Measurement of the Bottom Quark Contribution to Nonphotonic Electron Production in p + p Collisions at √s = 200 GeV

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The contribution of B meson decays to nonphotonic electrons, which are mainly produced by the semileptonic decays of heavy-flavor mesons, in $p + p$ collisions at $\sqrt{s} = 200$ GeV has been measured using azimuthal correlations between nonphotonic electrons and hadrons. The extracted B decay contribution is approximately 50% at a transverse momentum of $p_T \gtrsim 5$ GeV/c. These measurements constrain the nuclear modification factor for electrons from B and D meson decays. The result indicates that B meson production in heavy ion collisions is also suppressed at high p_T.

The suppression of nonphotonic electron yields from semileptonic decays of D and B mesons for p_T up to 9 GeV/c in central Au + Au collisions at Relativistic Heavy Ion Collider (RHIC) has been observed to be large [1], and similar to that of light quark hadrons [2]. Because of the dead cone effect, heavy quarks were expected to lose less energy than light quarks [3] if the dominant energy loss mechanism is gluon radiation [4]. Various models have been proposed to explain the large suppression of nonphotonic electron yields [5–7]. Theoretical calculations of the nonphotonic electron suppression crucially depend on the B/D ratios because the amount of radiative energy loss depends on the quark mass. Measuring the bottom quark contribution to nonphotonic electron yields in $p + p$ collisions is therefore important in order to understand the production of heavy quarks and to provide a baseline for the energy loss measurement of heavy quarks in the hot and dense medium produced in central Au + Au collisions.

In this Letter, we report a determination of the relative contribution from B decays to nonphotonic electron yields (r_B) by measuring the azimuthal correlations between nonphotonic electrons and charged hadrons ($e_{\text{non}\gamma} - h$), and between nonphotonic electrons and D^0 mesons ($e_{\text{non}\gamma} - D^0$) in $p + p$ collisions at $\sqrt{s} = 200$ GeV by the STAR experiment at RHIC. We fit the experimental $e_{\text{non}\gamma} - h$ correlations using a combination of PYTHIA calculations [8] for D and B meson decays and extract r_B as a function of p_T ($2.5 < p_T < 9.5$ GeV/c). An independent measurement of the r_B is obtained from $e_{\text{non}\gamma} - D^0$ correlations, by selecting the charge combinations $e^- - D^0(\to K^-)$ and $e^+ - \bar{D}^0(\to K^+)$, which provide relatively pure samples of B decays and charm pairs on near and away side ($\Delta\phi \sim \pi$) [9]. The combined measurements of the B decay contribution and of the nuclear modification factor (R_{AA}) for heavy-flavor decay electrons in Au + Au collisions constrain the value of the R_{AA} for electrons from B meson decays.

The $p + p$ data used in this analysis were taken by the STAR experiment [10] during the 2005 and 2006 RHIC runs. The main detectors for this analysis are the Time Projection Chamber (TPC) and the Barrel Electromagnetic Calorimeter (BEMC). The BEMC has a Shower Maximum Detector (SMD): proportional gas chambers with strip readout at a depth of ~ 5 radiation lengths (X_0) designed to measure shower shapes and positions. The acceptance for electrons in pseudorapidity and azimuth is $|\eta| < 0.7$ ($0 < \eta < 0.7$ in the 2005 run) and $0 < \phi < 2\pi$. The BEMC also serves as a trigger detector for high p_T electrons or photons, where single-tower transverse energy thresholds of 2.6 and 5.4 GeV were used. The total sampled luminosity was 11.3 pb^{-1} (0.65 pb^{-1}) for the 5.4 GeV (2.6 GeV) trigger threshold. We used triggered events with primary vertices located within 35 cm of the TPC's geometrical center along the beam direction.

Electrons were identified by measuring ionization energy loss (dE/dx) and track momentum (p) from TPC, the energy (E) deposition in the BEMC, and the shower profile in the SMD. A significant fraction of the hadron background was rejected by selecting tracks with a measured dE/dx in the TPC between -1 and $+3$ standard deviations from the expected mean dE/dx for electrons. Based on calibrations of the SMD response to electrons and hadrons, tracks whose shower projection occupies more than 1 strip in both ϕ and η SMD planes were selected as electron candidates. We required the energy-to-momentum ratio to be in the range $0.3 < p/E < 1.5$. The hadron contamination in the electron sample after applying these cuts is $\sim 2\%$ up to 5 GeV/c, increasing to $\sim 10\%$ at 9 GeV/c.

The electron sample has two components: (i) nonphotonic electrons and (ii) photonic electrons— those from photon conversion in the detector material between the interaction point and the TPC and Dalitz decays, mainly from π^0. Photonic electrons were identified by pairing electrons with oppositely charged partner tracks, determining the conversion or decay vertex, and calculating the invariant mass of the e^+e^- pair $M_{e^+e^-}$ [11]. To improve the invariant mass resolution, the so-called 2D invariant mass was calculated using only p_T and p_Z, which is equivalent to setting the opening angle in the transverse plane to zero [11]. Monte Carlo simulations indicate that the cut of 0.1 GeV/c^2 removes almost all photon conversion candidates for which the decay partner is reconstructed in the TPC. The efficiencies for photonic electron reconstruction (ϵ_{e_γ}) range from 65% at 3.0 GeV/c to 80% at 8.0 GeV/c, as determined from GEANT simulations. For the $e_{\text{non}\gamma} - h$ analysis, we first removed the electrons that have an opposite-sign partner such that $M_{e^+e^-} < 0.1$ GeV/c^2 from the inclusive electron sample. The remaining electrons form the "semi-inclusive" electron sample. The nonphotonic electron yields can be expressed as,

$$N_{e_{\text{non}\gamma}} = N_{e_{\text{semi}}} + N_{e_{\text{like}}} - N_{e_{\gamma}^{\text{not-reco}}} - N_h. \quad (1)$$

$N_{e_{\text{semi}}}$ is the number of semi-inclusive electrons. $N_{e_{\gamma}^{\text{not-reco}}}$ represents the number of photonic electrons which are not reconstructed by the invariant mass method and is defined as: $(1/\epsilon_{e_{\gamma}} - 1)(N_{e_{\text{unlike}}} - N_{e_{\text{like}}})$. $N_{e_{\text{like}}}$ is the number of non-photonic electrons that were rejected by the conversion cuts because they happened to form a pair with a random track which is determined using like-sign pairs. N_h is the remaining background from hadron contamination in the electron sample. Other weak decay contributions such as K_{e3} are negligible due to their long $c\tau$, and charmed baryons (mostly Λ_c) is expected to be very small contribution since the baryon yield is small compared to the meson yield ($\Lambda_c/D^0 \sim 0.1$ in PYTHIA) and the branching ratio for semileptonic decays is smaller for baryons than mesons. The $e_{\text{non}\gamma} - h$ azimuthal distributions were calculated as

$$\frac{dN^{e_{\text{non}\gamma}-h}}{d(\Delta\phi)} = \frac{dN^{e_{\text{semi}}-h}}{d(\Delta\phi)} + \frac{dN^{e_{\text{like}}-h}}{d(\Delta\phi)}$$
$$- \frac{dN^{e_{\gamma}^{\text{not-reco}}-h}}{d(\Delta\phi)} - \frac{dN^{h-h}}{d(\Delta\phi)}, \quad (2)$$

where each term is normalized to be per nonphotonic electron trigger. Each angle-difference distribution on the right-hand side of Eq. (2) was experimentally determined. The distribution $dN^{e_{\gamma}^{\text{not-reco}}-h}/d(\Delta\phi)$ was constructed from $dN^{e_{\gamma}^{\text{reco}}-h}/d(\Delta\phi)$ by removing the conversion partner to account for the fact that the partner electron is not reconstructed.

Figure 1 shows $dN^{e_{\text{non}\gamma}-h}/d(\Delta\phi)$ per trigger for nonphotonic electrons for two different trigger p_T selections. Associated particles were required to have $p_T > 0.3$ GeV/c and $|\eta| < 1.05$. The dotted (dashed) line in
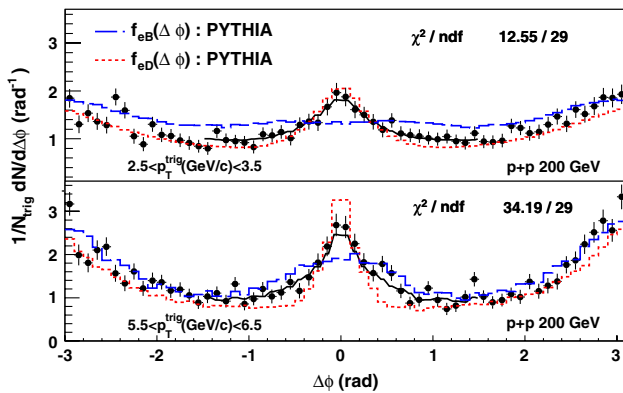

FIG. 1 (color online). Distributions of the azimuthal angle between nonphotonic electrons and charged hadrons normalized per nonphotonic electron trigger. The trigger electron has (top) $2.5 < p_T < 3.5$ GeV/c and (bottom) $5.5 < p_T < 6.5$ GeV/c. The curves represent PYTHIA calculations for D (dotted curve) and B (dashed curve) decays. The fit result is shown as the black solid curve.

the figure represents a PYTHIA version 6.22 calculation of the azimuthal correlations between electrons from D (B) meson decay and charged hadrons ($f_{e_D}(\Delta\phi)$, $f_{e_B}(\Delta\phi)$) [12]. PYTHIA was tuned to reproduce the shapes of p_T distributions for D mesons measured by STAR [12,13]. The PYTHIA calculation shows that the near-side peak for $f_{e_B}(\Delta\phi)$ is broader than that for $f_{e_D}(\Delta\phi)$. These shapes are dominated by decay kinematics. The fragmentation function does not affect the shape in a significant way. The fraction of nonphotonic electrons from B meson decay can be determined by fitting the near-side distribution function ($|\Delta\phi| < 1.5$):

$$\frac{1}{N_{\text{trig}}^{\text{non}\gamma}} \frac{dN^{e_{\text{non}\gamma}-h}}{d(\Delta\phi)} = r_B f_{e_B}(\Delta\phi) + (1 - r_B)f_{e_D}(\Delta\phi), \quad (3)$$

where r_B is the ratio of electrons from B meson decay to the total nonphotonic electron yield, $r_B = N_{e_B}/(N_{e_B} + N_{e_D}) = N_{e_B}/N_{e_{\text{non}\gamma}}$.

An independent measurement of r_B was performed using $e_{\text{non}\gamma} - D^0$ correlations. D^0 mesons were reconstructed via their hadronic decay $D^0 \rightarrow K^-\pi^+$ ($\mathcal{B} = 3.89\%$) by calculating the invariant mass of all oppositely charged TPC tracks in the same event. In this analysis, only events with a nonphotonic electron trigger were used for D^0 reconstruction. Furthermore, the kaon candidates were required to have the same charge sign as the nonphotonic electrons [9]. The combinatorial background of random pairs was evaluated by combining all charged tracks with the same charge sign from the same event. The requirement of a nonphotonic electron trigger suppresses the combinatorial background, yielding a signal (S)-to-background (B) ratio of about 14% and a signal significance ($S/\sqrt{S+B}$) of ~4.6.

Figure 2(a) shows the background-subtracted K/π invariant mass distribution. The peak position and width were determined using a Gaussian fit to the data. The $K\pi$ invariant mass distribution was obtained for different $\Delta\phi$ bins with respect to the trigger electron, and the yield of the associated D^0 mesons was taken as the area underneath the Gaussian fit to the signal. Figure 2(b) shows the azimuthal correlation of $e_{\text{non}\gamma} - D^0$, which exhibits near- and away-side correlation peaks with similar yields. The results are fitted with the correlation functions for charm and bottom production from PYTHIA and MC@NLO simulations having the relative B contribution as a free parameter [9]. The observed away-side correlation peak can be attributed to prompt charm pair production ($\sim 75\%$) and B decays ($\sim 25\%$), whereas the contributions to the near-side peak are mainly from B decays. We determined r_B by fitting the measured $e_{\text{non}\gamma} - D^0$ correlation with PYTHIA and MC@NLO and used the average of the two fits for the final value.

Figure 3 shows $r_B = N_{e_B}/(N_{e_B} + N_{e_D})$ extracted from $e_{\text{non}\gamma} - h$ correlations (filled circles) and $e_{\text{non}\gamma} - D^0$
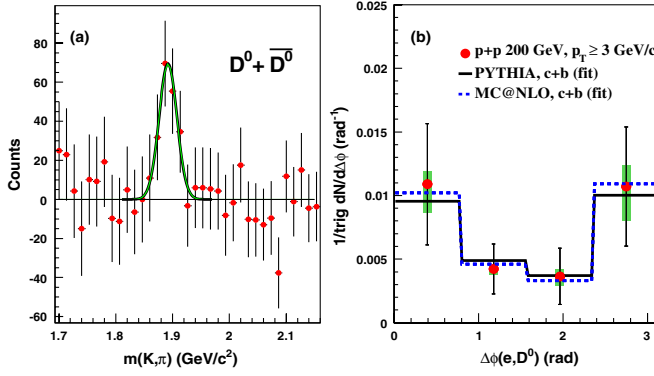
FIG. 2 (color online).   (a) Background-subtracted invariant mass distribution of $K\pi$ pairs requiring at least one nonphotonic electron trigger in the event. The solid line is a Gaussian fit to the data near the peak region. (b) Distribution of the azimuthal angle between nonphotonic electron (positron) trigger particles and $D^0(\bar{D}^0)$. The solid (dashed) line is a fit of the correlation function from PYTHIA (MC@NLO) simulations to the data points.

correlations (open circle) as a function of p_T. The vertical lines represent the statistical errors and the systematic uncertainties are shown as brackets. The systematic uncertainties due to electron identification ($\sim 7\%$), photonic electron rejection ($\sim 6\%$), the fit range ($\sim 10\%$) and the normalization of the azimuthal distribution ($\sim 10\%$), PYTHIA and MC@NLO predictions for $e_{\mathrm{non}\gamma} - D^0$ ($\sim 5\%$), and the D^0 signal extraction were estimated by varying the associated cut parameters and adding the individual contributions in quadrature. r_B increases with electron p_T and reaches approximately 0.5 ($N_{e_B}/N_{e_D} \sim 1$) around $p_T = 5$ GeV/c. r_B from the $e_{\mathrm{non}\gamma} - D^0$ correlation measurement at $p_T \sim 5.5$ GeV/c is consistent with r_B from $e_{\mathrm{non}\gamma} - h$ correlations. The curve in the figure is r_B from a FONLL pQCD calculation including theoretical uncertainties [14]. Similar ratios at $2 < p_T < 7$ GeV/c using a different

method have also been reported [15]. J/ψ di-electron decays can also contribute to nonphotonic electrons and STAR measurement of J/ψ at high p_T indicates that J/ψ decays could contribute nearly 10% around p_T 5 GeV/c. The estimated effect of the electrons from J/ψ decays on r_B is a few percent, much smaller than the current statistical and systematic uncertainties, and no correction was applied to our data.

Next, we explore the implications of the measured r_B for the R_{AA} of electrons from B meson decay in heavy ion collisions. The R_{AA} for heavy-flavor nonphotonic electrons (R_{AA}^{HF}) is given by

$$R_{AA}^{\mathrm{HF}} = (1 - r_B)R_{AA}^{e_D} + r_B R_{AA}^{e_B}, \qquad (4)$$

where $R_{AA}^{e_D}$ ($R_{AA}^{e_B}$) is the R_{AA} for electrons from D (B) mesons. From Eq. (4), $R_{AA}^{e_D}$ and $R_{AA}^{e_B}$ are related by the B decay contribution to the nonphotonic electron yields (r_B) in $p + p$ collisions. We have taken the R_{AA}^{HF} measurement from PHENIX [16,17] and fit the R_{AA}^{HF} above $p_T > 5$ GeV/c to a constant value and obtained: $R_{AA} = 0.167^{+0.0562}_{-0.0485}(\text{stat})^{+0.0512}_{-0.0815}(\text{syst}) \pm 0.0117(\text{norm})$, where the statistical and systematic errors are evaluated from weighted average over these $p_T > 5$ GeV/c points. We also calculate the weighted mean r_B value for $p_T > 5$ GeV/c including statistical and systematic errors from our measurement: $r_B = 0.54 \pm 0.0349(\text{stat}) \pm 0.0666(\text{syst})$. Then using Eq. (4) we calculate a likelihood distribution for $R_{AA}^{e_B}$ as a function of $R_{AA}^{e_D}$ and the results are shown in Fig. 4. The most probable values for the $R_{AA}^{e_D}$ and $R_{AA}^{e_B}$ correlation are shown by the line with open circles and the 90% Confidence Limit curves are represented by dashed lines. This result indicates that B meson yields are suppressed at high p_T in heavy ion collisions
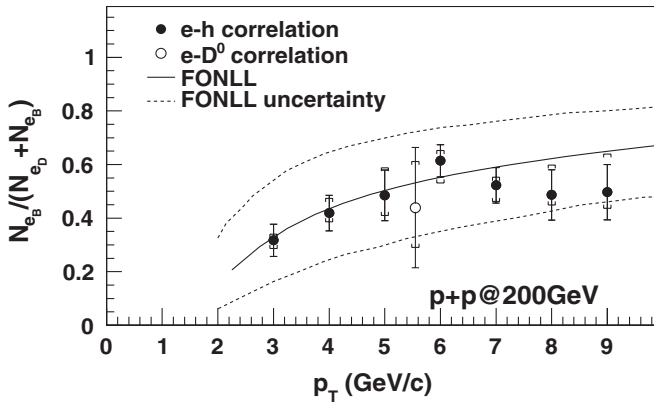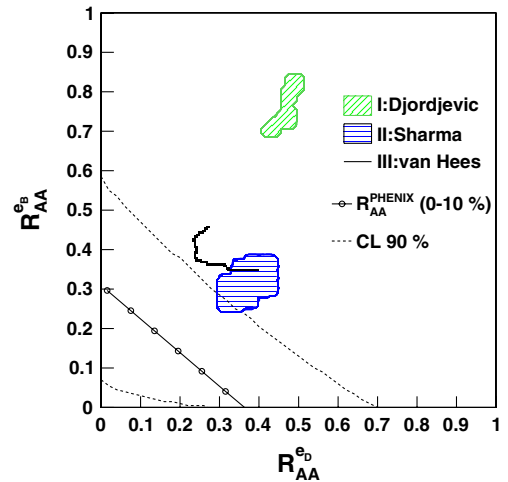

FIG. 3.   Transverse momentum dependence of the relative contribution from B mesons (r_B) to the nonphotonic electron yields. Error bars are statistical and brackets are systematic uncertainties. The solid curve is the FONLL calculation [14]. Theoretical uncertainties are indicated by the dashed curves.

FIG. 4 (color online).   Confidence level contours for nuclear modification factor R_{AA} for electrons from D ($R_{AA}^{e_D}$) and B ($R_{AA}^{e_B}$) meson decays and determined by combining the R_{AA} results and the r_B measurement for $p_T > 5$ GeV/c. Three different models of R_{AA} for D and B are described in the text.

presumably due to energy loss of the b quark in the dense medium [5] or of the heavy-flavor hadrons due to dissociation [6] or elastic scattering [7]. Our conclusion does not change if we use the R_{AA} measurement from [1] and ignore the J/ψ feed down contributions.

For comparison, we also show model calculations in Fig. 4. Model I includes radiative energy loss via a few hard scatterings with initial gluon density $dN_g/dy = 1000$ [5]. Model II includes cold nuclear matter effects, partonic energy loss and collisional dissociation [6]. Model III assumes a large elastic scattering cross section associated with resonance states of D and B mesons in the QGP [7]. The model contours in Fig. 4 are calculated from the p_T dependences of R_{AA} for D and B decay in the interval $5 < p_T \lesssim 9$ GeV/c. For model I and II, the uncertainties are also taken into account. The experimental results are consistent with models II and III but are incompatible with model I. Recently AdS/CFT theory has also been used to calculate the heavy quark energy loss in a strongly coupled quark-gluon plasma matter, for example [18,19]. The theory also predicts strong suppressions for charm and bottom, and the ratio of the nuclear modification factors is proposed to differentiate AdS/CFT calculation from others [20].

In summary, we measured the relative contribution from B decays to the nonphotonic electron production in $p + p$ collisions at $\sqrt{s} = 200$ GeV by using azimuthal correlations between nonphotonic electrons and hadrons (h, D^0). Our result indicates that the B decay contribution increases with p_T and is comparable to the contribution from D meson decay at $p_T \geq 5$ GeV/c. Our measurement is consistent with the FONLL calculation. The ratio of $N_{e_B}/(N_{e_D} + N_{e_B})$ combined with the large suppression of nonphotonic electrons indicates that R_{AA} for electrons from B hadron decays is significantly smaller than unity and therefore B meson production is suppressed at high p_T in heavy ion collisions. The constraint on R_{AA}^{eD} and R_{AA}^{eB} will help to differentiate theoretical model calculations for heavy quark energy loss in the dense medium.

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