Abstract. The dilepton mass spectrum consists of light vector meson decays in addition to decays from other hadronic and photonic sources. Thermal radiation and modification of light vector meson masses via chiral symmetry restoration may provide signals above known hadronic sources. The newly published PHENIX $\sqrt{s_{NN}} = 200$ GeV Au+Au dielectron continuum results are discussed. The PHENIX $\sqrt{s_{NN}} = 200$ GeV Cu+Cu results in centrality classes are shown, providing increased sensitivity to centrality dependent trends.

1. Introduction

Relativistic heavy ion collisions at RHIC produce a strongly-coupled medium, called quark gluon plasma (QGP) [1]. This state of matter is characterized by its high energy density and rapid thermalization time, its anisotropic or "elliptic" flow [2] and the energy loss experienced by light [3] and heavy quarks [4] in the medium. Dileptons are electro-magnetic probes of this matter and are produced throughout the entire time evolution of the collision system. They have no color charge and, therefore, no final state interactions, providing a clean measurement of the earliest stages of the collision.

The physics signals within the dilepton mass spectra include virtual photon emission, hadronic decays and semi-leptonic heavy flavor decays. Alterations of the mass spectrum due to interactions in the medium allow us to study additional properties of this matter. Sources for this modification include thermal radiation [5], chiral symmetry restoration producing a continuum enhancement due to broadening [6] and/or shifting [7] of the light vector meson masses, correlated charm modification due to suppression of high $p_T$ non-photonic single electrons [4], and $J/\psi$ suppression [8]. This proceeding focuses on the modifications in the low mass region, masses below that of the $\phi$, primarily due to thermal radiation and enhancement via alteration of the light vector meson masses.

Earlier results from multiple SPS experiments have shown modification of the $\rho$ meson in dimuon measurements [9], [10]. NA60's In-In results, in particular, strongly supported the mass broadening scenario over the purely dropping mass scenario; however the dropping mass scenario may still be a possibility when combined with broadening [11]. These proceedings highlight advancements in this subject from the PHENIX dielectron continuum results, including the Au+Au and p+p results recently accepted by Phys. Rev. C [12] and new Cu+Cu preliminary results in centrality bins.

2. Analysis

The PHENIX central arms, shown in Figure 1, track particles in the drift chamber (DC) and first pad chamber (PC1), providing a momentum resolution of $(0.7p^{1/2})\%$ [13]. Electron tracks
are identified by a Cherenkov ring in the ring imaging cherenkov detector (RICH) [14] and an electromagnetic shower in the electro-magnetic calorimeters [15]. The centrality, a measure of the collision’s nuclear overlap, is determined via coincidences between the beam beam counters and the zero degree calorimeter [16]. Once all electrons within an event are identified all possible dielectron pairs are made including like-sign and unlike-sign pairs. As a result many background pairs are generated. Removing background pairs is the crux of this analysis.

Two types of background pairs can be directly identified and rejected. These are pairs due to overlaps within the RICH and conversion pairs. Overlapping pairs within the RICH consist of pairs where the Cherenkov rings of the two electrons are not fully distinct. This results in a non-physical excess in both the like- and unlike-sign pair spectra which is removed by requiring a separation of twice the nominal ring size. Conversion pairs are opened by the central magnet’s field and can be characterized by their mass and their orientation with respect to the magnetic field. The pair’s mass is a conversion indicator because the electrons’ momenta are misreconstructed, tracking back to the collision vertex not the conversion vertex. This gives the pair a mass that is roughly proportional to the distance between the conversion point and the collision vertex. Since the location of conversion material is well known, we are able to determine a range of masses in which these false pairs lie. As a result of being opened by the magnetic field, the charges of the conversion pair are ordered and the decay plane of the pair is perpendicular to the magnetic field. A cut on the mass, charge order and opening angle orientation relative to the magnetic field allows us to remove conversion pairs.

2.1. Statistical background removal

The remaining backgrounds are removed statistically. The like-sign pairs are used as a test to ensure that all backgrounds are removed. This test is possible because the relative rates of the like-sign and unlike-sign backgrounds are well known; for many backgrounds the relative rate is one. Since the like-sign pairs contain zero physics signals, if we describe all of the like-sign pairs as a combination of background sources then we can remove all backgrounds in the unlike-sign pairs.

The largest source of background in heavy ion collisions arises from combinatorial pairs. Combinatorial background increases as the square of the multiplicity, or number of electrons per event. We are able to determine the shape of the combinatorial background as a function of mass and pair transverse momentum, $p_T$, by creating non-physical pairings across events. The normalization of the combinatorial background is determined using the like-sign pairs in a region where the combinatorial background dominates. A ratio of all like-sign pairs over the like-sign combinatorial shows that there exist remaining correlated backgrounds at the lowest masses.

These correlated backgrounds are due to two sources, cross pairs and jet pairs. Cross pairs are generated by decays that produce multiple lepton pairs. An example of this is a dalitz decay
Figure 2. The dielectron counts per event in the p+p (left), minimum bias (MB) Au+Au (center) and 0 − 10% Cu+Cu (right) systems. The top row contains like-sign pairs and backgrounds; the bottom row contains unlike-sign pairs and backgrounds. All like(unlike)-sign pairs are shown in black circles, combinatorial background pairs are shown in red, correlated pairs (all pairs with the combinatorial background removed) are shown in blue, cross pairs are shown as a black histogram, and jet pairs are in green.

with a photon conversion where four unlike-sign pairs are created and two like-sign pairs are created. One of the unlike-sign pairs is kept as part of our standard signal as a dalitz pair included in our cocktail comparison. Another unlike-sign pair will be identified and removed as a photon conversion. This leaves two additional unlike-sign pairs and two like-sign pairs all of which are correlated through the original pion. In this example we see something that is observed generally for cross pair backgrounds. Like-sign pairs are produced at the same rate as the additional unlike-sign pairs. We are able to simulate this source of background using EXODUS, a PHENIX-made event generator.

Jet pairs are produced by dalitz decays of multiple pions within a jet, the resulting like- and unlike-sign electron pairs are correlated by the jet. This background source is simulated with PYTHIA. Here we see again that the like- and unlike-sign pairs due to this background are produced at the same rate. In the heavy ion case, the away-side (dφ > 90°) component of the jet background is reduced to account for jet modification [17], [18].

The like-sign spectra are used to set the normalization factors of the three different backgrounds. All of the like-sign pairs are well described by the three backgrounds; example spectra for each system are shown in Figure 2. In the unlike-sign spectra the backgrounds can then be removed considering the like-sign background rates. This results in the relevant unlike-sign signal also in Figure 2. The background subtracted unlike-sign spectra are corrected for efficiency and inactive regions up to the ideal PHENIX aperture and are compared to the cocktail of known sources.

2.2. Cocktail Generation
The cocktail of known sources contains a hadronic component and a open heavy flavor component. The hadronic component of the cocktail consists of the direct and dalitz hadronic decays and is modeled using EXODUS. The measured pion pT spectra [19], [20], [22], [21] [23] is characterized by a modified Hagedorn function, $E \frac{d^2\sigma}{dpT} = A \left( e^{-(p_T + bp_T)^2} + \frac{p_T}{p_0} \right)^{-n}$, whose
parameters \((A, a, b, p_0, n)\) are input into EXODUS. Other mesons are extrapolated from this momentum information using \(m_T\) scaling \((p_T \rightarrow \sqrt{p_T^2 + m_{\text{meson}}^2 - m_{\text{meson}}^2})\). In cases where the mesons’ \(p_T\) distributions are measured the observed distributions are used [22-29].

The open heavy flavor component of the cocktail stems from two open charm (or open bottom) mesons that both semi-leptonically decay. The final state electron-positron pair, one from each meson, are correlated by the original \(c\bar{c}\) (or \(b\bar{b}\)) production. These sources are simulated with PYTHIA. In the \(p+p\) case, we are able to measure the charm and bottom cross sections by subtracting the hadronic sources estimated with EXODUS and fitting the remaining pairs to the generated PYTHIA shapes. This results in the charm cross section, \(\sigma_{c\bar{c}} = 544 \pm 39 \text{ (stat)} \pm 142 \text{ (sys)} \pm 200 \text{ (model)} \mu b\), and bottom cross section, \(\sigma_{b\bar{b}} = 3.9 \pm 2.5 \text{ (stat)} \pm 3 \text{ (sys)} \mu b\) [32]. The charm cross section agrees with the more precise PHENIX non-photonic single electron measurement’s result, \(567 \pm 57 \text{ (stat)} \pm 193 \text{ (sys)} \mu b\) [33]. In \(Au+Au\) and \(Cu+Cu\), the \(p+p\) heavy flavor components are scaled by the average number of binary collisions, \(N_{\text{coll}}\). The Drell Yan component is similarly generated in PYTHIA, included in the \(p+p\) fit, and scaled by \(N_{\text{coll}}\) for the heavy ion results.

3. Results

![Figure 3](image_url)

**Figure 3.** The dielectron mass spectra in MB, 0 – 10%, 10 – 20%, 20 – 40%, 40 – 60%, 60 – 92% \(Au+Au\) and \(p+p\) collisions are scaled and overlaid with their respective cocktails, one with the charm component from PYTHIA (solid) and one with an uncorrelated charm contribution (dotted). The grey boxes represent the systematic errors.

The measured \(Au+Au\) and \(p+p\) dielectron mass spectra are compared to their respective cocktails in Figure 3; the \(Au+Au\) minimum bias (MB), \(Au+Au\) in centrality bins and \(p+p\)...
result are shown. The MB, 0 − 10% and 10 − 20% Au+Au spectra have an excess above the cocktail in the region above the π and below the ω masses. In the case of the MB, this excess is remarkably large, a factor of 4.7 ± 0.4(stat) ± 1.5(sys) ± 0.9(model) above the expected cocktail yield. The Au+Au excess is largest in the most central collisions and recedes as the centrality decreases. The integrated yield increases faster than the square of the average number of participating nucleons in the collision ($N_{part}^2$). This is seen in Figure 4 where the yield in the mass region 0.15 to 0.75 GeV/c$^2$ over $N_{part}^2$ increases faster than linear in $N_{part}$.

![Figure 5.](image1.png)  
**Figure 5.** The dielectron mass spectra in 0 − 10% Cu+Cu collisions overlaid with the cocktail. The yellow bars represent the systematic errors.

![Figure 6.](image2.png)  
**Figure 6.** The dielectron mass spectra in 10 − 20% Cu+Cu collisions overlaid with the cocktail. The yellow bars represent the systematic errors.

The Cu+Cu centrality data, first published here, allows us to gain insight into the onset of the excess. The Cu+Cu 0 − 10% data contains an excess in the low mass region, as shown in Figure 5. The excess is not present in the 10 − 20% data, in Figure 6, or in the more peripheral centrality bins. This is consistent with the centrality trend seen in Figures 3 and 4. The Cu+Cu results provide valuable additional information about the emergence of the enhancement. With these new results, theories should attempt to describe the enhancement as a function of centrality.

3.1. Virtual photons

The p+p and MB Au+Au mass spectra in different pair $p_T$ slices are shown in Figures 7 and 8 respectively. In the p+p case the data matches the cocktail fairly well, particularly at low $p_T$; there is a small excess at high $p_T$. In the Au+Au case there exists an excess in all $p_T$ slices with the largest portion in the low $p_T$ ranges. This leads us to consider that the Au+Au excess has two sources, one that dominates at high $p_T$ and another that dominates at low $p_T$.

One such source is direct virtual photons that convert to dielectron pairs. Virtual photons are produced by the same processes that generate real photons. A direct photon component, or thermal photon component, is described according to Equation 1 when the mass is much smaller than the $p_T$ ($m < 0.3$ GeV/c$^2$ and $p_T > 1$ GeV/c)

$$\frac{d^2N_{ee}}{dm_{ee}dp_T} \sim \frac{2\alpha}{3\pi m_{ee}} \frac{1}{dp_T} \frac{dN_{\gamma}}{dp_T} [34].$$  

The photonic component is modeled in EXODUS, filtered by the acceptance and smeared by the detector resolution. This shape is shown in Figure 9. By looking at the ratio of the excess above the cocktail divided by the modeled direct photon shape, R, we can compare the mass
shape of the excess to the direct photon shape. When $p_T$ is greater than one, as in Figure 10, $R$ is flat as a function of mass; a direct photon source models this excess. For $p_T$ less than one, $R$ is not flat, as seen in Figure 11. At low $p_T$, there is more modification than a photonic source can describe. A second source of masses modification exists in the low $p_T$ region. This is most likely due to alteration of the light vector mesons via chiral symmetry restoration. The small p+p mass excess at high $p_T$ is fully described by a direct photon component.

The p+p data is well described by the cocktail plus a thermal photon component in both the mass spectra in $p_T$ slices and $2\pi$ acceptance corrected $p_T$ spectra in mass slices. The MB Au+Au $2\pi$ acceptance corrected $p_T$ spectra in mass slices are compared to the cocktail plus the photonic component (not shown). In the high $p_T$ regions, the spectra are well described at all masses. However, there is additional yield at low $p_T$ in mass regions above 0.3 GeV/$c^2$, again indicating a second source. Thus, the $p_T$ spectra measurements provide additional evidence that the low mass excess in Au+Au is produced by two sources. Direct (i.e. thermal) photons are the dominant source of the excess in the high $p_T$ yield. There is a second modification at low $p_T$, presumably due to chiral symmetry restoration.

3.2. Temperature measurements
A detailed analysis of the photonic source in dielectrons at PHENIX is presented in the paper [34]. The MB Au+Au thermal photon measurement provides the most direct extrapolation of the initial temperature of the fireball, projecting values of 300 to 600 MeV for thermalization times of 0.6 to 0.15 fm/c respectively [33-38]. The fireball created at RHIC has “the hottest temperature ever reached in a laboratory, about 250,000 times hotter than the center of the Sun [41].”

The temperature of the fireball is not the only temperature information carried by the
dielectron spectra. To measure the effective temperature of the low $p_T$ excess, we plot the $m_T - m_0$ spectra in the mass region 0.3 to 0.75 GeV/$c^2$ corrected into the full $2\pi$ angular acceptance in Figures 12 and 13. This $m_T$ spectrum has a kink structure with a much softer component at $m_T - m_0$ below 0.6 GeV/$c^2$ and a harder trend above 0.6 GeV/$c^2$ corresponding to the two sources of the excess in this mass region.

Figure 9. The MB Au+Au mass spectra in the $p_T$ range 1 to 1.5 GeV/c overlaid with the cocktail (blue) and the direct photon shape (red). Additional cocktail components are also shown and the result of a fit (black) determining the relative size of the direct photon component.

Figure 10. The ratio of the excess, data minus cocktail, over the direct photon shape (R) as a function of mass in the $p_T$ range 1 to 1.5 GeV/c. The yellow band displays a one sigma range on the fit determining the direct photon component.

Figure 11. The ratio of the excess, data minus cocktail, over the direct photon component of an exponential form of the cocktail in the mass range 1 to 1.5 GeV/c.

Figure 12. The MB Au+Au $m_T - m_0$ spectrum in the mass range 0.3 to 0.75 GeV/$c^2$. The spectrum is fit to the sum (solid) of two exponentials (dashed and dashed-dot) plus the cocktail.

Figure 13. The MB Au+Au $m_T - m_0$ spectrum in the mass range 0.3 to 0.75 GeV/$c^2$. The spectrum is fit to the sum (solid) of an exponential (dashed), a thermal component (dashed-dot), and the cocktail.

Figure 14. The local inverse slopes of the $m_T$ spectra in Figures 12 and 13 in the regions above (blue) and below (black) 0.6 GeV/$c^2$. The results of the fits in Figures 12 and 13 are shown in red. The lines represent the local slope of the cocktail in the mass ranges above (blue dashed) and below (black solid) 0.6 GeV/$c^2$. 
The $m_T - m_0$ spectrum is fit twice, once with two exponentials in Figure 12 and again with an exponential plus a photonic component in Figure 13. This results in soft effective temperatures for the region below 0.6 GeV/$c^2$, $92.0 \pm 11.4 \pm 8.4$ MeV and $86.5 \pm 12.7^{+11}_{-8.4}$ MeV respectively, and harder effective temperatures for the region above 0.6 GeV/$c^2$, $258.4 \pm 37.7 \pm 9.6$ MeV and $221 \pm 19 \pm 19$ MeV respectively. Hydrodynamic models relate the photonic effective temperature to the larger initial temperature by a factor between 1.5 and 3 [35]. The effective temperature of the photonic component, $221 \pm 19 \pm 19$ MeV, is consistent with the initial temperatures from the thermal photon measurement described earlier. These effective temperatures are compatible with calculations of the local slope of the $m_T - m_0$ spectrum in the regions above and below 0.6 GeV/$c^2$, as seen in Figure 14. The expected local slopes from the hadronic sources are displayed as well, agreeing in the high $m_T - m_0$ region but overestimating the low $m_T - m_0$ region. This suggests that the excess below 0.6 GeV/$c^2$, which is the majority of the excess, is very soft with an effective temperature of around 100 MeV, much lower than one would expect from the hadronic component of the cocktail or from a flowing source.

3.3. Theoretical comparisons
A variety of theoretical comparisons (not shown) have been made to the MB Au+Au mass, $p_T$ and $m_T - m_0$ spectra including Rapp and van Hees [42], Dusling and Zahed [43], and Cassing and Bratkovskaya [44]. Rapp and van Hees’ theory describes the light vector mesons’ spectral functions using the vector dominance model. In this theory, medium modifications are due to hadronic many-body interactions, and a shifting mass is modeled for comparison. Dusling and Zahed’s theory uses a chiral reduction formalism to calculate the spectral functions in vacuum; medium modification occurs as a result of the hydrodynamic evolution of the system. Cassing and Bratkovskaya’s theory applies a microscopic relativistic transport model (HSD) with the $\rho$ spectral function modified via collisional broadening and a tunable mass shift.

None of the theories currently describe the MB Au+Au data, particularly in the mass region around 0.5 GeV/$c^2$ where the excess is the largest. Rapp and van Hees and Cassing and Bratkovskaya both are close to the data for masses above 0.6 GeV/$c^2$. Comparisons of the MB Au+Au mass spectra in $p_T$ slices with the same theoretical calculations reveal that the difficulty lies in the low $p_T$ ranges. Comparisons with the $p_T$ and $m_T - m_0$ spectra produce similar discrepancies, particularly in the low $p_T$ and $m_T - m_0$ ranges. In each case, $m$, $p_T$ and $m_T - m_0$, the theories are close to the measured spectra at high $p_T$ or $m_T$ but a bit low. Including virtual photon processes, such as $q + g \rightarrow q + \gamma^*$, could improve all of the calculations at high $p_T$ or $m_T - m_0$. Resolving the discrepancy between the data and the theories at low $p_T$ or $m_T - m_0$ may prove more difficult.

4. Conclusion
The $p+p$ data is well described by the cocktail plus a virtual photon component. There is an excess in the low mass region of the dielectron spectra in the MB, 0 – 10% and 10 – 20% Au+Au and the 0 – 10% Cu+Cu data. The excess grows with centrality faster than $N_{Part}$ squared. We have identified two sources of the excess in the low mass region, a photonic component at high $p_T$ and a second modification at low $p_T$, possibly due to chiral symmetry restoration. The thermal photon component allows an extrapolation of the initial temperature of the fireball to between 300 and 600 MeV for thermalization times of 0.6 to 0.15 fm/c. The remainder of the excess, which is not described by thermal photons, contains the majority of the yield, dominates at low $p_T$ and is very soft with an effective temperature of around 100 MeV.

The future of this subject at PHENIX lies in forthcoming analyses. A d+Au analysis, which is in progress, will allow us to identify cold nuclear matter effects in the heavy ion dielectron spectra. Low energy scan measurements will differentiate between the theoretical models. The hadron blind detector [45] has been successfully taking data since the 2009 $p+p$ run and is
currently taking Au+Au data. This detector reduces the combinatorial background, our largest background source, by allowing identification and removal of pion dalitz and conversion decay electrons from our electron sample before making pairs. The results shown in these proceedings, coupled with the future analyses and detector upgrades described above, move the discussion of the dilepton excess at PHENIX beyond the discovery phase and into a detailed study of its onset and characteristics, opening a new window onto the properties of the QGP medium and the fundamental nature of QCD.

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