Abstract.
Dileptons and direct photons are penetrating probes of the QGP and are emitted during the entire space-time evolution of heavy ion collisions. Recent measurements of direct photons indicate an excess of photons with $1 < p_T < 4$ GeV/$c$ in Au+Au collisions beyond the $N_{coll}$ scaled $p+p$ yield. The large excess, interpreted as thermal radiation, can be fit to a variety of models consistent with high temperatures and low thermalization times. Measurements also indicate a large $v_2$ for $p_T < 4$ GeV/$c$ where thermal photons dominate. Such a large $v_2$ is difficult to reconcile with current theoretical models. In these proceedings we will summarize the latest measurements of direct photons and dileptons produced at RHIC energies including recently released dielectron spectrum from $p+p$, dAu, and Au+Au collisions in PHENIX.

1. Introduction
Photons and dileptons are produced in copious amounts during heavy ion collisions and can be considered excellent probes to understand the hot dense medium. Information from almost every stage of the collision is carried through electromagnetic radiation and this allows us to better understand the space-time evolution of the system. Direct photons have now been measured in PHENIX for a variety of systems including $p+p$, $d+Au$, Cu+Cu, and Au+Au at a wide range of energies and momentum [1, 2]. Some of the exciting results from recent measurements in PHENIX include the larger than expected flow of direct and thermal photons, as well as the larger than expected enhancement of dielectrons in the low mass region. Both of these results have profound implications for understanding the medium itself and both are difficult to describe with current theoretical models.

Direct photons, as opposed to hadron decay photons, are of particular interest in Heavy Ion Physics because they do not interact strongly with the QGP, preserving their initial momentum. A large enhancement of direct photons has been measured in Au+Au and appears consistent with an initial temperature between $T_0 = 300 - 600$ MeV and a short thermalization time $\tau = 0.2 - 0.6$ fm/$c$ [3]. Furthermore, large azimuthal anisotropies characterized by $v_2$, are measured in the particle emission and are thought to be a result of collective phenomena. For a strongly coupled system, even with very large pressure gradients, it would take time for flow to develop, so large $v_2$ would indicate later production time and lower momentum emission.

Dielectrons have also played a key role in understanding the QGP in heavy ion physics. A long history of measurements has painted a rather intriguing picture of what happens in such high energy densities found at RHIC. The rather significant enhancement observed in Au+Au at $\sqrt(s) = 200$ GeV of low mass dielectrons is also an indication of additional sources beyond known hadronic sources. The significant enhancement observed of low mass dielectrons is thought to be
a possible signal for chiral symmetry restoration or perhaps medium modifications to the vector mesons [4]. Dielectrons also provide us with a detailed thermometer allowing us to resolve such things as temperature and multi-component flow as well as provide checks on a variety of production mechanisms. Understanding the electromagnetic component of an expanding medium will allow us to better understand the finer details of QCD itself.

2. Dielectrons in PHENIX

![Dielectron mass spectra from PHENIX](image)

**Figure 1.** The invariant mass distributions of electron pairs (left), showing the enhancement in the low mass region. The enhancement as a function of centrality in which we see the majority of the enhancement being produced in central collisions (right).

The PHENIX detector is ideally suited for measuring photons and electrons. Previous measurements made by PHENIX in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV have shown strong enhancement of electron pairs compared to the expected hadronic cocktail in the low mass region $m_{ee} = 0.15 – 0.75$ GeV/$c^2$ by a factor of $4.7 \pm 0.4 \text{(stat.)} \pm 1.5 \text{(syst.)}$ for minimum bias collisions [3]. For Au+Au, the mass spectra has been divided into $p_T$ and centrality bins. It appears that the bulk of the enhancement can be described as originating from low $p_T$ pairs in central events. The very low signal to background ratio of $\sim 1/200$ in the low mass region, results in large systematic uncertainty, particularly in the region of interest. Such a large enhancement was not expected and has posed a mystery to many theorists. Dielectrons are also useful for extracting direct photon yields as well.

3. Direct photons in PHENIX

There are several techniques used in PHENIX to measure direct photons using both real and virtual photons. For high momentum photons, $p_T > 5.0$ GeV/$c$, we are able to measure directly the energy deposited in the electromagnetic calorimeter (EMCal) and statistically subtract hadron decay photons from the inclusive photon yield to get at the direct photons. For lower momentum photons this subtraction becomes difficult due to the limited energy resolution of the EMCal at $p_T < 5.0$ GeV/$c$ and we must use either virtual photons that internally convert into $e^+e^-$ pairs or measure real photons that externally convert in material into $e^+e^-$ pairs. As a cross-check, we can make sure that both methods are in agreement with each other.
π of photons at least 10 towers (photons.
The key to the method is the precise subtraction of the drift chamber as well as a profile cut on the EMCal.

Figure 1: (color online) The measured virtual-photon analysis as a function of it peaks at low pair data and subtracted after correcting for acceptance µ though PHENIX has observed a strong enhancement of π0, η and direct photons. The data is in red circles and clearly lies above known hadronic sources in blue. The excess is interpreted as arising from direct photons (right) [3].

Direct photons can be measured using the virtual photon method, which utilizes the relationship between real and virtual photons shown in Fig. 2. For our purposes we can assume any process which makes real photons will also have a fraction which manifest as electron pairs due to internal conversions. By selecting \( p_T \gg m \) or in our case, a kinematic region of \( m < 300 \) MeV and \( p_T > 1 \) GeV/c, we can select a region where the dilepton signal is dominated by internal conversions. The clear enhancement in Au+Au above the hadronic cocktail can be fit with a two component function \( F = (1 - r)f_c + rf_d \) where \( f_c \) is the cocktail fraction and \( f_d \) is the contribution from direct photons. We should note that \( r \) is the only parameter allowed to vary in this fit, since the shapes of \( f_c \) and \( f_d \) are already determined. Typically, analysis is done above the \( \pi^0 \) mass to remove the majority of hadronic background. The excess is used to infer the yield of real direct photons by extrapolating to \( m_{ee} = 0 \).

\[
    r_\gamma = \frac{\gamma_{dir}(m > 0.15)}{\gamma_{inc}(m > 0.15)} \frac{\gamma_{dir}(m = 0)}{\gamma_{inc}(m = 0)} = \frac{\gamma_{dir}}{\gamma_{inc}}
\]

Figure 3. PHENIX has measured low \( p_T \) direct photon ratio in various collision systems using the virtual photon method. The theory curves represent NLO pQCD calculations for \( \mu/p_T \) = 0.5, 1, and 2 (left). Nuclear suppression factors for direct photons in \( d+Au \) and \( Au+Au \) using both real and virtual photon methods and comparing to CNM effects (right) [2].
The direct photon ratio \( r_\gamma = \frac{\gamma_{\text{dir}}}{\gamma_{\text{inc}}} \) has been measured using the virtual photon method by PHENIX for \( p+p \), \( Au+Au \), \( Cu+Cu \), and now \( d+Au \) at \( \sqrt{s_{NN}}=200 \text{ GeV} \). For \( p+p \) and \( d+Au \) collisions, the yield is consistent with NLO pQCD calculations, while a clear enhancement above predictions exists for \( Cu+Cu \) and \( Au+Au \). Furthermore, nuclear suppression factors have been measured for \( d+Au \) and \( Au+Au \) in terms of \( R_{dA} \) and \( R_{AA} \). CNM effect measured in \( d+Au \) do not explain the excess observed in \( Cu+Cu \) and \( Au+Au \). This data supports the conclusion that additional sources arising from medium effects in \( Au+Au \) and \( Cu+Cu \) are not present in the baseline measurements of \( p+p \) and \( d+Au \) where a dense medium is not expected to be produced.

The direct photon yield can be determined from the product of \( r_\gamma \) and the inclusive yield \( \gamma_{\text{inc}}^\text{dir} = r_\gamma \gamma_{\text{inc}} \). The fits for \( p+p \) is based on a modified power law function \( A_{pp}(1+p_T^2/b)^{-n} \) and for \( Au+Au \) we use an exponential plus the \( T_{AA} \) scaled \( p+p \) fit, i.e. \( A e^{-p_T/T} + T_{AA} A_{pp}(1+p_T^2/b)^{-n} \).

Note that the only free parameters in the fit are the inverse slope parameter and the constant in front of the exponential. We observe a clear enhancement in \( Au+Au \) compared to the scaled \( p+p \) fit. This enhancement fits well to an exponential curve consistent with the view that it is thermal in origin.

Figure 4. Invariant yields for direct photons in \( p+p \) and \( Au+Au \) (left) [6]. On the right shows the same invariant yield in \( Au+Au \) but fit to a variety of theoretical models giving a range of temperatures and thermalization times [3].

4. Direct photon Elliptic Flow
A typical nucleus-nucleus collision starts with an initial spacial anisotropy, which turns into a momentum anisotropy due to large pressure gradients. Large azimuthal anisotropies are an indication of collective phenomena and carry information about where particles are produced in the collision. Since there are a variety of production mechanisms which overlap in transverse momenta, we can use this fact to distinguish between various production mechanisms. Sources originating early in the collision are typically hard processes from initial parton scattering and we should expect \( v_2 = 0 \). Later in the collision, softer processes such as thermal photons from the QGP and hadronic gas photons will contribute and we expect \( v_2 > 0 \). While thermal photons are obviously produced from a thermalized medium, initial state photons need not be in thermal equilibrium. There will also be a source from jet fragmentation and Bremsstrahlung photons which can have \( v_2 < 0 \) which is a reflection of the geometry and not dynamics [1].
We can begin by describing the steps in the analysis used to calculate direct photon $v_2$. The actual measurement of $v_2$ experimentally requires very good reaction plane resolution since we are essentially looking for an azimuthal asymmetry on an event-by-event basis.

$$R_\gamma = \frac{\gamma^{incl}(p_T)}{\gamma^{bg}(p_T)} = \frac{\epsilon(p_T)f(p_T)\cdot\left(\frac{N^{incl}(p_T)}{N^{\pi_0\gamma}(p_T)}\right)_{Data}}{\left(\frac{N^{had}(p_T)}{N^{\pi_0\gamma}(p_T)}\right)_{Sim}}$$

(2)

$$v_2^{\gamma,obs} = v_2^{\gamma,meas} - \left(\frac{N^{had}/N^{meas}}{N^{had}/N^{meas}}\right)v_2^{\gamma,had}$$

(3)

$$v_2^{\gamma,dir} = \frac{R_\gamma(p_T)v_2^{\gamma,inc} - v_2^{\gamma,bg}}{R_\gamma(p_T) - 1}$$

(4)

Here $v_2^{\gamma,obs}$ is the observed inclusive $v_2$ before correcting for RP resolution, $v_2^{\gamma,inc} = v_2^{\gamma,obs}/\sigma_{RP}$ is for inclusive photons after corrections, $v_2^{\gamma,bg}$ is the hadronic background, and $v_2^{\gamma,dir}$ is for direct photons. Essentially we need to establish $R_\gamma$ as the fraction of inclusive photons over decay photons, measure $v_2$ for inclusive photon yield correcting for hadron contamination, and subtract the hadron decay contributions from the inclusive photon to arrive at a direct photon $v_2$. It is worth noting that we only measure the $\pi^0$ $v_2$ which contributes about 80% of background. The other hadron $v_2$ is determined from $K E_T/n_q$ scaling, where $K E_T = m_T - m_0$ [1].

We observe a significant direct photon signal with a rather large $v_2$ comparable to the inclusive photon and $\pi^0$ $v_2$ at low momentum. We also observe $v_2$ dropping to zero for high $p_T > 5$ GeV where hard processes dominate. This poses an intriguing question of how thermal photons could develop such a large $v_2$ when they are thought to originate from such early thermalization times.

5. Theory Comparisons
It can be difficult to reconcile our current understanding of the evolution with both large $v_2$ and short thermalization times. We can turn to two different theoretical models [7, 8] which
both tend to under predict the data shown in Fig 6. Several other ideas are currently being
developed which may help shed light on this puzzle, but are not discussed in this proceedings
[9, 10, 11, 12].

Figure 6. Theory and data comparison using models provided by Chatterjee, Srivastava [7]
(left) and H. van Hees, C. Gale, and R. Rapp (right) [8]

6. Summary
Dileptons and photons have great potential to probe strongly interacting matter and explore
general properties of the Quark Gluon Plasma. Many new results have been studied and reported
on here. The dielectron mass spectrum and direct photon spectrum has been presented for \(p+p\),
\(d+Au\) and \(Au+Au\). Strong enhancement is observed in both dielectron spectra and direct
photon spectra in central \(Au+Au\) collisions. In the case of direct photons, we also observe a
large azimuthal asymmetry in the particle emission rates indicating a large flow component to the
data. RHIC results are pushing forward our knowledge and understanding of the electromagnetic
component of heavy ion collisions.

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