Suppression of Non-photonic Electrons from Enhancement of Charm Baryons in Heavy Ion Collisions

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At intermediate transverse momentum (2 < p_T < 6 GeV/c), the baryon-to-meson ratio in Au+Au collisions is enhanced compared to p+p collisions. Since charm-baryon decays produce electrons less frequently than charm-meson decays, the non-photonic electron spectrum is sensitive to the \( \Lambda_c/D \) ratio. In this report we study the dependence of the non-photonic electron spectrum on the baryon-to-meson ratio for charm hadrons. As an example, we take the \( \Lambda_c/D \) ratio to have the same form as the \( \Lambda/K_S^0 \) ratio. In this case, even if the total charm quark yield in Au+Au collisions scales with the number of binary nucleon-nucleon collisions (\( N_{bin} \)), the electron spectrum at 2 < p_T < 5 GeV/c is suppressed relative to \( N_{bin} \) scaled p+p collisions by as much as 20%.

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Introduction. — Non-photonic electrons from heavy flavor decays can be used to study charm production even when direct measurements of heavy flavor hadrons are experimentally unfeasable. Radiative energy loss models that successfully describe the large hadron suppression experimentally unfeasable. Radiative energy loss models predict such a large suppression to have the same form as the \( \Lambda/K_S^0 \) ratio. In this report we assume that the \( \Lambda_c/D \) ratio is the same as the \( \Lambda/K_S^0 \) ratio. Unless specified otherwise, the symbol \( D \) represents the sum of \( D^0, D^+ \), and \( D_s \). PYTHIA \( ^{12} \) is used to generate the decay electron spectrum from the input charm hadrons. We find that even when the total charm hadron production in Au+Au collisions scales with the number of binary nucleon-nucleon collisions \( N_{bin} \), the non-photonic electron spectrum when the total charm hadron \( R_{AA} = 1 \) \( ^{13} \), the non-photonic electron spectrum at intermediate \( p_T \) can be suppressed by as much as 20%. We also present the non-photonic electron spectrum when the total charm hadron \( R_{AA} \) follows the measured charged hadron \( R_{AA} \) \( ^{14} \). We find that if charm baryons are enhanced as much as lighter flavor baryons, preliminary non-photonic electron measurements imply a smaller suppression of charm quarks than light quarks \( ^{15} \).

Results. — Fig. 1 shows the \( \Lambda/K_S^0 \) ratio in p+p and Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV \( ^{11} \). The \( \Lambda/K_S^0 \) ratio is larger than the \( p/\pi \) ratio and the baryon enhancement becomes even stronger for multi-strange baryons \( ^{16} \). In the following analysis we take the \( \Lambda_c/D \) ratio to have the same form as the \( \Lambda/K_S^0 \) ratio. For \( p_T > 6.5 \) GeV/c where the \( \Lambda/K_S^0 \) ratio is unknown, we take the value \( \Lambda_c/D = 0.33 \). Since the source of the baryon enhancement at intermediate \( p_T \) is still under debate, it’s difficult to assess the validity of our assumed \( \Lambda_c/D \) ratio. Possible explanations for the enhancement include \( ^{6} \) radial flow pushing heavy baryons from lower \( p_T \) into the intermediate \( p_T \) region, baryon junction dynamics, and enhanced production through coalescence or recombination of quarks. We are not aware, however, of predictions for the \( p_T \) dependence of the \( \Lambda_c/D \) ratio.

Fig. 2 shows the spectra for \( D^0, D^\pm, D_s \), and \( \Lambda_c \). The spectra are derived such that the sum of the \( D^0, D^\pm, D_s \), and \( \Lambda_c \) spectra follows a power-law, the \( \Lambda_c/D \) ratio has
the form shown in Fig. 1 and the D-meson spectra all have the same $p_T$ dependence. Since we are interested in the shape of the spectra, the scale of the y-axis is arbitrary. The non-photonic electron spectrum will also be sensitive to the $D^+ / D^0$ and the $D_s / D^0$ ratios (the $D_s \rightarrow e + anything$ branching ratio is $8^{+6}_{-5}$% [10]). An increase in the $D_s / D^0$ ratio can therefore lead to fewer decay electrons depending on the poorly known branching ratio. At intermediate $p_T$, the $K / \pi$ ratio in Au+Au collisions is enhanced compared to p+p collisions [17]. One can also investigate how modifications to the $D_s / D^\pm$ ratio in Au+Au collisions affect the non-photonic electron spectrum. Since the enhancement in the $\Lambda / K^0_S$ ratio is larger than the enhancement in the $K / \pi$ ratio, and since the branching ratios for $D_s \rightarrow e + anything$ and $D^0 \rightarrow e + anything$ are similar, we expect a charm baryon enhancement to have a larger effect on the decay electron spectrum. For this reason, in this report we use $p_T$ independent relative D-meson abundances of 18, 7, and 5 for $D^0$, $D^\pm$, and $D_s$ respectively [18].

In Fig. 2 we show the effect of a $\Lambda_c$ enhancement on the charm decay electron spectrum. The ratio of two cases is taken: $\Lambda_c / D$ follows the shape of the $\Lambda / K^0_S$ ratio in Au+Au collisions, or it follows the shape of the $\Lambda / K^0_S$ ratio in p+p collisions. A suppression of electrons from heavy flavor decays due to the larger charm baryon-to-meson ratio in Au+Au collisions is visible. The suppression in this figure is a result of smaller $\Lambda_c \rightarrow e + anything$ branching ratio, which has large uncertainties. The highest and lowest curves show the cases corresponding to the upper and lower experimental uncertainties on the branching ratio [10]. The figure demonstrates that even if the total charm yield follows $N_{bin}$ scaling, the non-photonic electron spectrum may be suppressed. The magnitude of the suppression depends on the $\Lambda_c / D$ ratio and the $\Lambda_c \rightarrow e + anything$ branching ratio. The $\Lambda_c / D$ ratio in Au+Au collisions is unknown but for the charm baryon-to-meson ratio assumed here, the suppression can be as large as 20%.

The presence of a charm baryon enhancement will change the charm quark energy loss inferred from the preliminary non-photonic electron $R_{AA}$ data. In Fig. 3 we show the effect of a $\Lambda_c$ enhancement on the charm decay electron spectrum. The ratio of two cases is taken: $\Lambda_c / D$ follows the shape of the $\Lambda / K^0_S$ ratio in Au+Au collisions, or it follows the shape of the $\Lambda / K^0_S$ ratio in p+p collisions. A suppression of electrons from heavy flavor decays due to the larger charm baryon-to-meson ratio in Au+Au collisions is visible. The suppression in this figure is a result of smaller $\Lambda_c \rightarrow e + anything$ branching ratio, which has large uncertainties. The highest and lowest curves show the cases corresponding to the upper and lower experimental uncertainties on the branching ratio [10]. The figure demonstrates that even if the total charm yield follows $N_{bin}$ scaling, the non-photonic electron spectrum may be suppressed. The magnitude of the suppression depends on the $\Lambda_c / D$ ratio and the $\Lambda_c \rightarrow e + anything$ branching ratio. The $\Lambda_c / D$ ratio in Au+Au collisions is unknown but for the charm baryon-to-meson ratio assumed here, the suppression can be as large as 20%.
we show the case when the total charm $R_{AA}$ has the same shape as charged hadron $R_{AA}$. In the lower $p_T$ region, this assumption may not be realistic since the total charm quark production is expected to follow $N_{bin}$ scaling. The error introduced, however, will mostly affect the region below $p_T = 1.5$ GeV/c and may be irrelevant to the higher $p_T$ regions of interest. Our analysis shows that if the $\Lambda_c/D$ ratio has the form assumed in this report, the PHENIX non-photonic electron data at $p_T < 6$ GeV/c is 35% greater than charged hadron $R_{AA}$. At $p_T$ near 6 GeV/c the derived decay electron $R_{AA}$ at $p_T < 6$ GeV/c will be smaller than the total charm $R_{AA}$.

In this report we have not considered contributions to the non-photonic electrons from beauty decays. The $p_T$ value where the yield of electrons from beauty decays is larger than from charm decays is experimentally unknown. Theoretical calculations indicate that the cross-over happens somewhere between $p_T = 3$ GeV/c and $p_T = 10$ GeV/c. The branching ratios for beauty mesons and baryons are not well known. We refer the reader to Ref. [20] for discussion of the contribution of beauty to the non-photonic electron spectrum.

In the intermediate $p_T$ region, the preliminary non-photonic electron data are systematically above our calculations for the decay electron $R_{AA}$. In the case that the heavy flavor baryons have an enhancement similar to the light flavor baryons, the non-photonic electron data indicate that the suppression for charm quarks is smaller than that for light quarks. We varied the input total charm hadron $R_{AA}$ and made a $\chi^2$ comparison to the PHENIX data (with the systematic and statistical errors added in quadrature). For $p_T > 2.0$ GeV/c, the PHENIX non-photonic electron data are better represented when the total charm hadron $R_{AA}$ is 35% greater than charged hadron $R_{AA}$. At $p_T$ near 6 GeV/c the derived decay electron $R_{AA}$ matches the charged hadron $R_{AA}$ and the preliminary non-photonic electron $R_{AA}$ data reported in Ref. [19]. We find that the $\Lambda_c/D$ ratio has the form assumed in this report, the PHENIX non-photonic electron data at intermediate $p_T$ prefer a total charm hadron $R_{AA}$ 35% larger than the total charm hadron $R_{AA}$. At $p_T$ near 6 GeV/c the derived decay electron $R_{AA}$ matches the charged hadron $R_{AA}$ and the preliminary non-photonic electron $R_{AA}$ data reported in Ref. [19]. This may indicate that at $p_T = 6$ GeV/c (within the large errors) the total charm hadron suppression is as large as the light hadron suppression. In light of the results of this analysis, however, we believe one must also consider that a charm baryon enhancement could extend to a higher $p_T$ than assumed here. Direct measurements of heavy flavor hadrons are therefore needed in order to accurately assess the energy loss of charm quarks.

Summary. — We have studied the effect of the $\Lambda_c/D$ ratio on the non-photonic electron $R_{AA}$. We find that even when the total charm hadron production scales with the number of binary nucleon-nucleon collisions, an increase in the $\Lambda_c/D$ ratio similar to that seen for the $\Lambda/K_S^0$ ratio can lead to a suppression in central Au+Au collisions of non-photonic electrons at intermediate $p_T$. This may help explain why the non-photonic electron $R_{AA}$ is smaller than was predicted by radiative energy loss models: models which are able to describe the light hadron $R_{AA}$. If the $\Lambda_c/D$ ratio has the form assumed in this report, the PHENIX non-photonic electron data at intermediate $p_T$ prefer a total charm hadron $R_{AA}$ 35% larger than the total charm hadron $R_{AA}$. At $p_T$ near 6 GeV/c the derived decay electron $R_{AA}$ matches the charged hadron $R_{AA}$ and the preliminary non-photonic electron $R_{AA}$ data reported in Ref. [19]. This may indicate that at $p_T = 6$ GeV/c (within the large errors) the total charm hadron suppression is as large as the light hadron suppression. In light of the results of this analysis, however, we believe one must also consider that a charm baryon enhancement could extend to a higher $p_T$ than assumed here. Direct measurements of heavy flavor hadrons are therefore needed in order to accurately assess the energy loss of charm quarks.

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than the charged hadron $R_{AA}$ — implying less energy loss for charm quarks than light quarks. If the relative fractions of charm hadrons are not altered in Au+Au collisions compared to p+p collisions, the non-photonic electron $R_{AA}$ values are difficult to understand within current radiative energy loss models. Since the non-photonic electron measurements depend on the $D^0/D_s$, $D^\pm/D_s$ and the $\Lambda_c/D$ ratio, direct measurements of heavy-flavor hadron yields are needed to draw firm conclusions regarding energy loss for heavy quarks. These measurements will only be possible at RHIC with detector upgrades [21].

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