au collisions. The error bars are statistical and the boxes depict the preliminary systematic uncertainties. NLO pQCD, as well as Pythia LO pQCD calculations, predict that in a range between 3 and 6 GeV/c, the amount of electrons coming from B meson decays becomes dominant. STAR is capable of measuring non-photonic electrons in a momentum range above this transition. Although pQCD can predict the shape of the non-photonic electron spectrum in p+p collisions rather well, it fails to describe the absolute electron yield by a factor $\approx 5$. The shape of the spectrum can not be described if only the contribution from charm decays would be taken into account.

Figure 2 shows the nuclear modification factors $R_{AA}$ and $R_{dAu}$ for non-photonic electrons as a function of $p_T$. The $R_{dAu}$ ratio (Figure 2a) seems to be systematically above unity for the
entire \( p_T \) range, consistent with a small Cronin enhancement. An increased suppression from peripheral to central Au+Au events (Figure 2b-d) with respect to binary scaling is observed. Assuming that there is no other source of non-photonic electrons, this suppression indicates a strong interaction and large energy loss of heavy quarks in the medium created at RHIC. Moreover, the amount of suppression in most central Au+Au collisions is similar to that of light hadrons.

Figure 2: Nuclear modification factors \( R_{AA} \) for (a) d+Au, (b) Au+Au 40-80\%, (c) Au+Au 10-40\%, and (d) Au+Au 0-5\% comparison with models.

Figure 2d also shows the calculations of the \( R_{AA} \) from three theoretical models. In all cases, the contribution from charm and bottom quarks were taken into account. In the first model (dash-dotted curve), the medium is characterized by the time averaged BDMPS transport coefficient, \( \hat{q} = 10 \, GeV^2/fm \), for central Au+Au collisions. This value of \( \hat{q} \) is consistent with the measurement of \( R_{AA} \) of the light hadrons. In the second model (dashed curve), the DGLV theory of radiative energy loss has been applied and the created nuclear matter is characterized...
by a gluon density of $dN_g/dy = 1000$, the value derived from light-quark meson suppression. In addition, the contribution from elastic energy loss has been taken into account\cite{13} (solid line). For the sake of comparison, a curve (dash-dot) representing the contribution only from charm sources is shown. In the third model\cite{14} (dotted curve), the authors focus on elastic scattering of heavy quarks in the medium mediated by resonance excitations (D and B) off light quarks as well as by t-channel gluon exchange.

Although the data have large systematic and statistical errors, the data points tend to lie below the model calculations at high $p_T$. It is important to note that the model calculations also have large uncertainties, such as the amount of relative contribution from beauty/charm decays, that influence the final $R_{AA}$. The FONLL calculation of the electron spectra from NLO pQCD\cite{10} depends also on many parameters, such as mass of the heavy quarks, $x_F$ (fragmentation scale) and $x_R$ (renormalization scale). Varying these parameters, one sees, that the $p_T$ range of the spectrum where beauty contribution starts to dominate over charm can be as low as $\approx 3$ GeV/c or as high as $\approx 10$ GeV/c. Another issue is that the measured charm cross-section and also non-photonic electron spectra in p+p collisions are about a factor $\approx 5-6$ higher than FONLL predictions, although one would expect that due to the large mass of the c and b quarks, pQCD should predict the spectra rather well. Also, a further understanding of p+p collisions is necessary before we can make a final statement about heavy quark energy loss.

Recently the $R_{AA}$ of non-photonic electrons has been also calculated within the Langevin model of heavy quark propagation in the created medium\cite{15}. The propagation of the heavy quark in the medium is characterized by a diffusion coefficient, $D$. It was shown that electron $R_{AA}$ can be explained within this model if the value of $D$ is between $12/(2\pi T)$ and $3/(2\pi T)$. Contributions from charm as well beauty semileptonic decays were taken into account.

4 Conclusions

The non-photonic electron spectra measured by STAR for p+p, d+Au, Au+Au collisions up to $p_T \approx 8$ GeV/c were presented. An increasing suppression of non-photonic electrons with the collision centrality in Au+Au collisions is observed. This may be related to a stronger than predicted interaction between heavy quarks and the medium created at RHIC. The analysis of the full statistics from the 2004 Au+Au run will permit a more detailed study of the medium modifications for heavy quarks and allow for a better understanding of quark energy loss mechanisms.

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