Heavy flavor production in p+p and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from single leptons over a wide kinematic range

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The PHENIX experiment at the Relativistic Heavy Ion Collider has measured single electrons at midrapidity and single muons at forward and backward rapidities ($1.2 < |y| < 2.2$) for p+p and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The inclusive lepton spectra exhibit excesses over light hadron sources. The excesses are attributed to semileptonic decays of charm and bottom hadrons and compared to the perturbative QCD predictions. The NLO pQCD calculation underpredicts the excess lepton production in $p+p$ collisions. The excess lepton production in $d+Au$ collisions scales with N_{coll} at midrapidity, and shows suppression/enhancement relative to the same scaling in d/Au-going direction within large uncertainties.

1. Introduction

The parton model combined with the perturbative Quantum ChromoDynamics (pQCD) is applied to violent strong interaction processes characterized by a large scale. Heavy quark production belongs to the category of violent strong interaction processes due to its large mass serving as the scale [1]. The parton model is often applied to charm quark production while classification of the charm quark as a heavy quark is not yet fully settled. Predictions for charm hadroproduction exist from lower collision energies including the FNAL fixed target program [2]. Naive application of parton model to ion collisions, i.e. interaction of point-like particles making up nucleons, results in a scaling with the number of colliding nucleon pairs, N_{coll}. Systematic studies of charm production in $p+p$ and p+nucleus collisions have been proposed as a sensitive way to measure the parton distribution functions in nucleons and the nuclear shadowing effects [3].

Semileptonic decays of the heavy quark produce hard leptons due to its large mass and produce a large hard lepton excess over the light hadron sources. PHENIX determines excess leptons over a wide kinematic range to address heavy quark production.

2. Measurements

PHENIX uses global detectors to characterize the collisions, a pair of central spectrometers at midrapidity to measure electrons, hadrons, and photons, and a pair of forward(north)/backward(south) spectrometers to measure muons (see Fig. 1) [4]. PHENIX determines the *excess leptons*, referred to here as the *non-photonic electrons* or the *prompt*
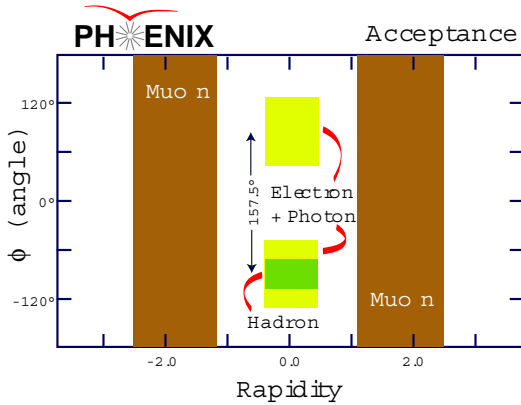
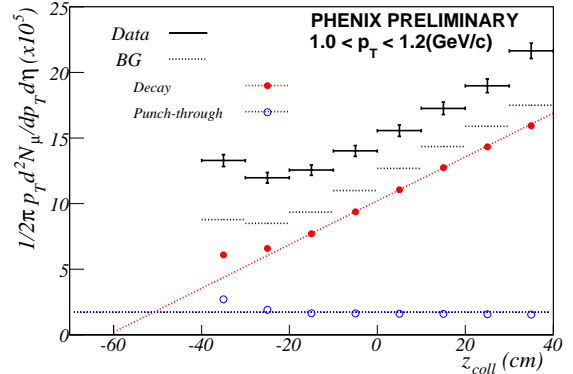**Figure 1.** Acceptance of the PHENIX experiment

Figure 2. Inclusive muon production vs z_{coll}. Light hadron contributions are also shown.

muons, by subtracting the contributions by light hadrons from the measured inclusive leptons.

2.1. Non-photonic electrons

Inclusive electrons contain two components: (1) *non-photonic* - presumably semileptonic decays of mesons containing heavy (charm and bottom) quarks, and (2) *photonic* - Dalitz decays of light neutral mesons ($\pi^0, \eta, \eta', \rho, \omega$, and ϕ) and photon conversions in the detector material. PHENIX uses two approaches, *converter subtraction* and *cocktail subtraction*, to estimate the photonic component.

The converter subtraction is a data-driven approach. A photon converter (a thin brass tube of 1.7% radiation length thickness) is installed for a special period of runs. The photon converter multiplies the photonic contribution to the electron yield in a well-defined manner and hence the photonic component can be estimated. The cocktail subtraction simulates electron production from the known light hadron sources and subtract them from the inclusive spectra. Dalitz decay of π^0 and photon conversion are the dominant source of photonic electron according to the simulation. The converter and the cocktail subtraction are two independent methods and yield consistent results.

2.2. Prompt muons

Inclusive muons contain three major components: (1) *decay muons* - muons from the decays of light hadrons (π's and K's), (2) *punch-through's* - hadrons that punch through all absorbers and are mis-identified as muons, and (3) *prompt muons* - muons produced in the close proximity of collision location and presumably from the decays of heavy flavor.

Decay muons and punch-through's are separated from the rest through their distinct characteristics (Fig. 2). The yield of inclusive muons shows a linear dependence on the collision location z_{coll} due to muons from the decay of $\pi^{\pm}$'s and $K^{\pm}$'s prior to the first absorber material located after position along the beam axis $z = -40$ *cm*. We fit the histogram with the function $a + b \cdot z$, and the slope gives the yield per unit length of muons from hadron decay. The slopes obtained for various transverse momentum p_T

range are described well at low p_T and constrained at high p_T by a data-driven light hadron generator. Trajectories reconstructed for analysis include partially penetrating ones as well as completely penetrating muons and punch-through's. Partially penetrating trajectories are due to the abundant light hadrons, and their yields are linked to the amount of punch-through's through the absorber material of known thickness. Excess over two sources are identified as due to the prompt muons.

3. Result

The excess lepton production at midrapidity and forward/backward rapidities is reported for p+p and d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

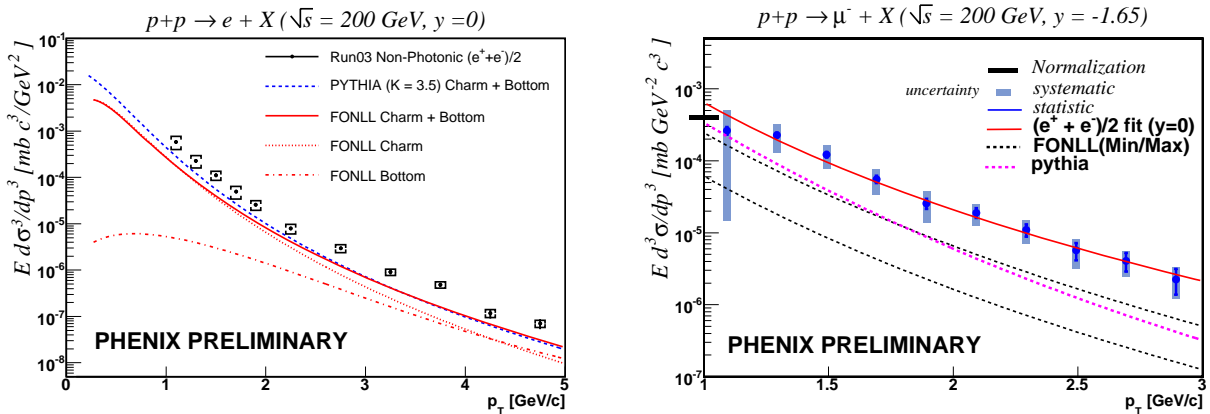### 3.1. p+p collisions at $\sqrt{s} = 200$ GeV

Figure 3. Excess lepton production with PYTHIA LO and FONLL pQCD calculations.

The invariant differential cross section of excess leptons are shown with PYTHIA and *Fixed-Order plus Next-to-Leading-Log*(FONLL [5]) calculation in Fig. 3. The PYTHIA/FONLL calculation includes heavy quark production via LO(Leading Order)/NLO(Next to Leading Order) pQCD calculation and its subsequent decay into leptons. The calculations underpredict the data at high p_T within marginal uncertainties.

The plot for prompt muons includes fit of electron spectra, and shows the excess lepton spectra at y = 0 and at y = 1.65 are similar over the observed p_T range. The underprediction of the data by the calculation at forward rapidity is even stronger than the one at midrapidity due to the stronger rapidity dependence of production in the calculations.

3.2. d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

The non-photonic electron production in $d+Au$ collisions exhibits scaling with N_{coll} indicating point-like interactions [6]. Fig. 4 shows nuclear modification factor defined as

$$R_{dAu}(p_T, \eta) \equiv (\frac{1}{2 \cdot 197} \cdot \frac{d^2\sigma^{d+Au \to \mu+X}}{dp_T d\eta}) / (\frac{d^2\sigma^{p+p \to \mu+X}}{dp_T d\eta}) \tag{1}$$
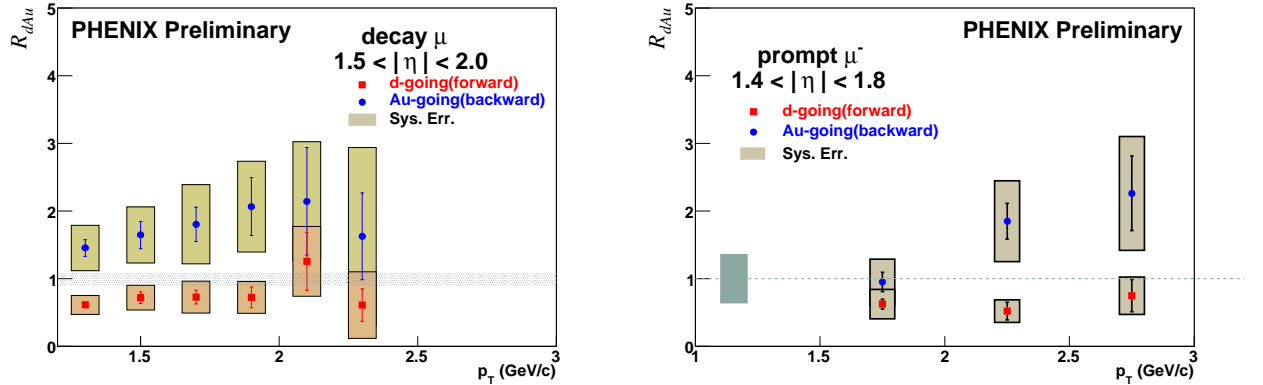
Figure 4. R_{dAu} for the decay and the prompt muons, d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

for the decay and the prompt muons. R_{dAu} for d-going(forward)/Au-going(backward) side are smaller(suppression)/larger(enhancement) than 1 (N_{coll} scaling) within large uncertainties.

4. Summary

PHENIX measured excess leptons over light hadron sources for p+p and d+Au collisions. FONLL, current NLO pQCD calculation (semileptonic decays of charm and bottom hadrons), underpredicts the measured excess for p+p collisions though within marginal uncertainties. Efforts to reduce the uncertainties are in progress. If the observed trend remains, the most likely source of excess hard leptons is, within the standard model, still semileptonic decay of the heavy quark through virtual $W^{\pm}$ since the production through virtual γ implies abundance of a hard radiation or large mass lepton pairs not yet observed. We presented $R_{dAu}(p_T)$ of the decay and the prompt muons at forward/backward rapidities for d+Au collisions. Modification of the N_{coll} scaling is seen at forward/backward rapidities within large uncertainties.

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