MEASUREMENT OF NON-PHOTONIC ELECTRON ANGULAR CORRELATIONS WITH CHARGED HADRONS

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Correlations of non-photonic electrons with charged hadrons are studied using the PYTHIA Monte Carlo event generator in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV. We propose experimental methods to estimate the relative contributions to non-photonic electrons from charm and bottom decays. We present the measurement of azimuthal correlations between non-photonic electrons and charged hadrons in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV from STAR. The results are compared to PYTHIA simulations to estimate the relative contributions of D and B meson semi-leptonic decays to non-photonic electrons. Our preliminary result indicates that at $p_T \sim 4.0 - 6.0$ GeV/c the measured B contribution to non-photonic electrons is comparable to D contribution, and is consistent with the FONLL calculation.

1. Introduction

High transverse momentum particles in central Au+Au collisions are found to be significantly suppressed compared to that from p+p collisions. This is consistent with the picture that high energy partons are quenched when propagating through the dense medium created in central nucleus-nucleus collisions and this suppression is thus a probe for the Quark Gluon Plasma. Light hadron suppression at RHIC has been described by a gluon radiation energy loss mechanism. Recent RHIC data show that the suppression of non-photonic electrons (electrons from heavy quark decays) has almost the same magnitude as that of light hadrons in central Au+Au collisions. This implies that heavy quarks may lose a substantial amount of energy, which cannot be explained by current theoretical predictions based on gluon radiation as the dominant mechanism for energy loss. Heavy quark would lose much less energy because the gluon radiation is suppressed at small angles due to the mass of heavy quarks (dead cone effect). Recent calculations including both gluon radiation and collisional energy loss increase the heavy quark energy loss. In both scenarios electrons from charm decays are always more suppressed than those from bottom. However, theoretical calculations contain large uncertainties with respect to the relative contributions to non-photonic electrons from charm and bottom quarks. Another important tool to study the Quark Gluon Plasma properties is the angular anisotropy $v_2$. Observation of heavy quark
hydrodynamic flow is a unique probe for the early stage of a partonic phase. A nonzero non-photonic electron $v_2$ has been measured for $p_T < 2.0$ GeV/c, while at higher $p_T$ (although uncertainties are still large) the $v_2$ is observed to decrease with $p_T$. The same $D$ and $B$ hadron $v_2$ can lead to very different non-photonic electron $v_2$ due to the different decay kinematics between $D$ and $B$ hadrons.

The quantitative understanding of the non-photonic electron suppression at high $p_T$ and $v_2$ requires the knowledge of the relative charm and bottom contributions to non-photonic electrons.

In this paper, correlations of non-photonic electrons with charged hadrons are studied using the PYTHIA event generator in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV. We develop an innovative method which uses the azimuthal correlations between non-photonic electrons and charged hadrons to estimate the relative $D$ and $B$ contributions to non-photonic electrons. We present the preliminary results on the measurement of azimuthal correlations between high-$p_T$ non-photonic electrons and charged hadrons in p+p collisions at 200 GeV from STAR. We will use comparisons of the experimental results with PYTHIA simulations to estimate $B$ and $D$ decay contributions to non-photonic electrons as a function of $p_T$ for $p_T > 2.5$ GeV/c.

2. PYTHIA Simulation

We have studied the correlations between non-photonic electrons and inclusive charged hadrons in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV from PYTHIA v6.22. The parameters for charm quarks are: PARP(67) = 4 (factor multiplied to $Q^2$), $< k_t > = 1.5$ GeV/c, $m_c = 1.25$ GeV/$c^2$, $K_{factor} = 3.5$, MSTP(33) = 1 (inclusion of $K$ factors), MSTP(32) = 4 ($Q^2$ scale), CTEQ5L PDF and $\delta$ fragmentation function. The parameters for bottom quarks are the same as for charm quarks except $m_b = 4.8$ GeV/$c^2$. The details of PYTHIA parameter setup are discussed in Reference.

The left panel of Fig. 1 shows the $\Delta \phi$ distributions between non-photonic electrons and inclusive charged hadrons with six electron trigger $p_T$ cuts and the associated hadron $p_T > 0.3$ GeV/c. The distributions are scaled by the number of electron triggers. The solid curves and dashed curves are for $B$ decays and for $D$ decays, respectively. There is a significant difference between $B$ and $D$ meson decays in the near-side correlations. The width of near-side peak for electrons from $D$ meson decays is much narrower than those for the $B$ decays. The wide width from $B$ meson decays is due to the larger energy release ($Q$ value) in the $B$ meson semileptonic decays leading to a broad angular correlation between daughter hadrons and electrons in the laboratory frame. For an electron at high $p_T$ from $B$ meson decays, the $B$ meson does not have to be at high transverse momentum because the electron can get large momentum from the $b$-quark mass. In the case of $D$ meson decays, the $D$ meson needs to have a large momentum in order to boost
the daughter electron to a high $p_T$. Fig. 2 shows the distributions of electron $p_T$ versus its parent $p_T$. We found the difference in the near-side correlations between $D$ decays and $B$ decays is largely due to the decay kinematics, not the production dynamics. Variations on fragmentation function from default Peterson function to $\delta$ function and on the parameter PARP(67) from 1 to 4 do not change the shape of the correlations in a significant way. This difference can help us estimate the relative $B$ and $D$ contributions to the yields for non-photonic electrons. We will use the $\Delta \varphi$ distributions from $B$ decays and $D$ decays in PYTHIA to fit the $\Delta \varphi$ distributions from the real data and thus measure the $B$ contribution, $B/(B+D)$.

We further studied the particle production within a cone around triggered high $p_T$ electrons from heavy quark decays. We focused on the scalar summed $p_T$ distributions of inclusive charged hadrons in the cone ($p_T$ refers to the transverse momentum in the laboratory frame). Here the cone is defined by $|\eta_h - \eta_e| < 0.35$.
Fig. 3. (color online) (a) Invariant mass distributions of $e^+e^-$ pairs (OppSign, grey filled area) and combinatorial background (SameSign, red solid line) in p+p collisions. (b) The ratio of inclusive electron to photonic background as a function of $p_T$ in p+p collisions.

Fig. 4. (color online) $\Delta \phi_{non-pho}$ distributions and the comparison to PYTHIA simulations for four electron trigger cuts with associated hadron $p_T^{(assoc)} > 0.3$ GeV/c. The data are shown as dots, the simulations are depicted by blue dashed lines for $B$ meson decays and red dotted lines for $D$ meson decays. The green solid curves are the fits to data points using PYTHIA curves.

and $|\varphi_h - \varphi_e| < 0.35$ ($\eta$ is pseudorapidity and $\varphi$ is azimuthal angle). The summed $p_T$ distributions of inclusive charged hadrons in three triggered electron $p_T$ ranges are shown in the right panel of Fig. 1. The distributions are scaled to unity. The dashed lines are for $D$ decays and the solid lines are for $B$ decays. We also can see
that there is a significant difference between $B$ decays and $D$ decays. The summed $p_T$ distributions for $D$ meson decays are much wider than those for $B$ meson decays. This difference can also be used to distinguish $B$ and $D$ decay contributions. It will be more valuable for the small acceptance experiments to investigate the $B$ decay contribution using summed $p_T$ distributions.

3. STAR Data Analysis

The data used in this analysis is $p+p$ events at $\sqrt{s_{NN}} = 200$ GeV recorded by STAR in RUN V. The main detectors utilized in this analysis are the STAR Time Projection Chamber (TPC)\(^{20}\) and the STAR Barrel Electromagnetic Calorimeter (BEMC) with the Shower Maximum Detector (SMD)\(^{21}\). To obtain sufficient statistics at high-$p_T$, we used high tower triggers corresponding to an energy deposition of at least 2.6 GeV (HT1) and 3.5 GeV (HT2) in a single tower of the BEMC. Around 2.4 million HT1 events and 1.7 million HT2 events were used for the results presented in this paper.

Electron identification was carried out by combining ionization energy loss in the TPC with energy deposition in the EMC and shower profile in the SMD. The measurement of the ionization energy loss, $dE/dx$, for charged tracks in the TPC gas is used to identify electrons in the first stage. Requiring the $dE/dx$ values of the selected tracks to be near the expected electron band in the region $p_T > 2.0$ GeV/c rejects a significant fraction of the hadron background. After extrapolating the TPC tracks to the BEMC, we require the ratio $p/E$ to be less than 1.5 using the momentum information from the TPC, $p$, and the tower energy information from the BEMC, $E$. Electrons will deposit almost all of their energy in the BEMC while this is not true for hadrons. Further hadron rejection is provided by the shower maximum detector (SMD), which allows us to cut on the shower size with high spatial resolution. We require the profile of the electro-magnetic shower to be within the expectation for electrons. Combining the power of TPC and BEMC, we can achieve an inclusive electron sample with purity $> 98\%$ in the $p_T$ region up to 6.5 GeV/c. More detailed descriptions of the electron reconstruction techniques can be found in References.\(^{6,22}\)

The dominant photonic electron background is from photon conversions and
\(\pi^0, \eta\) Dalitz decays, whose \(e^+e^-\) pairs have small invariant masses. We combine the electron candidates with tracks passing a very loose cut on \(dE/dx\) around the electron band. The invariant mass distribution of \(e^+e^-\) pairs (OppSign) is depicted by the grey filled area in panel (a) of Fig. 3. The OppSign contains the true photonic background as well as the combinatorial background, where non-photonic electrons may be falsely identified as photonic electrons. The combinatorial background, which is small in \(p+p\) collisions, can be estimated by calculating the invariant mass of same-sign electron pairs (SameSign) shown as red solid line in panel (a) of Fig. 3. A cut of mass < 0.1 GeV/\(c^2\) rejects most of photonic background. Panel (b) of Fig. 3 shows the ratio of inclusive electron to photonic background as a function of \(p_T\). The bars (boxes) on the data indicate the size of statistical (systematic) errors. A significant excess of electrons with respect to the background has been observed, where the excess electrons are mostly from heavy quark semi-leptonic decays. In RUN V there was a larger amount of material producing photon conversions in the STAR experimental configuration. This led to inclusive electron to photonic background ratios from RUN V systematically lower than those from RUN III (IV).6

In order to extract the angular correlation between non-photonic electrons and charged hadrons, we start with the semi-inclusive electron sample. We remove the OppSign sample after the mass cut from the inclusive electron sample. The remaining electrons form the "semi-inclusive" electron sample. The relationship of these samples is: semi-inc = inc - OppSign with the mass cut = inc - (reco-pho + combinatorics) = inc - (pho - not-reco-pho + combinatorics) = non-pho + not-reco-pho - combinatorics. Therefore the signal can be obtained by the equation: \(\Delta \varphi_{\text{non-pho}} = \Delta \varphi_{\text{semi-inc}} - \Delta \varphi_{\text{not-reco-pho}} + \Delta \varphi_{\text{combinatorics}}\). \(\Delta \varphi_{\text{not-reco-pho}}\) can be calculated using \(\Delta \varphi_{\text{reco-pho}}\) by an efficiency correction after removing the photonic partner of the reconstructed-photonic electron. The reason to remove the photonic partner is that for the reconstructed-photonic electron the photonic partner is found while for not-reconstructed-photonic electron the partner is missing. The resulting e-h correlations for reconstructed photonic electrons and not reconstructed photonic electrons cannot be related to each other by an efficiency correction factor alone. Therefore \(\Delta \varphi_{\text{not-reco-pho}}\) can be obtained by the equation:
$\Delta \varphi_{\text{not-reco-pho}} = (1/\varepsilon - 1)\Delta \varphi_{\text{reco-pho-no-partner}}$, where $\varepsilon$ is the photonic electron reconstruction efficiency and $\Delta \varphi_{\text{reco-pho-no-partner}}$ means reconstructed photonic electron azimuthal correlations with charged hadrons after removing the photonic partners. The corresponding efficiency can be calculated from simulations and is $\sim 70\%$.

4. Results and Discussions

Fig. 4 shows the $\Delta \varphi_{\text{non-pho}}$ distributions and the comparison to PYTHIA simulations for four electron trigger cuts with associated hadron $p_T(\text{assoc}) > 0.3$ GeV/c. The data are shown as dots, the blue dashed curves and the red dotted curves are from PYTHIA simulations for $B$ decays and for $D$ decays, respectively. We use PYTHIA curves to fit the data points with the $B$ contribution as a parameter in the fit function: $\Delta \varphi_{\text{exp}} = R \times \Delta \varphi_B + (1-R) \times \Delta \varphi_D$, where $R$ is the $B/(B+D)$ ratio. The fits are shown as green solid curves in Fig. 4. The fit results are consistent within statistical errors when we vary the fit range in $\Delta \varphi$ from $\pm 1$ to $\pm \pi$ as shown in Fig. 5. As a cross check, we fixed the $B/(B+D)$ ratio to see how the fit $\chi^2$ changes. Fig. 6 shows the fit $\chi^2$ as a function of the $B/(B+D)$ ratio with the fit range in $\Delta \varphi$ from $-1.5$ to $1.5$ for two trigger $p_T$ cuts. The $\chi^2$ is sensitive to the $B/(B+D)$ ratio, and so is it for other trigger $p_T$ cuts and for other fit ranges. As a systematic check, we allowed an overall normalization factor in the fit function to float. It gives a normalization factor close to unity, and consistent $B/(B+D)$ ratios.

The $B$ semi-leptonic decay contribution to non-photonic electrons as a function of $p_T$ is shown in Fig. 7. The bars show the size of statistical errors. The grey band indicates the data uncertainties including statistical errors, and systematic uncertainties introduced by photonic electron reconstruction efficiency (dominant), different fit ranges and different fit functions. The blue solid curves show the range of relative bottom contribution from the Fixed Order Next-to-Leading Log (FONLL) calculations. The dashed line is the $B/(B+D)$ ratio in FONLL used for the default non-photonic electron $R_{AA}$ calculation. The preliminary STAR data are consistent with the FONLL calculation. Taking the observed non-photonic electron suppression in central Au+Au collisions at RHIC together with the measured $B/(B+D)$ ratio in p+p collisions suggests that $B$ mesons may be suppressed in dense medium. A calculation from Adil and Vitev predicts suppression of $B$...
mesons comparable to that of $D$ mesons at transverse momentum as low as $p_T \sim 10 \text{ GeV/c}$.

5. Conclusion

In conclusion, correlations of non-photonic electrons with charged hadrons are studied using the PYTHIA model in 200 GeV $p+p$ collisions. The measurement of azimuthal correlations between non-photonic electrons and charged hadrons in $p+p$ collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$ from STAR has been presented. The experimental results are compared with PYTHIA simulations to measure the relative $B$ contribution to non-photonic electrons. Within the present statistical and systematic errors, the preliminary data analysis based on PYTHIA model indicates at $p_T \sim 4.0 - 6.0 \text{ GeV/c}$ the measured $B$ contribution to non-photonic electrons is comparable to the $D$ contribution and that the measured $B/(B+D)$ ratios are consistent with the FONLL theoretical calculation. Together with the observed suppression of non-photonic electrons in central Au+Au collisions, the measured $B/(B+D)$ ratios imply that the bottom quark may be suppressed in central Au+Au collisions at RHIC.

This work is partially supported by NSFC under the Grant No. 10575042, 10610285.

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$3.5 < p_T^{(trig)} < 4.5$ GeV/c

Fit range: -1.5,1.5
$4.5 < p_T^{\text{(trig)}} < 5.5$ GeV/c

Fit range: $-1.5, 1.5$