e^+e^- Pair Production at Very Low Transverse Momentum in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV and U+U Collisions at $\sqrt{s_{NN}} = 193$ GeV at STAR

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We present the first measurements of e^+e^- pair production at very low transverse momentum ($p_T < 0.15$ GeV/c) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and U + U collisions at $\sqrt{s_{NN}} = 193$ GeV using the STAR detector at the Relativistic Heavy Ion Collider. A significant excess, with respect to known hadronic contributions, is observed in 60-80% central heavy-ion collisions over the whole M_{ee} range. Remarkably, the excess almost entirely happens below $p_T \approx 0.15$ GeV/c, and can not be explained by a theoretical model calculation incorporating in-medium broadened ρ spectral function. Moreover, the observed excess yield has no significant centrality dependence. In addition, the steepness of p_T^2 distribution exhibits mild invariant mass and collision species dependence.

Keywords: Very low p_T e^+e^- pair; photon interactions; peripheral heavy-ion collisions.

1. Introduction

Dileptons play an essential role in studying the hot, dense, and strongly interacting matter, created in Relativistic Heavy-Ion Collider (RHIC),¹ because they are generated at all stages of the collisions and escape with minimum interaction with strongly interacting medium. Previous dilepton measurements at Super Proton Synchrotron (SPS)^{2,3} and RHIC⁴⁻⁶ showed a significant enhancement with respect to the known hadronic sources (cocktail) in the mass region below ~ 700 MeV/ c^2 , which can be consistently described by an in-medium broadened ρ model calculation.⁷ The measurements of NA60 collaboration in the mass region $M_\phi < M_\psi < M_{J/\psi}$ also provided the first indication of thermal dileptons from a partonic source,³ which is expected to become significant at top RHIC energy.⁸

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On the other hand, dileptons can also be produced via photon interactions.⁹ The latter, including photon-photon and photonuclear processes, are conventionally studied in Ultra-Peripheral Collisions (UPC) with impact parameter larger than twice the nuclear radius.^{10–16} Dileptons produced by the photon-photon and coherent photonuclear processes have a distinct feature, their production peaks at very low transverse momenta (p_T). However, the invariant mass distributions of l^+l^- pairs from these two processes are different. The mass distribution concentrate on the corresponding vector meson from photonuclear production and is continuous from photon-photon interactions. Recently, the ALICE and STAR collaborations reported a significant J/ψ excess yield at very low p_T in peripheral heavy-ion collisions.^{17,18} This remarkable excess can not be explained by existing transport models incorporating only hot and cold medium effects,^{19,20} however, could be qualitatively explained by coherent photonuclear production mechanism.^{17,21} Since the nucleus is broken in peripheral heavy-ion collisions, it is non-trivial to incorporate the coherence conditions for the low p_T J/ψ . For instance, how are the photon emitter and target modified and how is the coupling between the photon and the gluon field affected by the hadronic interaction? Nevertheless, if indeed, the coherent photonuclear production were the underlying mechanism for the observed J/ψ excess, the coherent photon-photon production would be there and contribute to the e^+e^- pair production. The measurements of mass differential e^+e^- pair production at very low p_T for different collision systems and energies thus become necessary to verify and further constrain the photon interactions in hadronic collisions.

In these proceedings, we report centrality and invariant mass dependences of inclusive e^+e^- pair production at $p_T < 0.15$ GeV/ c in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and U + U collisions at $\sqrt{s_{NN}} = 193$ GeV. The excess e^+e^- yields with respect to the hadronic sources are also presented as a function of centrality and p_T^2 . A model calculation based on an in-medium broadened ρ spectral function is compared with the measurements.

2. Experiment and analysis

The Au + Au data used for this analysis were collected by the STAR experiment during the 2010 and 2011 RHIC runs, while the U + U data were collected in 2012. A total of $\sim 7.2 \times 10^8$ Au + Au and $\sim 2.7 \times 10^8$ U + U minimum-bias (0-80%) events are used. Two sub-detectors, Time Projection Chamber (TPC) and Time of Flight (TOF), are used to identify the electrons. The TPC provides tracking and ionization energy loss (dE/dx) for the particle identification. The TOF measures velocity of the particles and enables us to reject the slow hadrons from electrons. By combining the TPC and TOF, an electron purity of $\sim 95\%$, integrated over the measured p_T region, can be achieved in Au + Au and U + U minimum-bias collisions.

The foreground is reconstructed by combining identified electrons and positrons in the same event. The like-sign technique, combining the same charge sign electrons

into pairs in the same event, is used to account for the combinatorial and correlated backgrounds. Due to dead areas of the detector and the different bending directions of positively and negatively charged particle tracks in the transverse plane, the unlike-sign and like-sign pairs have different acceptances. A mixed-event technique is used to correct for the acceptance difference as a function of pair invariant mass (M_{ee}) and p_T ⁴. After the background removal, the raw spectra are then corrected on efficiency. For measurements in Au+Au collisions, the efficiency-corrected spectra are obtained separately for 2010 and 2011 data sets, and then combined using the statistical errors as weights.

3. Results and discussion

Figure 1 shows the centrality dependence of efficiency-corrected e^+e^- invariant mass spectra in Au + Au and U + U collisions for pair $p_T < 0.15$ GeV/c. These spectra are not corrected on the STAR acceptance ($p_T^e > 0.2$ GeV/c, $|\eta^e| < 1$, and $|y_{ee}| < 1$). The enhancement factors (data/cocktail), are found to be most significant in 60-80% collisions. The enhancement gets less and less significant as one goes from peripheral to semi-peripheral (40-60%) and to semi-central (10-40%) collisions.

Fig. 1. Centrality dependence of e^+e^- invariant mass spectrum within the STAR acceptance ($p_T^e > 0.2$ GeV/c, $|\eta^e| < 1$, and $|y_{ee}| < 1$) from Au + Au collisions (Left) and U + U collisions (Right) for e^+e^- pair $p_T < 0.15$ GeV/c. The mass spectra are compared to hadronic cocktail simulations shown as solid lines. The vertical bars on data points depict the statistical uncertainties, while the systematic uncertainties are shown as grey boxes. The shaded bands on the solid lines depict the systematic uncertainties on the cocktail.

The p_T distributions of e^+e^- pairs in two mass regions (0.4-0.76 and 1.2-2.6 GeV/c²) are shown in Fig. 2 for 60-80% Au+Au and U+U collisions, where the enhancement factors are the largest. Interestingly, the observed excess is found to concentrate below $p_T \approx 0.15$ GeV/c, while the hadronic cocktail, also shown in the figure, can describe the data for $p_T > 0.15$ GeV/c in both mass regions of Au + Au and U + U collisions.

Fig. 2. The e^+e^- pair p_T distributions within STAR acceptance for different mass regions in 60-80% Au+Au (Left) and U+U (Right) collisions compared to cocktail simulations (solid curves).

The invariant mass distributions for excess pairs with respect to hadronic cocktails for $p_T < 0.15$ GeV/c are shown in the left panel of Fig. 3 for 60-80% collisions. Theoretical calculation based on in-medium broadening of the ρ -meson spectral function⁷ is also shown for comparison. While this broadened ρ model calculation has successfully explained the SPS³ and RHIC data⁴⁻⁶ in large p_T bins, it cannot describe the enhancement observed at very low p_T in peripheral heavy-ion collisions. The integrated excess yields over three mass regions (0.4-0.76, 0.76-1.2, and 1.2-2.6 GeV/c²) are shown in the right panel of Fig. 3 as a function of centrality. Compared to the hadronic cocktail also shown in the panel, the excess yields exhibit a much weaker dependence on the collision centrality, suggesting that hadronic interactions are unlikely to be the source of the excess e^+e^- pairs. The decreasing trend of enhancement factor (data/cocktail), as shown in Fig. 1, is mainly caused by the increasing contribution from hadronic cocktail.

To further explore the low p_T excess, the STAR acceptance-corrected p_T^2 distributions of the excess yields for 60-80% collisions are shown in the left four panels of Figs. 4. The STAR acceptance factor is estimated as the yield ratio of reconstructed e^+e^- pairs in the STAR detector over the input e^+e^- pairs with $|y_{ee}| < 1$, which depends strongly on the kinematics of underlying production mechanisms. For these preliminary p_T^2 results, the hadronic two-body decay toy Monte Carlo simulation is used to generate the input e^+e^- pairs, and the acceptance factor has pretty mild p_T^2 dependence for $p_T^2 < 0.08$ (GeV/c)², especially for the high mass region ($M_{ee} > 0.76$ GeV/c²). An exponential function ($Ae^{-Bp_T^2}$) is used to determine the steepness of the p_T^2 distributions. The first data points are excluded from the fit due to their sudden drop, and the large p_T^2 data points with statistical errors greater than 100% are also excluded from the fit. the slope parameters (B) from U + U collisions are systematically larger than those from Au + Au collisions, although they are only within 2.2σ , 1.8σ , and 1.4σ away from each other in the three investigated mass regions (0.4-0.76, 0.76-1.2, and 1.2-2.6 GeV/c²), respectively. Furthermore, the slope

Fig. 3. (Left) The low p_T ($p_T < 0.15$ GeV/c) e^+e^- excess mass spectra within STAR acceptance in 60-80% Au+Au and U+U collisions, compared with a broadened ρ model calculation. (Right) The centrality dependence of integrated excess yields for three mass regions in Au + Au and U + U collisions. The centrality dependence of hadronic cocktail yields in the mass region of 0.76-1.2 GeV/c² is also shown for comparison.

Fig. 4. (Left) The p_T^2 distributions of excess yields in the mass regions of 0.4-0.76 and 1.2-2.6 GeV/c² in 60-80% Au+Au and U+U collisions. (Right) The corresponding slope parameters of p_T^2 distributions in Au+Au and U+U collisions.

parameters in both U + U and Au + Au collisions decrease slightly as the pair mass increases. The slope differences between 0.4-0.76 and 1.2-2.6 GeV/c² mass ranges are 1.7σ and 1.0σ for Au + Au and U + U collisions, respectively.

4. Summary and outlook

We report STAR measurements of e^+e^- pair production at $p_T < 0.15$ GeV/c in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and U + U collisions at $\sqrt{s_{NN}} = 193$ GeV. The e^+e^- continuum in a wide mass region is significantly enhanced with respect to hadronic cocktails in 60-80% centrality for both collision species. Remarkably, the entire observed excess is found below $p_T \approx 0.15$ GeV/c and the excess yield exhibits no significant centrality dependence. The p_T^2 distributions of excess yields

in 60-80% Au + Au and U + U collisions are also reported, and the slope parameters of these distributions show interesting but mild invariant mass and collision species dependences. The observed excess for $p_T < 0.15$ GeV/ c is very likely to be linked to the photon interactions, especially photon-photon production, in hadronic heavy-ion collisions. STAR will collect data from isobaric collisions ($^{96}\text{Ru}+^{96}\text{Ru}$ vs. $^{96}\text{Zr}+^{96}\text{Zr}$) in 2018. The isobaric collisions data will help quantitatively disentangle photon interaction contributions for the observed excess, since the photon flux from photon-photon and photonuclear interactions scales $\propto Z^4$ (nuclear charge) and $\propto Z^2$, respectively.

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