Analysis of non-photonic electrons in Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV

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Abstract Heavy-flavor semileptonic decays are expected to dominate the spectrum of non-photonic electrons produced from collisions at the energies of the Relativistic Heavy Ion Collider. The non-photonic electron yield is suppressed by approximately a factor of 5 in central Au + Au events at $\sqrt{s_{NN}} = 200$ GeV relative to $p + p$ events with the same collision energy. Most theoretical models predict less non-photonic-electron suppression than is observed experimentally. We present a preliminary measurement of the yield of non-photonic electrons in Cu + Cu events at $\sqrt{s_{NN}} = 200$ GeV, as well as the nuclear modification factor.

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1 Introduction

Heavy quarks are produced primarily through gluon-gluon fusion during initial nucleon hard scattering in a nucleus-nucleus collision [1]; subsequent heavy-quark production is believed to be negligible. Heavy quarks can therefore be used to study a nucleus-nucleus collision throughout its evolution, from the formation of a quark-gluon plasma to chemical freeze-out.

As they pass through a quark-gluon plasma, partons may lose energy through gluon bremsstrahlung and elastic collisions with other partons [2–4]. For a quark of mass M and energy E , gluon radiation is suppressed for angles less than M/E [5]. This phenomenon, the dead cone effect, leads to the expectation that heavy quarks should lose less energy through gluon radiation compared to light quarks as they travel through the medium. Heavy-quark energy loss through elastic collisions may be similar in magnitude to the radiative energy loss [6, 7].

Various heavy-flavor decay channels, including D -meson hadronic decays [8] and heavy-flavor-hadron decays to muons [9] and electrons, have been studied by the STAR collaboration. $e^\pm$ produced along with (anti)neutrinos in weak decays are called non-photonic $e^\pm$. The spectrum of non-photonic $e^\pm$ is expected to be dominated by the semileptonic decays of heavy-flavor hadrons (e.g. $D^0 \rightarrow e^+ + K^- + \nu_e$); non-photonic $e^\pm$ therefore serve as proxies for heavy quarks. e^-e^+ pairs from γ conversions and Dalitz decays (primarily of π^0 and η) constitute the primary sources of background to the non-photonic $e^\pm$ signal [10]. A small contribution to the non-photonic $e^\pm$ yield also comes from K_{e3} decays ($K^\pm \rightarrow \pi^0 + e^\pm + \nu_e(\bar{\nu}_e)$) and $K_L^0 \rightarrow \pi^\mp + e^\pm + \nu_e(\bar{\nu}_e)$.

Non-photonic $e^\pm$ yields have been measured by the STAR and PHENIX collaborations in Au + Au collisions and $p + p$ events at $\sqrt{s_{NN}} = 200$ GeV; this yield has also been measured by the STAR collaboration in $d + Au$ collisions at the same energy [8, 11–15]. The total charm cross-section $\sigma_{c\bar{c}}$ is extracted by the STAR collaboration from a combined fit of measurements of D^0 mesons and non-photonic $e^\pm$ (as well as muons in Au + Au collisions) [8, 11]. The PHENIX collaboration uses measurements of non-photonic $e^\pm$ to determine $\sigma_{c\bar{c}}$ [14, 15]. Both collaborations observe that $\sigma_{c\bar{c}}$ scales in proportion to $\langle N_{bin} \rangle$ the mean number of binary nucleon-nucleon collisions in a nucleus-nucleus collision. This is consistent with the assumption that charm (anti)quarks are produced predominantly from hard scattering of the nucleons in the initial stages of a nucleus-nucleus collision [13]. The values of $\sigma_{c\bar{c}}$ measured by the PHENIX collaboration tend to be lower than those measured by the STAR collaboration by a factor of ~ 2 ; the causes of this disagreement are under investigation. While PHENIX and STAR measure different values for the total charm cross-section, both collaborations observe similar nuclear modification factors for non-photonic $e^\pm$ in Au + Au events. STAR observes that $R_{AA} = 0.2$ – 0.3 for $p_T > 5$ GeV/ c for

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Fig. 1 (a) The energy-loss-cut efficiency α_E and the purity α_P are determined by fitting the $\ln(dE/dx)$ distribution with the sum of three Gaussians, which account for $e^\pm$, charged pions, and other hadrons (from right to left). The solid vertical lines show the range of the energy-loss cut. (b) Invariant-mass distributions of unlike-charge pairs

(black, solid), combinatorial background (blue, dashed), and photonic $e^\pm$ (red, filled; the difference between the two other distributions). The dashed purple vertical line indicates the 150-MeV/ c^2 invariant-mass cut used to identify photonic $e^\pm$

central Au + Au events; similar suppression is observed for light-flavor hadrons in central Au + Au events [16–18].

Theoretical models of parton energy loss in the quark-gluon plasma [19–22] tend to under-predict the suppression of non-photonic $e^\pm$ when the light-flavor-hadron R_{AA} data are used to constrain model parameters (such as $\hat{q}$ in the DGLV models or dN_g/dy in the BDMPS models). The DGLV and BDMPS models do describe the observed non-photonic- $e^\pm$ suppression if only c -quark decays contribute to the non-photonic $e^\pm$ spectrum. The observed non-photonic- $e^\pm$ suppression is also reproduced by the collisional dissociation model [23], in which heavy quarks fragment to form D and B mesons, which subsequently dissociate as they pass through the medium. Short formation times for the heavy-flavor mesons allow such formation-dissociation cycles to occur multiple times and the heavy quarks lose energy.

Non-photonic $e^\pm$ yields and nuclear modification factors have been found in Au + Au collisions at various values of $\langle N_{part} \rangle$, the mean number of nucleons that participated in collisions during a nucleus-nucleus collision at a given centrality. In Cu + Cu collisions, the same quantities can be studied at similar values of $\langle N_{part} \rangle$ but with different collision geometries. In this paper, I describe the procedures used to identify inclusive $e^\pm$ and identify the photonic $e^\pm$ background in Cu + Cu events at $\sqrt{s_{NN}} = 200$ GeV. The electronic version of this paper includes color versions of the figures. All data presented below are for the 0–54% centrality bin.

2 Analysis method

10^7 minimum-bias and 1.9×10^6 high-tower-triggered events (an integrated luminosity of $253 \mu\text{b}^{-1}$) were analyzed. An event was recorded by the high-tower trigger if one or more towers in the Barrel Electromagnetic Calorimeter (BEMC) [24, 26] had an energy above approximately 3.75 GeV. At low transverse momentum, $e^\pm$ were extracted from minimum-bias events; at high p_T , $e^\pm$ were extracted from high-tower events.

2.1 Electron identification

The STAR [24] Time Projection Chamber (TPC) [25], the Barrel Electromagnetic Calorimeter (BEMC) [26], and the Barrel Shower Maximum Detector (BSMD) [26] are used to identify $e^\pm$. The TPC is a cylindrical gas detector 4.2 m long and 4 m in diameter (covering pseudorapidity $|\eta| < 1.8$) through which a uniform electric field of ≈ 135 V/cm is applied. Electrons liberated in the ionization of the gas drift in the electric field to the ends of the cylinder and are detected by the Multi-Wire Proportional Chamber readout system. The TPC sits in a 0.5-T solenoidal magnetic field; STAR can measure charged-particle momenta from 0.1–30 GeV/ c based on measurements of track curvature in this field. The BEMC is a lead/scintillator sampling calorimeter that sits outside the TPC. It is approximately 20 radiation lengths deep, has full azimuthal coverage, and currently covers pseudorapidity $|\eta| < 1$ (the BEMC covered only $0 < \eta < 1$ when the data presented in this article were recorded). The BSMD is a wire proportional chamber that sits ≈ 5.6 radiation lengths inside the BEMC. It provides measurements

of the shapes and positions of electromagnetic showers with finer resolution than the towers of the BEMC. We search for $e^\pm$ in the pseudorapidity range $-0.7 < \eta < 0.7$ to reduce the number of background $e^\pm$ from photon conversions in the inner support structures of the detector. An energy-loss cut ($3.5 \text{ keV/cm} < dE/dx < 5 \text{ keV/cm}$) is used to identify $e^\pm$ in the TPC. Many low-momentum hadrons have energy-loss values that fall within this cut; we restrict this analysis to $e^\pm$ with momentum $> 1.5 \text{ GeV}/c$.

Further $e^\pm$ identification is provided by cutting on the ratio p/E_{tow} , where p is the track momentum in the TPC and E_{tow} is the energy deposited in the BEMC tower to which that track points. In contrast to hadrons, nearly all of the energy of an $e^\pm$ is deposited in the BEMC; therefore, $p/E_{\text{tow}} \sim 1$ for $e^\pm$. In this analysis, tracks with $p/E_{\text{tow}} < 2$ are accepted. Tracks in high-tower triggered events must match towers which fulfill the trigger condition. Finally, showers produced by $e^\pm$ in the BEMC are on average larger than showers produced by hadrons of the same momentum. To be identified as an $e^\pm$, a track must point to a BEMC shower that produced signals at least two strips wide in both the η and ϕ planes of the Barrel Shower Maximum Detector.

To calculate the efficiency of these particle identification cuts (with the exception of the TPC energy-loss cut) we embed simulated $e^\pm$ into real Cu + Cu events and find the fraction ρ of simulated $e^\pm$ that are reconstructed and identified as $e^\pm$. This efficiency is typically 0.35–0.45 for $p_T > 3 \text{ GeV}/c$ and decreases with decreasing p_T . These simulations do not account for temporary losses in the geometrical acceptance of the BEMC due to hot or dead areas. The average acceptance $\langle A \rangle$ of the BEMC (including the BSMD) for $0 < \eta < 0.7$ is 0.78 ± 0.04 for the time period during which these data were collected. To correct for the TPC energy-loss cut and account for residual hadron contamination, we use the procedure illustrated in Fig. 1a. In each momentum bin, we fit the energy-loss distribution of TPC tracks that passed all other $e^\pm$ identification cuts. The fit function is the sum of three Gaussians, which quantify the yields of $e^\pm$ and hadrons. The integrals of the fit Gaussians are used to calculate two correction factors. The energy-loss cut efficiency α_E is the ratio of the number of $e^\pm$ that fall inside the energy-loss cut to the total number of $e^\pm$. This quantity is 0.7–0.8 with no strong p_T dependence. The purity α_P is the ratio of the number of $e^\pm$ inside the energy-loss cut to the total number of particles inside that cut. The purity is typically 0.9–1 and decreases with increasing p_T . Finally, the $e^\pm$ yields in the high-tower-triggered events were rescaled to compensate for the enhancement of these yields due to the trigger (cf. [11]).

2.2 Background identification

Photon conversions and Dalitz decays are the primary sources of background to the non-photonic $e^\pm$ signal. The

photonic $e^\pm$ background is identified by fully or partially reconstructing these decays, which produce low-invariant-mass e^-e^+ pairs. We find the invariant mass of charged-track pairs, which consist of an identified $e^\pm$ and a partner with $p > 100 \text{ MeV}/c$. The distance of closest approach between the two tracks must be $< 1.5 \text{ cm}$. We record N_{-+} the number of oppositely charged pairs with invariant mass $< 150 \text{ MeV}/c^2$. However, many of these combinations are random, not true γ -conversion or Dalitz-decay pairs. To account for this, we find the combinatorial background, which is $2\sqrt{N_{--}N_{++}}$, where N_{--} and N_{++} are the numbers of like-charge pairs with invariant mass $< 150 \text{ MeV}/c^2$. The photonic $e^\pm$ yield is the difference between N_{-+} and the combinatorial background (see Fig. 1b).

To determine the efficiency of this procedure, we embed simulated $\pi^0 \rightarrow \gamma\gamma$ decays into real events, as well as π^0 Dalitz decays ($\pi^0 \rightarrow \gamma e^-e^+$) at the natural 1.5% branching ratio [10]. The photons from these pion decays convert to e^-e^+ pairs, producing a pure sample of simulated photonic $e^\pm$. We then find the background rejection efficiency ε_B , the fraction of these simulated e^-e^+ pairs to be identified as photonic background. The background rejection efficiency is 0.7–0.8 and does not depend strongly upon the momentum of the identified $e^\pm$ or collision centrality.

The factors calculated in the previous sections (ρ , $\langle A \rangle$, α_E , α_P , and ε_B) are used to determine the yields of inclusive, photonic, and non-photonic $e^\pm$ (I , P , and N) according to (1)–(3) below. (I_0 is the uncorrected yield of inclusive $e^\pm$.)

$$I = \frac{\alpha_P}{\langle A \rangle \rho \alpha_E} I_0, \quad (1)$$

$$P = \frac{1}{\langle A \rangle \rho \alpha_E} \cdot \frac{1}{\varepsilon_B} (N_{-+} - 2\sqrt{N_{--}N_{++}}), \quad (2)$$

$$N = I - P. \quad (3)$$

For example, for the minimum-bias data set at $p_T = 2.7 \text{ GeV}/c$,

$$I = (4.2 \pm 0.1(\text{stat.}) \pm 0.4(\text{sys.})) 10^{-5} [\text{GeV}/c]^{-2},$$

$$P = (2.8 \pm 0.2(\text{stat.}) \pm 0.3(\text{sys.})) 10^{-5} [\text{GeV}/c]^{-2}, \quad \text{and}$$

$$N = (1.4 \pm 0.2(\text{stat.}) \pm 0.1(\text{sys.})) 10^{-5} [\text{GeV}/c]^{-2}.$$

3 Results

Figure 2 shows (a) the preliminary merged minimum-bias and high-tower spectra and (b) the preliminary nuclear modification factor R_{AA} for non-photonic $e^\pm$ in Cu + Cu collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$. STAR has previously found the non-photonic $e^\pm$ yield in $p + p$ collisions at the same collision energy [12]; that yield is used in the calculation

Fig. 2 (a) $e^\pm$ yields for 200-GeV Cu + Cu collisions in the 0–54% centrality bin, with statistical errors (lines) and systematic errors (boxes). (b) Non-photonic- $e^\pm$ nuclear modification factor ($\langle N_{part} \rangle = 82.2$)

of $R_{AA} \cdot \langle N_{bin} \rangle$, the mean number of binary collisions between nucleons, was taken to be 82.2 for the 0–54% centrality bin in 200-GeV Cu + Cu collisions. $R_{AA} = 0.62 \pm 0.10(stat.)^{+0.14}_{-0.16}(sys.)$ for $p_T > 3$ GeV/c.

This high- p_T R_{AA} for 200-GeV Cu + Cu collisions is consistent with the high- p_T R_{AA} for 200-GeV Au + Au collisions [13] at similar values of $\langle N_{part} \rangle$. The nuclear modification factor for $\pi^\pm$ in 200-GeV Cu + Cu collisions has been measured by the STAR collaboration [27] for three centrality bins. For the 20% most central collisions, $0.4 < R_{AA}(p_T > 2.5 \text{ GeV/c}) < 0.6$; for the 20–40% centrality bin, $0.6 < R_{AA}(p_T > 2.5 \text{ GeV/c}) < 0.8$. The high- p_T non-photonic $e^\pm$ R_{AA} is consistent with the suppression observed for charged pions.

4 Conclusions

The STAR Collaboration has measured the non-photonic $e^\pm$ yield in 200-GeV Cu + Cu events. We identify $e^\pm$ through their energy loss in the Time Projection Chamber, the fraction of their energy deposited in the Barrel Electromagnetic Calorimeter, and the size of the electromagnetic shower measured by the Barrel Shower Maximum Detector. The main sources of photonic $e^\pm$ background are photon conversions and Dalitz decays, which produce low-invariant-mass e^-e^+ pairs; the photonic $e^\pm$ yield is found through an invariant-mass reconstruction of these pairs. We have presented preliminary measurements of the non-photonic $e^\pm$ yield and nuclear modification factor in 200-GeV Cu + Cu collisions in the 0–54% centrality bin. For $p_T > 3$ GeV/c, $R_{AA} = 0.62 \pm 0.10(stat.)^{+0.14}_{-0.16}(sys.)$. This suppression appears to be consistent with previously observed trends. The suppression measured for non-photonic $e^\pm$ in the 0–54% centrality bin is consistent with the charged-pion nuclear

modification factor in the 0–20% and 20–40% centrality bins. The non-photonic- $e^\pm$ suppression observed in 200-GeV Cu + Cu collisions is consistent with the suppression STAR observed in 200-GeV Au + Au collisions with similar values of $\langle N_{part} \rangle$. This suggests that the differences in collision geometry between the Cu + Cu and Au + Au systems do not influence the magnitude of the heavy-quark energy loss.

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