PROCEEDINGS OF SCIENCE

Low-p_T e^+e^- pair production in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV and U+U collisions at $\sqrt{s_{\rm NN}}$ = 193 GeV at STAR

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We present the first measurement of e^+e^- pair production at p_T < 0.15 GeV/c in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV and U+U collisions at $\sqrt{s_{\rm NN}}$= 193 GeV with the STAR experiment. Significant enhancement with respect to known hadronic contributions is observed in the 40-80% centrality class of these collisions. The yield excess peaks distinctly at low p_T with a width ($\sqrt{\langle p_T^2\rangle}$) between 40 and 60 MeV/$c$. Model calculations of photon-photon interaction describe the observed excess yields but fail to reproduce the p_T^2 distributions.

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1. Introduction

Dileptons play an essential role in studying the hot, dense, and strongly interacting matter, created at Relativistic Heavy Ion Collider (RHIC) [1], because they are produced during the entire evolution of the collisions and escape with minimum interaction with strongly interacting matter. Dileptons can also be produced via photon-photon and photonuclear interactions [2], which are known to peak distinctly at very low transverse momenta (p_T). The photon interaction processes are traditionally studied in ultra-peripheral collisions (UPC) with impact parameters larger than twice the nuclear radius [3–9]. Recently, ALICE and STAR collaborations reported a significant J/ψ excess yield at very low p_T in peripheral heavy-ion collisions [10, 11], which could be qualitatively explained by coherent photonuclear production mechanism [10–12]. The explanation implies that the photon-photon interactions would also occur and contribute to e^+e^- pair production. 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 such collisions, the photon-photon interactions could be further used to probe the electromagnetic properties of QGP, e.g., the possible existence of residual magnetic fields [13].

In these proceedings, we report on centrality and invariant mass dependence of inclusive e^+e^- pair production at $p_T < 0.15$ GeV/c in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV and U+U collisions at $\sqrt{s_{\rm NN}}$ = 193 GeV [14]. The observed excess of e^+e^- yields with respect to the known hadronic sources are presented as a function of centrality and p_T^2. Model calculations that include an in-medium modified ρ spectral function, QGP radiation [15], photon-photon processes [16–18], and coherent photonuclear interactions [12] are compared with the measurements.

2. Experiment and analysis

STAR [19] has collected 7.2×10^8 Au+Au and 2.7×10^8 U+U minimum-bias (0-80%) events during the 2010, 2011, and 2012 RHIC runs. The Time Projection Chamber (TPC) [20] and Time-of-Flight (TOF) [21] detectors are used to identify the electrons and positrons. The TPC is used for both tracking and particle identification via specific energy loss (dE/dx) measurement while the TOF measures velocity of the particles and enables us to reject the hadrons from electrons. By combining the TPC and TOF, the electron purity of $\sim$95% for $p_T^e > 0.2$ GeV/c can be achieved in Au+Au and U+U minimum-bias collisions.

The unlike-sign pair distribution (signal and background) is generated by combining electron and positron candidates in the same event. The like-sign technique, combining the same charge sign electrons into pairs in the same event, is used to estimate 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 pair acceptances are not identical. A mixed-event technique is used to correct for the acceptance difference as a function of pair invariant mass (M_{ee}) and p_T. The raw signal, obtained by subtracting the background from the unlike-sign distribution, is corrected for the detector inefficiency.

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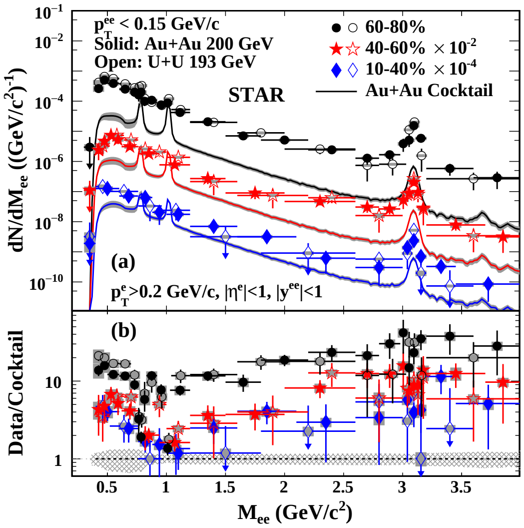

Figure 1: (Color online) (a) The centrality dependence of e^+e^- invariant mass spectra from Au+Au and U+U collisions for pair $p_T < 0.15$ GeV/c. The vertical bars on data points depict the statistical uncertainties while the systematic uncertainties are shown as grey boxes. (b) The corresponding ratios of data over cocktail.

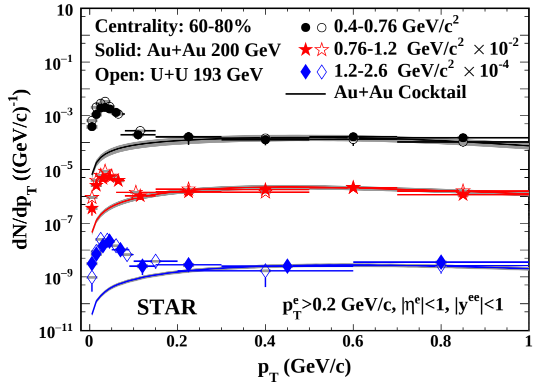

Figure 2: (Color online) The e^+e^- pair p_T distributions for different mass regions in 60-80% Au+Au and U+U collisions compared to cocktails. The systematic uncertainties of the data are shown as gray boxes. The gray bands depict the systematic uncertainties of the cocktails.

3. Results and discussion

Figure 1(a) shows the centrality dependence of efficiency-corrected e^+e^- invariant mass spectra within the STAR acceptance ($p_T^e > 0.2$ GeV/c, $|\eta^e| < 1$, and $|y_{ee}| < 1$) in Au+Au and U+U collisions for pair $p_T < 0.15$ GeV/c while the corresponding enhancement factors (data/cocktail) are shown in Fig. 1(b). A significant enhancement with respect to known hadronic sources (cocktail) is observed for the whole measured mass region in the most peripheral (60-80%) collisions. Meanwhile, the enhancement factors get less significant as one goes from peripheral to semi-peripheral (40-60%) and to semi-central (10-40%) collisions.

To gain more insight into the significant low-p_T e^+e^- excess, the e^+e^- pair p_T distributions in 60-80% Au+Au and U+U collisions with the most significant enhancement factors are shown in Fig. 2 for three mass regions (0.4-0.76, 0.76-1.2 and 1.2-2.6 GeV/c^2). Interestingly, the observed excess is found to concentrate below $p_T \approx 0.15$ GeV/c, while the hadronic cocktail can describe the data for $p_T > 0.15$ GeV/c in all three mass regions.

The excess in the invariant mass spectra (data - cocktail) for $p_T < 0.15$ GeV/c is shown in Fig. 3(a) and 3(b) for 60-80% and 40-60% centralities, respectively. Theoretical calculations incorporating an in-medium broadened ρ spectral function and QGP radiation [15], which consistently describe SPS [22, 23] and RHIC [24–26] data over a wide p_T region, cannot describe the enhancement observed at very low p_T in 40-80% centrality heavy-ion collisions. The integrated excess yields show much less significant centrality dependence than those from hadronic cocktail, as depicted in Fig. 3(c). These two phenomena suggest that hadronic interactions only are unlikely to be the source of the excess e^+e^- pairs. In order to investigate the origin of the low-p_T e^+e^- enhancement, two types of theoretical models [12, 16–18] based on equivalent photon approximation (EPA) method [27], are used to account for the photon interactions in Au+Au collisions and compared to our results. The main difference of these models is that the model by Zha *et al.* [16] takes into account the e^+e^- production within the geometrical radius of the nucleus. Based on model calculations, the contributions from photonuclear produced ρ and ϕ vector mesons are found to be negligible while photon-photon interactions become dominant sources. The photon-photon contributions from Ref. [16] describe the 60-80% centrality data fairly well (χ^2/NDF = 19/15, where NDF is the number of degrees of freedom, in 0.4-2.6 GeV/c^2), while the results from STARlight underestimate that data (χ^2/NDF = 32/15). In 40-60% centrality, both models can describe the data within the large statistical uncertainties.

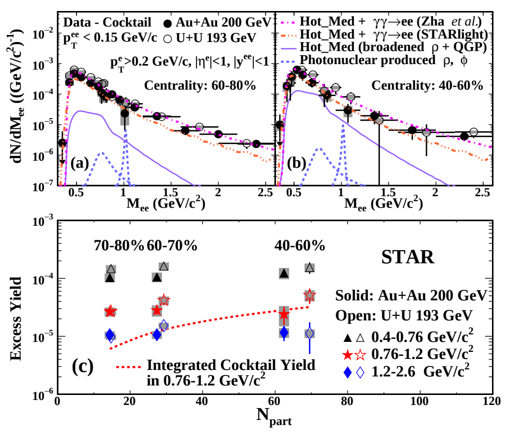

Figure 3: (Color online) The low-p_T e^+e^- excess mass spectra (data − cocktail) in (a) 60-80%, (b) 40-60% for Au+Au and U+U collisions, compared with model calculations for Au+Au collisions in the corresponding centrality bins. (c) The centrality dependence of integrated excess and hadronic cocktail yields in both collisions.

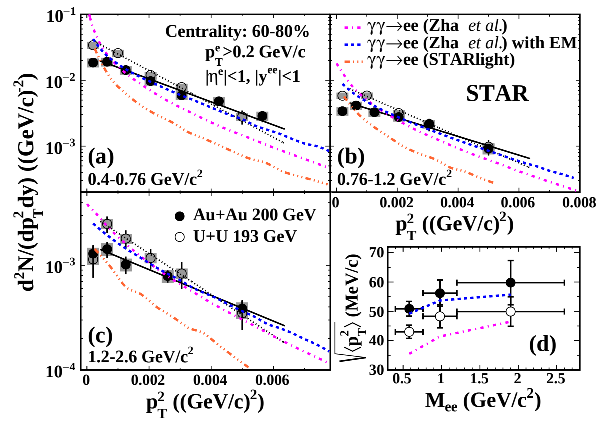

Figure 4: (Color online) The p_T^2 distributions of excess yields within the STAR acceptance in the mass regions of (a) 0.4-0.76, (b) 0.76-1.2, and (c) 1.2-2.6 GeV/c^2 in 60-80% collisions. The solid and dotted lines are exponential fits to the data. (d) The corresponding $\sqrt{\langle p_T^2 \rangle}$ of excess yields. The vertical bars on data points are the combined statistical and systematic uncertainties.

The p_T^2 ($\approx -t$, the squared four-momentum transfer) distributions of the excess yields within the STAR acceptance for 60-80% central Au+Au and U+U are shown in Fig. 4(a)-(c) for three different mass regions. The calculations from [16], which successfully describe the observed excess yields, fail to reproduce the p_T^2 spectra. The calculation from STARlight is lower than that from [16] but has a similar p_T shape. The $\sqrt{\langle p_T^2 \rangle}$ characterizing the p_T broadening, is calculated for both data and aforementioned photon-photon models. In data, a fit of the exponential function ($Ae^{-p_T^2/B^2}$) is performed by excluding the first data points and extrapolated to the unmeasured higher p_T^2 region to account for the missing contribution. The uncorrelated systematic uncertainties arising from the raw signal extraction are added in quadrature to the statistical errors, and the resulting total uncertainties are included in the fits. The invariant mass dependence of the extracted $\sqrt{\langle p_T^2 \rangle}$ from Au+Au collisions are systematically larger than from U+U collisions and both increase slightly with increasing pair mass, as shown in Fig. 4(d). However, the systematic trends are marginally at the level of 1.0-2.3σ. The values of the $\sqrt{\langle p_T^2 \rangle}$ from Au+Au data are about 6.1σ, 3.3σ, and 1.8σ above models [16,18] in the 0.4-0.76, 0.76-1.2 and 1.2-2.6 GeV/c^2 mass regions, respectively. The general agreement between the data and model calculations for p_T and invariant mass distributions of l^+l^- pairs produced by photon-photon interactions in UPC [4,6,8] are suggestive of possible other origins of the p_T broadening in peripheral collisions as shown in Fig. 4(d), e.g. the residual magnetic field. To illustrate the sensitivity the $\sqrt{\langle p_T^2 \rangle}$ measurement may have to a postulated magnetic field trapped in a conducting QGP [13], we assume each and every pair member generated by model [16] traverses 1 fm through a constant magnetic field of 10^{14} T perpendicular to the beam line ($eBL \approx 30$ MeV/c, where B is 10^{14} T, L is 1 fm) [28,29]. The corresponding p_T^2 distributions of e^+e^- pairs are found to describe data much better as compared to the same model without incorporating the magnetic field effect. Both models [16,18] used in this proceedings assume there is no impact-parameter dependence of the e^+e^- pair p_T distribution from initial photon-photon interaction, however, the latest model calculation [30] shows strong impact-parameter dependence of the cross section and p_T spectra of e^+e^- pair production from initial photon-photon interaction. If such a dependence exists, then it will have to be taken into account in the future analyses before extracting the possible medium effects.

4. Summary

In summary, we report measurements of e^+e^- pair production with $p_T < 0.15$ GeV/c in non-central Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV and U+U collisions at $\sqrt{s_{\mathrm{NN}}}$ = 193 GeV. The e^+e^- yields are significantly enhanced over a wide mass range with respect to the hadronic cocktails in the 40-80% collisions for both collision species. The entire observed excess is found to be below $p_T \approx 0.15$ GeV/c and the excess yield exhibits a much weaker centrality dependence as compared to the expectation for hadronic production. The p_T^2 distributions of the excess yields in the three mass regions in 60-80% Au+Au and U+U collisions are also reported. The $\sqrt{\langle p_T^2 \rangle}$ of these distributions show weak invariant mass and collision species dependence. Based on comparisons with model calculations, the observed excess for $p_T < 0.15$ GeV/c is very likely linked to photon-photon production and represents the first observation showing the magnitude of two-photon interactions in heavy-ion collisions with hadronic overlap. In addition, model calculations of photon-photon interactions describe the observed excess yields but fail to reproduce the p_T^2 distributions. Compared to the model without the magnetic field effect, the same model calculations incorporating magnetic field effect are found to describe the p_T^2 distributions much better.

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