Transverse momentum and centrality dependence of high-$p_T$ non-photonic electron suppression in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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The STAR collaboration at RHIC reports measurements of the inclusive yield of non-photonic electrons, which arise dominantly from semi-leptonic decays of heavy flavor mesons, over a broad range of transverse momenta ($1.2 < p_T < 10 \text{ GeV}/c$) in $p+p$, $d+Au$, and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$. The non-photonic electron yield exhibits unexpectedly large suppression in central $Au+Au$ collisions at high $p_T$, suggesting substantial heavy quark energy loss at RHIC. The centrality and $p_T$ dependences of the suppression provide constraints on theoretical models of suppression.

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High $p_T$ hadron production measurements at the Relativistic Heavy Ion Collider (RHIC) show a strong suppression of the single-particle inclusive yields in nuclear collisions $[1,2]$. The suppression is commonly thought to arise from partonic energy loss in dense matter due to induced gluon radiation $[3]$, with its magnitude depending strongly on the color charge density of the medium. This makes it a sensitive probe of the matter created in heavy-ion collisions, where a quark-gluon plasma may form if sufficient energy density is achieved.

Charm and bottom quarks are produced dominantly through high-$Q^2$ partonic interactions. Heavy flavor cross-sections and $p_T$ spectra have been calculated at next-to-leading-order (NLO) for both $p+p$ and $A+Au$ collisions $[3,4]$, including nuclear matter effects $[5]$. Although pQCD calculations agree well with heavy quark production in collider experiments at higher energies, they disagree with recent RHIC measurements $[6,7]$. Nevertheless, measurements of heavy quark production potentially provide new constraints on partonic energy loss mechanisms $[11,12]$. Gluon radiation in a forward cone is suppressed for heavy quarks at moderate energy (dead cone effect) $[11,12]$, with corresponding reduction in medium induced energy loss and less suppression of heavy-quark mesons than light quark mesons.

Direct reconstruction of heavy flavor mesons via hadronic decay channels $[4]$ is difficult in the complex environment of high energy nuclear collisions. Heavy quark production can also be studied through measurements of electrons (positrons) from semileptonic decays. Additional hadron rejection is based on the shower depth $\delta p/p$ and track momentum from the TPC, embedding simulated electrons into real events. It is significant on Gaussian fits similar to those in Figure 1.

**TABLE I: Corrections and systematic uncertainties for the non-photonic electron yield at $p_T = 2$ and 8 GeV/c.**

| Correction | $p+p$ | 2 GeV/c | $p+p$ | 8 GeV/c |
|------------|-------|---------|-------|---------|
| Acceptance | $0.80 \pm 0.03$ | $0.75 \pm 0.15$ | $0.84 \pm 0.05$ | $0.75 \pm 0.16$ |
| PID efficiency | $0.25 \pm 0.03$ | $0.13 \pm 0.03$ | $0.45 \pm 0.03$ | $0.45 \pm 0.03$ |
| hadron contamination | $0.04 \pm 0.04$ | $0.04 \pm 0.04$ | $0.04 \pm 0.04$ | $0.04 \pm 0.04$ |
| Bkgd reco. eff. ($e\mu$) | $0.65 \pm 0.06$ | $0.56 \pm 0.06$ | $0.56 \pm 0.06$ | $0.56 \pm 0.06$ |
| Bremsstr. & $\delta p/p$ | $0.86 \pm 0.14$ | $0.90 \pm 0.1$ | $1.1 \pm 0.1$ | $1.1 \pm 0.1$ |
| EMC trigger | $0.10 \pm 0.08$ | $1.00 \pm 0.05$ | $1.00 \pm 0.05$ | $1.00 \pm 0.05$ |
| Cross section | $0.14 \pm 0.14$ | $0.14 \pm 0.14$ | $0.14 \pm 0.14$ | $0.14 \pm 0.14$ |

Electrons are selected by cutting on TPC energy loss $dE/dx < 5.1$ keV/cm. $dE/dx_{min}$ is around 3.5 keV/cm, with the specific value having weak dependence on the event multiplicity and increasing slowly with track momentum, to optimize electron efficiency and hadron rejection while preserving more than 50% of the electrons in the $dE/dx$ distribution. The residual hadron background satisfying the $dE/dx$ cut is estimated based on Gaussian fits similar to those in Figure 1.

Table I shows the combined electron tracking and identification efficiency (“PID efficiency”), determined by embedding simulated electrons into real events. It is sig-
FIG. 1: (a) $dE/da$ projections for $5 < p_T (\text{GeV}/c) < 7$ in central Au+Au events after EMC and SMD cuts. The lines are Gaussian fits for $p + K$, $\pi$, and electron yields. (b) Invariant $e^+e^-$ mass spectrum. (c) Ratio of inclusive and background electron yield vs. $p_T$ for $p+p$ and Au+Au collisions. Vertical bars are statistical errors, boxes are systematic uncertainties.

Significantly below unity due to tracking efficiency ($\sim 70\%$), exclusion of electrons due to the energy leakage to neighboring towers, and SMD response. Its increase from $p_T = 2$ to $8 \text{ GeV}/c$ is due to increasing SMD efficiency.

**Electron background:** Background from photonic sources is due largely to photon conversions ($\sim 85\%$) in the detector material between the interaction point and the TPC ($X/X_0 \sim 4.5\%$) and $\pi^0$ and $\eta$ Dalitz decays ($\sim 15\%$). The photonic electron yield is measured using the invariant mass distribution of track pairs detected in the TPC. One track of the pair is required to fall in the EMC acceptance, satisfying $p > 1.5 \text{ GeV}/c$ and electron PID cuts, with the other track having $p_T > 0.15 \text{ GeV}/c$ within the TPC acceptance and a loose cut around the electron $dE/da$ band. Figure 1b shows the invariant mass distribution of pairs with the same or opposite charge sign. The same-sign distribution is due to random (combinatorial) pairs. An alternative combinatorial distribution formed by embedding single simulated electrons into real events agrees with the same-sign distribution within statistical uncertainties.

The shaded region in Figure 1c is the difference between the opposite and same-sign distributions and represents the photonic yield. It exhibits a peak at zero invariant mass due to conversions, and a tail at non-zero mass due to Dalitz decays [24]. Selecting $m < 150 \text{ MeV}/c^2$ accepts $\sim 98\%$ of all $\pi^0$ and $\eta$ Dalitz pairs in this distribution. The efficiency $\varepsilon_B(p_T)$ to identify a photonic electron in the EMC by this procedure was estimated by embedding [25] the main background sources ($\pi^0$ and $\gamma$) with a realistic momentum distribution derived from recent RHIC data [26] into real events.

The photonic electron yield $N_{ph}$ is calculated in each $p_T$ bin via $N_{ph} = (N_{\text{incl}} - N_{\text{like}})/\varepsilon_B$. Additional background, mainly from $\omega$, $\phi$, and $\rho$ decays, was estimated using PYTHIA [27] and HIJING [28] simulations to be $\sim 2 - 4\%$ of $N_{ph}$ [4] and is included in the systematic uncertainty of $N_{ph}$. Figure 1c depicts the ratio of the inclusive to the photonic electron spectra for $p+p$ and Au+Au collisions. The Figure shows a clear electron excess. Within uncertainties, the non-photonic excess is independent of centrality at high $p_T$.

**Non-photonic electron yield:** The trigger efficiency was determined by comparing the electron candidate spectrum in the minimum bias and triggered data sets. At high-$p_T$ the ratio of the spectra is compatible with the online scale-down factor applied to minimum bias events. The non-photonic spectrum is the difference of the inclusive and photonic spectra. Additional corrections are applied for momentum resolution and bremsstrahlung, determined from simulations.

**Systematic uncertainties:** Systematic uncertainties were determined by varying cut parameters within reasonable limits. The uncorrelated systematic uncertainty of the electron yield is dominated by the electron identification efficiency and photonic background reconstruction at low $p_T$ and the correction for residual hadron background at high $p_T$.

Figure 2 shows the fully corrected non-photonic electron spectra for 200 GeV $p+p$, $d+Au$, and Au+Au collisions. The curves correspond to FONLL (Fixed Order Next-to-Leading Log) predictions [7] for semileptonic $D$ and $B$ meson decays. The calculated spectrum is scaled by 5.5 (see below).

Figure 3 upper part (points), shows the ratio of mea-
Figure 3 shows predictions for electron $R_{AA}$ from semi-leptonic $D$- and $B$-meson decay in central Au+Au collisions using calculations of heavy quark energy loss. Curve I uses DGLV radiative energy loss via multiple soft collisions with initial gluon density $dN_g/dy = 1000$, consistent with light quark suppression. Curve II uses BDMPS radiative energy loss via multiple soft collisions with transport coefficient $\hat{q}$, $\hat{q}$ is set to 14 GeV$^2$/fm, though light quark hadron suppression provides only a loose constraint $4 < \hat{q} < 14$ GeV$^2$/fm. Both calculations predict much less suppression than observed.

This discrepancy may indicate significant collisional (elastic) energy loss for heavy quarks. Curve III is a DGLV-based calculation including both radiative and collisional energy loss, together with path length fluctuations. The calculated suppression is also markedly less than that observed. For Curve IV, the heavy quark energy loss is due to elastic scattering mediated by resonance excitations ($D$ and $B$) and LO $t$-channel gluon exchange. This calculation also predicts significantly less suppression than observed.

Dead cone reduction of energy loss is expected to be more significant for bottom than charm quarks in the reported $p_T$ range. Curve V, which is the same calculation as curve II but for $D$-meson decays only, agrees better with the data. Since there is better agreement of data and theory for bottom than charm production at the Tevatron, the scale factor 5.5 between calculated and measured $p+p$ electron yields may overestimate the $B$-decay contribution at RHIC, i.e. $D$ decays may in fact dominate the electron yields in the reported $p_T$ range, favoring calculation V. A direct measurement of $D$-mesons at high-$p_T$ is required to understand energy loss of heavy quarks in detail. Finally, multi-body mechanisms may also contribute to heavy quark energy loss.

We have reported the measurement of high-$p_T$ non-photonic electrons in $p+p$, $d+Au$, and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. A pQCD calculation for heavy quark production in $p+p$ collisions underpredicts the data, although agreement is found at larger $\sqrt{s}$.
though it describes the overall shape of the $p_T$ distribution relatively well. Large yield suppression is observed in central Au+Au collisions, consistent with substantial energy loss of heavy quarks in dense matter. The suppression is larger than that expected from radiative energy loss calculations, suggesting that other processes contribute significantly to heavy quark energy loss. This unique sensitivity to the energy loss mechanisms makes the measurement of heavy quark suppression an essential component of the study of dense matter. Full description of the interaction between partons and the medium will require further detailed measurements of charm and bottom separately.

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Erratum: Transverse momentum and centrality dependence of high-\(p_T\) non-photonic electron suppression in Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV

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In the original Letter [1] we reported on measurements of the transverse momentum spectra of non-photonic electrons in \( p+p, \ d+\text{Au}, \) and \( \text{Au}+\text{Au} \) collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \).

We have uncovered a mistake in the application of the background finding efficiency in the subtraction of the background from Dalitz decays and photon conversion. While the effective background reconstruction efficiency quoted in the original paper is correct, the ones actually applied were 10-15% higher. Because of this the background levels reported were underestimated and consequently the yields of non-photonic electrons published were higher than their actual values. This mistake affected results from all three collision systems used in [1].

![Figure 1](image1.png)

**FIG. 1:** (c) Ratio of inclusive and background electron yield vs. \( p_T \) for \( p+p \) and \( \text{Au}+\text{Au} \) collisions. Vertical bars are statistical errors, boxes are systematic uncertainties.

Figure 1 shows the revised ratio of inclusive over background electron yield as a function of \( p_T \) for \( p+p \) and \( \text{Au}+\text{Au} \) collisions. Due to the increase in background the ratio decreased systematically over the full \( p_T \) range.

![Figure 2](image2.png)

**FIG. 2:** Non-photonic electron spectra. Vertical bars are statistical errors, boxes are systematic uncertainties. The curves correspond to FONLL (Fixed Order Next-to-Leading Log) predictions [2] for semileptonic \( D \) and \( B \) meson decays.

Recent studies reported that feed-down from \( J/\psi \) decays contributes noticeably to the observed non-photonic electron signal [3]. This correction is not applied to the spectra shown in Fig. 2 but will be included and discussed in detail in a recent analysis of high statistics data [3].

Comparisons of the corrected \( p+p \) spectrum with a pQCD FONLL calculation and the result from the PHENIX collaboration [3] are shown in Fig. 3. Within statistical errors our measurement agrees well with the pQCD calculation and the STAR and PHENIX results are consistent with each other. The results at low \( p_T \) that were derived from a separate analysis using STAR’s Time of Flight detector [6] were also investigated and found to be correct.

![Figure 3](image3.png)

**FIG. 3:** Ratio between measured non-photonic electron spectra and FONLL pQCD calculations [2]. The shaded band around that line reflects the experimental uncertainty in this ratio.

Since the mistake made in the background finding efficiency affects the \( p+p, \ d+\text{Au}, \) and \( \text{Au}+\text{Au} \) data in a similar fashion, the nuclear modification factor, \( R_{AA} \), for \( d+\text{Au} \) and \( \text{Au}+\text{Au} \) collisions shown in Fig. 4 shifts only slightly in central value, but the statistical errors are larger than those in [1]. The main conclusion of the original Letter remains valid: a large suppression of non-photonic electron yield in central \( \text{Au}+\text{Au} \) collisions is observed, consistent with substantial energy loss of heavy quarks in dense matter created at RHIC.

Figures 3 and 4 show the corrected non-photonic electron spectra for 200 GeV \( p+p, \ d+\text{Au}, \) and \( \text{Au}+\text{Au} \) collisions. The curves correspond to FONLL (Fixed Order Next-to-Leading Log) predictions [2] for semileptonic \( D \) and \( B \) meson decays.

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FIG. 4: The nuclear modification factor, $R_{AA}$, for $d+Au$ and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

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