Open heavy flavor measurements with the PHENIX experiment at RHIC

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Abstract. The PHENIX experiment has measured single electron spectra at RHIC in proton-proton (p-p), deuteron-gold (d-Au), and gold-gold (Au-Au) collisions at an available energy per nucleon-nucleon pair of $\sqrt{s_{NN}} = 200$ GeV. Contributions from photonic sources, i.e. Dalitz decays of light mesons and photon conversions, are subtracted from the inclusive spectra. The remaining non-photonic single electron spectra are dominated by semileptonic decays of particles carrying heavy flavor. Implications of these systematic measurements for heavy flavor production in cold and hot nuclear systems are discussed.

1. Introduction

Particles carrying heavy flavor, i.e. charm or beauty quarks, are sensitive probes of the hot and dense medium created in high energy heavy-ion collisions.

The production of heavy flavor quark-antiquark pairs proceeds mainly via gluon-gluon fusion in the very early stage of the collision, not only through leading order pair production processes but also via higher order QCD mechanisms involving flavor excitation or gluon splitting diagrams [1]. While the total yield is sensitive to the initial gluon density [2, 3] as well as to nuclear effects such as shadowing, the phase space distribution of heavy flavor should shed some light on the dominant production mechanisms in initial state hard scattering processes. In addition, thermal production from gluon-gluon scattering in later stages of the collision might play a role, providing some sensitivity on the initial temperature reached in a nuclear collision.

Once being produced, a heavy quark-antiquark pair propagates through the collision zone and forms either a bound quarkonium state or separates and hadronizes into two particles carrying open heavy flavor. In case a deconfined phase of nuclear matter is formed during the collision, the yield of heavy quarkonia might either be reduced due to the expected screening of the QCD attractive potential [4] or possibly even enhanced due to quark-antiquark coalescence [5] or statistical recombination [6]. While open heavy flavor measurements will provide an essential baseline for quarkonia suppression/enhancement studies [7], they are of prime interest in their own right as well. Modifications of the gluon distribution function in cold nuclear matter should manifest themselves in differences in the heavy flavor yields and spectra between p-p and p-A collisions. High $p_T$ hadrons carrying light quarks only are strongly suppressed at central rapidity in Au-Au collisions at RHIC [8] [9] [10] [11]. Medium induced gluon radiation, which might be the mechanism driving the observed...
suppression, could be reduced for heavy quarks \cite{12, 13}. Therefore, a comparison of the spectra of particles carrying heavy flavor, or their decay products, produced in elementary and nuclear collision systems should reveal crucial information regarding the mechanisms responsible for the observed energy loss of hard scattered partons in heavy-ion collisions at RHIC. Further insight regarding the interaction of heavy quarks with the nuclear medium can be gained from the measurement of the elliptic flow strength $v_2$, which addresses the question whether collectivity is borne out already on the parton level at RHIC \cite{14, 15}.

2. Experimental techniques

The direct reconstruction of heavy-flavor decays, \textit{e.g.} $D^0 \rightarrow K^- \pi^+$, is difficult in the high-multiplicity environment of a heavy-ion collision. An alternative approach is to determine the contributions from semileptonic heavy-flavor decays, \textit{e.g.} $D \rightarrow eK\nu$, to single lepton and lepton pair spectra.

At RHIC, the PHENIX experiment \cite{16} is ideally suited for such studies since it is optimized for the measurement of leptons. Electrons are measured in the PHENIX central arm spectrometers, which cover the pseudorapidity range $|\eta| < 0.35$. At forward and backward pseudorapidity ($1.2 < |\eta| < 2.4$) two dedicated muon spectrometers are available.

Up to now, the PHENIX open heavy-flavor program focuses on the analysis of single electron spectra, $(e^+ + e^-)/2$, measured at central rapidity. The momenta of charged particles are determined via tracking through a magnetic field using drift and pad chambers. Electron candidates are identified by associated hits in a ring imaging Cerenkov detector (RICH) passing a ring shape cut, and they are confirmed by an associated shower in an electromagnetic calorimeter (EMC) with an energy that is close to the measured momentum. Accidental coincidences between RICH hits and hadron tracks lead to a background level of about 10%. Employing an event-mixing technique, this background is estimated and statistically subtracted from the electron sample.

The sources contributing to the inclusive electron spectra can be grouped into two classes:

- **Photonic** electrons originate from Dalitz decays of light neutral mesons ($\pi^0$, $\eta$, $\rho$, $\omega$, $\eta'$, and $\phi$) and conversions of photons in material.

- **Non-photonic** electrons are primarily from semileptonic decays of heavy flavored particles. On the level of a few percent, dielectron decays of light vector mesons ($\rho$, $\omega$, and $\phi$) and weak decays of kaons contribute to the non-photonic electron spectra as well, in particular at low $p_T$.

The non-photonic electron spectra are constructed by measuring the inclusive electron spectra and then subtracting the photonic contributions. The photonic electron spectra are determined mainly via two methods:

- For the \textit{cocktail} method the contributions from Dalitz (and dielectron) decays are calculated with a hadron decay generator \cite{17}, where the hadron yields and phase space distributions are parameterized according to available data. The electron spectra from photon conversions are very similar in shape to the corresponding Dalitz electron spectra, as confirmed in detailed simulations. The yield ratio depends on the material in the detector acceptance and is typically in the order of one.
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- For the converter method a thin photon converter (1.7% $X_0$ brass) is introduced into the detector acceptance close to the interaction point for a fraction of the running period. By measuring the electron spectra with and without the converter being present in the setup, the fraction of electrons originating from photonic sources can be inferred [18].

These two techniques are complementary to each other. The converter method allows for a precise measurement of the non-photonic electron spectrum at low $p_T$ (in particular below 1 GeV/c), where the ratio of non-photonic to photonic electrons is so small ($\leq 20\%$) that the cocktail method suffers from substantial systematic uncertainties, mainly due to the independent normalization of inclusive electron spectra and the cocktail input. Therefore, the converter method is the tool of choice for the measurement of the total non-photonic electron cross section, since this is dominated by the electron yield at low $p_T$. Towards higher $p_T$, the ratio of non-photonic to photonic electrons increases rapidly, eliminating the main uncertainty in the cocktail subtraction technique. At the same time, the converter method suffers from statistics limitations due to the decreasing photonic electron yield with increasing $p_T$. Hence, for the measurement of the spectral shapes of non-photonic electrons it is beneficial to use the cocktail method. A third technique is the so-called $e\gamma$-coincidence technique, which relies on the fact that electrons from photonic sources are accompanied by a photon. This method can provide a further independent cross check of the photonic electron measurement, but the requirement of registering a photon in coincidence with an electron results in a significantly reduced statistical precision compared with the other two techniques.

3. The reference: p-p collisions at $\sqrt{s} = 200$ GeV

A baseline for open charm production in nuclear collisions is given by the preliminary spectrum of non-photonic electrons from p-p collisions at $\sqrt{s} = 200$ GeV shown in Fig. 1 [19]. The spectrum was derived from a cocktail analysis and confirmed by

Figure 1. Invariant spectra of electrons from non-photonic sources measured in p-p collisions at $\sqrt{s} = 200$ GeV together with an empirical fit (left panel) and the error band used for estimating the charm production cross section (right panel), as discussed in Ref. [19]. At low $p_T$, the systematic errors are substantial due to the small ratio of the non-photonic signal to the inclusive electron yield.
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Figure 2. Invariant spectra of electrons from non-photonic sources measured in d-Au collisions at $\sqrt{s_{NN}} = 200$ GeV scaled down by the nuclear thickness function $T_{AB}$ in four centrality classes [19]. The solid line is the best fit to p-p data as shown in Fig. 1.

Converter and $e\gamma$ analyses. The analyzed RHIC Run-2 data sample comprises 15M minimum-bias triggers and 420M sampled minimum-bias triggers associated with an ERT trigger that required a coincidence between calorimeter and RICH. It is interesting to note that for $p_T > 1.5$ GeV/c the electron spectrum is harder than expected from PYTHIA calculations of charm and bottom pair production, where the PYTHIA parameters were tuned to existing data from lower energy experiments [17]. This might be due to the fragmentation function being harder than implemented in default PYTHIA or it could point to the fact that other production mechanisms beyond leading order gluon-gluon and quark-antiquark fusion play an important role at RHIC energies. Since in the low $p_T$ region, which dominates the total cross section, the agreement between PYTHIA and the data is quite reasonable, the total charm production cross section was determined by extrapolating with PYTHIA from the measured central rapidity region to the full phase space. The cross section obtained via this extrapolation technique is $\sigma_{c\bar{c}} = 709\mu$b $\pm [85]_{stat} \pm [332]_{sys}$.

4. Cold nuclear matter: d-Au collisions at $\sqrt{s_{NN}} = 200$ GeV

The measurement of non-photonic electron spectra from d-Au collisions in RHIC Run-3 allows to investigate whether any cold nuclear matter effects, e.g. different
gluon distribution functions for protons and gold nuclei, modify charm and/or bottom production. Fig. 2 shows preliminary non-photonic electron spectra from d-Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV in four centrality classes [19], scaled down by the nuclear thickness function \( T_{AB} \) [20], in comparison with the reference fit to p-p data from Fig. 1. The preliminary d-Au analysis uses the converter subtraction technique, based on a converter-in data set of 5M minimum-bias events plus 312M minimum-bias equivalent events sampled by the ERT trigger and a converter-out data set of 5M minimum-bias events plus 600M ERT sampled events, respectively. Within the experimental uncertainties the d-Au non-photonic electron spectra are in good agreement with the p-p spectra for all centrality classes, indicating no strong cold nuclear matter effects on heavy flavor production at central rapidity at RHIC.

5. Hot nuclear matter: Au-Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV

Fully corrected spectra of non-photonic electrons from Au-Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV are shown in Fig. 3 for five centrality classes [18]. As for the d-Au analysis, the converter method was used employing data samples of 2.2M converter-in and 2.5M converter-out minimum bias events. The centrality dependence of heavy flavor production can be addressed by calculating the integrated non-photonic electron yield and fitting it to the function \( AN_{coll}^{\alpha} \). In the absence of medium effects, one would
expect heavy flavor production to scale linearly with $N_{\text{coll}}$, i.e. $\alpha = 1$. This consistency check with the binary scaling hypothesis is shown in Fig. 4. We find $\alpha = 0.938 \pm 0.075$ (stat.) $\pm 0.018$ (sys.), which indicates that the total yield of non-photonic electrons in the considered $p_T$ range, and therefore the total initial charm yield, is consistent with $N_{\text{coll}}$ scaling. The statistics of the non-photonic electron spectra above $p_T \approx 2.5$ GeV/c are not sufficient to address the important issue of potential medium modifications of the phase space distribution of heavy flavor in Au-Au collisions at RHIC. A currently ongoing cocktail analysis of the full Run-2 Au-Au data sample might provide first insight into this issue, but a detailed investigation will require the analysis of the high statistics Au-Au data set that was recorded in Run-4.

In this context, the measurement of the elliptic flow strength $v_2$ of electrons from non-photonic sources is of particular importance since it might allow to distinguish different dynamical scenarios from each other. A preliminary analysis from Run-2 Au-Au data at $\sqrt{s_{NN}} = 200$ GeV is shown in Fig. 5. The data are compared with two extreme charm flow scenarios. While the thermalization scenario assumes that the charm quarks fully thermalize and participate in hydrodynamic flow on the parton level, the no-reinteractions scenario assumes that charm quarks follow unmodified, pQCD like dynamics and acquire a non-zero $v_2$ only by coalescence with a flowing light quark [15]. Only the analysis of the Run-4 Au-Au data sample will provide enough statistics to distinguish between these two scenarios.

6. Summary and Conclusions

PHENIX has investigated the production of heavy flavor, mainly charm, at RHIC in a systematic measurement of electrons from non-photonic sources in p-p, d-Au, and Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV at central rapidity. These data imply that the total open charm yield scales with the number of binary collisions $N_{\text{coll}}$ for all systems and centralities, as expected for point-like pQCD processes. Whether the initially produced heavy quarks are then influenced by the medium in the subsequent dynamical evolution of the nuclear system is a question of paramount importance. Detailed answers, however, will have to wait for the analysis of the high statistics
Run-4 data sample where about 1.5B minimum bias Au-Au events were recorded. This data set will also allow to broaden the PHENIX open heavy flavor program by single muon and lepton pair measurements. Ultimatively, the direct reconstruction of particles carrying heavy flavor will become feasible with a silicon pixel vertex spectrometer which is an integral part of the PHENIX upgrade program and will facilitate to measurement of the displaced vertices of heavy flavor decays.

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