Measurement of high-$p_T$ Single Electrons from Heavy-Flavor Decays in $p + p$ Collisions at $\sqrt{s} = 200$ GeV

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The momentum distribution of electrons from decays of heavy flavor (charm and beauty) for midrapidity $|y| < 0.35$ in $p + p$ collisions at $\sqrt{s} = 200$ GeV has been measured by the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) over the transverse momentum range $0.3 < p_T < 9$ GeV/c. Two independent methods have been used to determine the heavy flavor yields, and the results are in good agreement with each other. A fixed-order-plus-next-to-leading-log $p$QCD calculation agrees with the data within the theoretical and experimental uncertainties, with the data/theory ratio of $1.72 \pm 0.02_{\text{stat}} \pm 0.19_{\text{sys}}$ for $0.3 < p_T < 9$ GeV/c. The total charm production cross section at this energy has also been deduced to be $\sigma_{c\bar{c}} = 567 \pm 5_{\text{stat}} \pm 22_{\text{sys}}$ mb.

Heavy-flavor (charm and beauty) production serves as a testing ground of QCD. Because of the large quark mass, it is expected that next-to-leading order perturbative QCD (NLO pQCD) can describe the production cross section of charm and beauty at high energy, particularly at high $p_T$. At the Tevatron, beauty production in decays has been observed \cite{3}. Measurements of heavy-flavor distributions. Furthermore in Au+Au collisions at RHIC \cite{4, 5} have a limited understanding of the reaction mechanism for heavy-flavor production is crucial for reliably extracting these distributions. Moreover in Au+Au collisions at RHIC strong suppression of single electrons from heavy-flavor decays has been observed \cite{2}. Measurements of heavy-flavor production in $p + p$ collisions provide a baseline for studying hot and dense matter effects in heavy ion reactions. Earlier measurements at RHIC \cite{1, 2, 3} have a limited $p_T$ range with substantial experimental uncertainties, so an improved measurement is crucial.

We report the production cross section of electrons, $(e^+e^-)/2$, at mid-rapidity in $p+p$ collisions at $\sqrt{s} = 200$ GeV for $0.3 < p_T < 9$ GeV/c measured by the PHENIX experiment. Contributions from semi-leptonic decays of heavy-flavor are determined using two independent methods. This measurement has over two orders of magnitude larger statistics with much reduced systematic uncertainties compared to our previous measurement \cite{2}.

The data were collected by the PHENIX detector \cite{6} during the 2005 RHIC run using the two central arm spectrometers. Each spectrometer covers $|\eta| < 0.35$ in pseudo-rapidity and $\Delta \phi = \pi/2$ in azimuth. It includes a drift chamber (DC) and pad chambers (PC1) for charged particle tracking, a Ring Imaging Čerenkov detector (RICH) for electron identification, and an electromagnetic calorimeter (EMCal) for electron identification and trigger. Beam-beam counters (BBCs), positioned at pseudo-rapidities $3.1 < |\eta| < 3.9$, measure the position of the collision vertex along the beam ($z_{\text{vtx}}$) and provide the interaction trigger. In this run, helium bags, one for each arm, were placed in the space between the beam pipe and DC to reduce multiple scattering and photon conversion.

Two datasets are used for the analysis: (1) the minimum bias (MB) dataset recorded by the BBC trigger, and (2) a “photon” trigger (PH) dataset triggered at level-1 requiring a minimum energy deposit of 1.4 GeV in an overlapping tile of 4 $\times$ 4 EMCal towers in coincidence with the BBC trigger. The PH trigger has $\approx 100 \%$ efficiency for high $p_T$ electrons above 2 GeV/c in the active trigger tiles. The BBC trigger cross section is 23.0 $\pm$ 2.2 mb. Since only $\approx 50 \%$ of inelastic $p + p$ collisions satisfy the BBC trigger condition, only a fraction of the inclusive electron production events is triggered.

This $p_T$ and process independent fraction is determined to be $\epsilon_{\text{bias}} = 0.79 \pm 0.02$ from the yield ratio of high $p_T$ $\pi^0$ with and without the BBC trigger. After selection of good runs and a vertex cut of $|z_{\text{vtx}}| < 20$ cm, an integrated luminosity ($L$) of 45 nb$^{-1}$ in the MB dataset and 1.57 pb$^{-1}$ in the PH dataset are used for the analysis.

Charged particle tracks are reconstructed using DC and PC1 and confirmed by a hit in EMCal within 4$\sigma$ in position. The momentum resolution is $\sigma_p/p \sim 0.7 \% \pm 0.9\% (\text{GeV/c})$, and the momentum scale is calibrated within $1\%$ using the reconstructed mass of $J/\psi \rightarrow e^+e^-$. Electron identification (eID) requires at least two associated hits in RICH, a shower shape cut in EMCal, and a cut in the ratio $E/p$ where $E$ is energy measured in EMCal. We require $0.7 < E/p < 1.3$ for $0.8 < p_T < 5$ GeV/c. For lower $p_T$, the minimum value of $E/p$ decreases with decreasing $p_T$ to 0.55 at $p_T = 0.3$ GeV/c. The $E/p$ cut removes background electrons from photon conversions and semi-leptonic decay of kaons ($K \rightarrow e\nu\pi(K_{e3})$) that occur far from the vertex, and most of the remaining hadron background. The hadron contamination after the $E/p$ cut is $3\%$ at $p_T = 0.3$ GeV/c and less than $1\%$ for $0.8 < p_T < 5$ GeV/c with eID efficiency of approximately 90 $\%$.

For $p_T > 5$ GeV/c, where pions also emit Čerenkov photons in RICH, tighter electron identification cuts are applied. We require at least 5 associated hits in RICH, a tighter shower shape cut in EMCal, and $0.8 < E/p < 1.3$. With these cuts, the electron measurement is extended to 9 GeV/c in $p_T$. The eID efficiency of the tighter cuts is $p_T$ independent, and is determined to be $57\%$ of that for $p_T < 5$ GeV/c by applying the same tighter cuts for $p_T < 5$ GeV/c. With the tighter cuts, hadron contamination is negligible for $p_T < 7$ GeV/c. For $7 < p_T < 8$ (8 $< p_T < 9$) GeV/c, a 20$\%$ (40$\%$) hadron contaminatio-
determined to be 0.40 ± 0.04 GeV/c. This contribution is comparable to or greater than that from the η for p_T > 5 GeV/c. Non-photonic backgrounds are also included in the cocktail. Since the K_{e3} background depends on the analysis cuts, it is evaluated by a full GEANT simulation.

In the “converter subtraction” method [12], we introduce an additional photon converter (a thin brass sheet of 1.67% X_0) around the beam pipe for part of the run. The converter multiplies the photonic electron background by a fixed factor, R_{γ} ≈ 2.3, which is determined precisely via GEANT simulation. R_{γ} is larger than in [12] since we have less conversion material in the 2005 run. The photonic background N^{γ}_{e} is determined as N^{γ}_{e} = (N^{NC}_{e} - (1 - e)N^{C}_{e})/(R_{γ} - 1 + e), where N^{C}_{e} and N^{NC}_{e} are electron yield with and without the converter, respectively; and e (2.1%) represents a small loss of electrons due to the converter. The non-photonic component is then determined as N^{N\text{on-γ}}_{e} = N^{NC}_{e} - N^{γ}_{e}. Small remaining non-photonic background, such as K_{e3} and hadron contamination, are subtracted.

These two methods are complementary to each other. The converter method is more accurate, and it allows us to extract a heavy-flavor signal down to p_T = 0.3 GeV/c where the signal is only ≈ 10% of inclusive electrons. In addition, the measured photonic background N^{γ}_{e} is used to confirm and to calibrate the normalization of the calculated cocktail yields. A drawback of the method is statistical precision: the converter run contains only a small fraction (≈ 7% in the 2005 run) of the data. The cocktail method can use the full statistics at high p_T, where the photonic background becomes a small fraction of inclusive electrons.

Systematic uncertainties are categorized into (a) inclusive electron spectra, (b) cocktail subtraction, and (c) converter subtraction. Category (a) is common to both analyses, and includes the uncertainties in luminosity (9.6%), geometrical acceptance (4%), eID efficiency (3%), and the PH trigger efficiency (3% at the plateau). Uncertainties in cocktail subtraction (category (b)) include the normalization (8%) and p_T dependent shape uncertainty (2% at p_T ≈ 2 GeV/c, increasing to 6% at 9 GeV/c). In the converter analysis (category (c)) the dominant uncertainties are in R_{γ} (2.7%) and in the relative acceptance in the converter and the normal runs (1.0%). These uncertainties are propagated into the uncertainties in the heavy-flavor electron yields and added in quadrature.

Figure [14] shows the ratio of the measured N^{γ}_{e} to the cocktail calculation as a function of p_T. The ratio is consistent with unity within the uncertainties of the cocktail. At high p_T (> 1.8 GeV/c), the ratio is 0.94 ± 0.02 stat on average. Since this is within the uncertainty of the cocktail normalization, we rescale the cocktail yields by this factor. This removes the 8% normalization uncertainty in the cocktail.
the converter subtraction method on the MB data set is used; at intermediate $p_T$ ($1.6 < p_T < 2.6$ GeV/$c$) the converter method on the PH dataset is used; and at high $p_T$ ($p_T > 2.6$ GeV/$c$) the cocktail method on the PH dataset is used.

The data are compared with a fixed-order-plus-next-to-leading-log (FONLL) pQCD calculation [13, 14]. The total charm cross section is derived by integrating the FONLL calculation. The contributions of charm and beauty are also shown. For $p_T > 4$ GeV/$c$, the beauty contribution becomes dominant. In Fig. 3 (b), the ratio of the data to the FONLL calculation is shown. The ratio is nearly $p_T$ independent over the entire $p_T$ range. Fitting to a constant for $0.3 < p_T < 9.0$ GeV/$c$ yields a ratio of $1.72 \pm 0.02^{\text{stat}} \pm 0.19^{\text{sys}}$. Similar ratios are observed in charm production at high $p_T$ at the Tevatron [2]. The upper limit of the FONLL calculation is compatible with the data. Recently STAR reported [12] that non-photonic electron production in $p+p$ at $\sqrt{s} = 200$ GeV is 5.5 times larger than predicted by the same FONLL calculation. We do not observe such a large discrepancy. We note that the photonic electron background in our spectrometer is approximately 1/10 that of STAR due to the small amount of conversion material in the PHENIX acceptance.

The total charm cross section is derived by integrating the heavy-flavor electron cross section for $p_T > 0.4$ GeV/$c$: $d\sigma_c(p_T > 0.4)/dy = 5.95 \pm 0.59 \pm 2.0 \mu b$. 

In Fig. 2 filled circles (squares) show the ratio of non-photonic electrons relative to photonic background determined by the converter (cocktail) method. The non-photonic electrons are dominantly heavy-flavor decay signals. The remaining non-photonic background contributions have been calculated and are shown in Fig. 2. The two methods are consistent with each other. The ratio monotonically increases with increasing $p_T$, becoming greater than unity for $p_T > 2.4$ GeV/$c$, and saturates at $\approx 3$ for $p_T > 5$ GeV/$c$. The large signal-to-background ratio is due to the small amount of conversion material in the spectrometer acceptance.

Figure 3 (a) shows the invariant differential cross section of electrons from heavy-flavor decays. The error bars (bands) represent the statistical (systematic) errors. The curves are the FONLL calculations (see text). (b) Ratio of the data and the FONLL calculation. The upper (lower) curve shows the theoretical upper (lower) limit of the FONLL calculation. In both panels a 10% normalization uncertainty is not shown.
The systematic error is obtained by integrating the upper and lower systematic error limits of the differential cross sections, since the systematic errors are essentially coherent. The cross section is then extrapolated to $p_T = 0$ using the spectrum shape predicted by FONLL: $d\sigma_e(p_T > 0)/dy = 10.9 \pm 1.1 \pm 3.8 \mu b$. We have assigned 10% to the systematic uncertainty of the extrapolation, and have subtracted contribution from beauty and beauty cascade decays ($0.1 \mu b$). We determine the charm production cross section, $d\sigma_{c\bar{c}}/dy = 123 \pm 12 \pm 45 \mu b$, by using a $c \to e$ total branching ratio of $9.5 \pm 1.0\%$, calculated using the following charmed hadron ratios: $D^+/D^0 = 0.45 \pm 0.1$, $D_s/D^0 = 0.25 \pm 0.1$, and $\Lambda_c/D^0 = 0.1 \pm 0.05$. The rapidity distribution of electrons is broader than that of $D$ mesons due to decay kinematics. A correction to this effect (7%) has been applied. Using the rapidity distribution from HVQMNR [16] with CTEQ5M [17] PDF, the total charm cross section is determined to be $\sigma_{c\bar{c}} = 567 \pm 57^{\text{stat}} \pm 224^{\text{sys}} \mu b$. We have assigned 15% systematic error to the extrapolation. This result is compatible with our previous measurement [4] ($920 \pm 150 \pm 540 \mu b$) and the value derived from Au+Au collisions [12] ($622 \pm 57 \pm 160 \mu b$ per $NN$ collisions). The FONLL cross section ($256 \pm 400 \mu b$) is compatible with the data within its uncertainty. STAR has reported a somewhat larger value in $d+Au$ [8] ($1.3 \pm 0.2 \pm 0.4$ mb per $NN$ collisions). Although the data extend to high $p_T$ where the beauty contribution is expected to be dominant, the present analysis does not separate charm and beauty contributions. The beauty cross section predicted by FONLL is $1.87^{+0.99}_{-0.67} \mu b$, and the upper FONLL curve is consistent with the data.

In conclusion, we have measured single electrons from heavy-flavor decays in $p+p$ collisions at $\sqrt{s} = 200$ GeV. The new data reported here provide a crucial baseline for the study of heavy quark production in hot and dense matter created in Au+Au collisions. The agreement between the data and the FONLL pQCD calculation within the theoretical and the experimental uncertainties suggests that a reliable extraction of gluon polarization from heavy-flavor production in polarized $p+p$ collisions is attainable.

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