Dileptons And Photons At RHIC Energies

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Abstract
Comparing dilepton data from Au+Au to p+p collisions at RHIC energies PHENIX revealed two striking features: (i) a large excess of the dilepton yield at low mass and low \( p_T \) in central Au+Au and (ii) a significant enhancement of direct real photon radiation. Both features can be interpreted as thermal radiation from the hot quark matter produced at RHIC. Unlike at lower beam energies, at RHIC the contribution from the hot hadronic phase alone seems insufficient to account for the data. This suggests large contributions from a partonic phase. Both experimental and theoretical progress are required for more detailed conclusions.

1. Introduction
Electromagnetic radiation is regarded as an ideal tool to probe strongly interacting matter [1]. Experiments at SPS produced a wealth of data and inspired much theoretical work that advanced our understanding of meson properties in matter and the relation to chiral symmetry restoration [2, 3]. The PHENIX experiment continues the experimental investigation at RHIC in a new energy domain. In this review I report on the recent PHENIX results and discuss the comparison to model calculations.

Figure 1 shows a schematic \( e^+e^- \) pair mass distribution as expected from p+p collisions at RHIC energies. The \( e^+e^- \) pairs are either from pseudo-scalar or vector-meson decays, typically after the collision on the time scale of the strong interaction, or from hard-scattering processes like open heavy-flavor production, Drell-Yan pair production or quark-gluon (qg) Compton scattering, all occurring early in the collision. In addition to these sources quark matter produced in heavy ion collisions may emit thermal radiation, leave imprints from medium modifications of the meson properties, and modify the contribution from hard-scattering processes.

Isolating the medium effects from the expected sources is the experimental challenge and this challenge is two fold. First one needs to determine and subtract the pair background, which in central Au+Au collisions is more than a factor of hundred larger than the signal. This subtraction is very involved and dominates the systematic uncertainties. After many years of analysis effort this subtraction is well under control (see [4, 5] for details). The second challenge is to accurately determine the expected sources shown schematically in Fig. 1. PHENIX was able to determine these expected sources from data on meson production cross sections (see Fig. 2 and [6]) and on heavy-flavor production [7, 8], measured in the same experiment.

2. Reference data from p+p collisions
Data from p+p collisions are used to test the analysis method and serves as precision reference for data from heavy ion collisions. The data are published in [6]. They are compared to the
expected yield in Fig. 3. It is evident from the ratio data-to-expected given in the lower panel that the data are in excellent agreement with the expectation within the systematic uncertainties of about 30%.

The data are very precise and can be used to independently measure some of the expected contributions. This was done for the vector mesons $\omega, \phi$ [9] and $J/\psi$ [10] as well as for heavy-flavor production [6] and $q\bar{q}$ Compton scattering. The latter contribution can be isolated in the kinematic region where the mass is smaller than the transverse momentum [11, 12]. The ratio of direct-to-inclusive virtual photons can then be extrapolated to mass equal zero and compared to perturbative QCD calculations [13]. As shown in Fig. 4 the agreement is very good.

3. Data from Au+Au collisions

With our understanding of the expected sources we have a solid baseline to search for effects off the medium. Already from a first glance at the mass distribution from Au+Au collisions (Fig. 5) one finds a striking enhancement of the data above the expected yield that was established in p+p collisions. In the mass range from 150 to 750 MeV/c$^2$ the yield is a factor $3.4^{+0.2}_{-0.2}(\text{stat})^{+1.7}_{-1.3}(\text{sys})^{+0.7}_{-0.3}(\text{model})$ above the expectation.

In order to investigate the enhancement in more detail one can study its centrality and momentum dependence. The centrality dependence of the integrated yield is shown in Fig. 5 for two mass ranges $m < 100$ MeV/c$^2$ and 150 to 750 MeV/c$^2$, respectively. The yield in the lower mass bin is dominated by pairs from $\pi^0$ Dalitz-decays and consequently follows the centrality dependence of the pion yield. However, the yield in the higher mass range, which includes the enhancement, deviates from the expected dependence and indicates that central collisions contribute most of the observed enhancement. The yield from $\pi\pi$ or $q\bar{q}$ annihilation in the medium...
Figure 3: Electron-positron pair data from 200 GeV p+p collisions observed by the PHENIX experiment [6]. The solid line depicts the contribution from hadron decays estimated on the basis of the most precise available data on neutral meson production and charm/bottom production. Data are corrected for efficiency and require both electron and positron in the detector acceptance.

Figure 4: Ratio of direct-to-inclusive dilepton pairs in the kinematic range $m < p_T$. The data are compared to perturbative QCD calculations for direct photon production [13].

Figure 5: Inclusive $e^+e^-$ mass spectrum from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured by PHENIX. The presentation is identical to that in Fig. 3. The statistical errors are shown as bars and the systematic errors are marked independently by a band around each data point.
should also increase faster than the number of participants, but it is not clear if the data can be explained quantitatively.

Splitting the data in bins of pair $p_T$ reveals that in the mass range from 150 to 750 MeV/$c^2$ the yield is enhanced at all $p_T$, but not uniformly. The enhancement is largest at the lowest $p_T$. To quantify this more PHENIX has measured the transverse mass ($m_T$) distributions, corrected for pair acceptance, and determined local slopes as function of pair mass. The inverse local slope or $T_{\text{eff}}$ for the two regions $0 < m_T < 1$ GeV and $1 < m_T < 2$ GeV is plotted in Fig. 7 as a function of mass. Also shown is $T_{\text{eff}}$ expected from hadron decays alone. In general neither expectation from hadron decays nor the data show a strong variation of the effective temperature over the observed mass range. In the higher $m_T$ range the effective temperatures are similar to the expectation, 280 MeV compared to 220 MeV in the data. In the lower $m_T$ range the data have a significantly smaller slope of 120 MeV than the expected 200 MeV. Unfortunately, limited statistics prohibits a more detailed analysis. More precise data are needed to subtract the hadron decay contribution and isolate the enhancement. However, the effective temperature of the low $m_T$ component is a rather robust measurement and the result will not change much once the excess can be isolated.

I now turn the attention to the contributions from hard scattering processes. Due to the limited statistical accuracy not much can be said about the contribution from charm production. The data shown in Fig. 5 are consistent with the extrapolation of the p+p cross-section using binary scaling, which is labeled $c\bar{c}$ (PYTHIA) in Fig. 5. However, data on charm production [8] indicate a large degree of interaction of charm quarks with the medium in central Au+Au collisions, which must also modify the angular correlation between $c$ and $\bar{c}$. If the momentum direction of the $c$ and $\bar{c}$ quarks would randomized in the medium the data should be compared to the curve labeled $c\bar{c}$ (random correlation), which leaves room for other contributions above 1 GeV/$c^2$.

Interesting results emerge when looking at the kinematic region of $m << p_T$, where direct virtual photon emission was observed in p+p collisions. Details of the analysis, in particular
a discussion of the validity of extrapolating virtual photons back to the real photon point at mass equal zero, can be found in [11, 12]. The final result for the direct-to-inclusive virtual photon ratio, shown in Fig. 8, indicates a significant excess beyond the expectation from initial state $qg$ Compton scattering. Fig. 9 shows the direct photon spectrum resulting from Fig. 8. Here the virtual photon data were extrapolate to the real photon point, which in this case means setting the direct-to-inclusive ratio for virtual photons equal to the one for real photons. The data are consistent with results obtained from calorimeter measurements at higher $p_T$ in the same experiment. While $p+p$ data follow the expectation from pQCD an excess is found in Au+Au. The inverse slope of the excess, after subtracting the scaled $p+p$ data are $T_{\text{eff}} \sim 220$ MeV. This effective temperature can be interpreted as limit on the initial temperature of the reaction volume. Work to confirm these results with data from real photons is underway and has produced consistent upper limits.

4. Model comparison and discussion

Much work has gone into modeling dilepton and photon production from the fireball created in heavy ion collisions at SPS energies [2]. After some 20 years of experimental and theoretical development the following picture has emerged. Electromagnetic radiation is predominantly emitted from hadron-hadron collisions at times when the spectral function of mesons are significantly broadened compared to vacuum. The colliding hadrons participate in the collective expansion and consequently the dileptons show radial flow. While emission at the partonic level is also observed it does not contribute significantly to the overall yield [2].

The same sources must also contribute to dilepton production at RHIC energies. In Fig. 10 models, which describe SPS data, are confronted with dilepton mass distribution [14, 15, 16]. Ev-
idently, the predicted yield underestimates the data and these models are insufficient to describe RHIC data. Most likely the contributions from the partonic phase must be more significant than realized. At closer inspection it turns out that the model calculations shown in Fig. 10 include only $q\bar{q}$-annihilation but not the contribution from $qg$ Compton scattering in the medium.

Figure 10: Comparison of Au+Au data to various models that successfully describe data from lower energies. Only calculation assuming broadening of the meson masses in the medium are shown.

Figure 11: Comparison of Au+Au data on direct photon emission with theoretical models.
Model calculations of thermal photon emission based on perturbative QCD show that $qg$ Compton scattering is very important [12]. In a QGP the gluon densities might be so large that $qg$ Compton scattering outshines $q\bar{q}$-annihilation and the perturbative approach may be insufficient all together. In Fig. 11 various models are compared with real photon data [17]. All models agree roughly with the observed slope. The initial temperature in the models varies from 300 to 600 MeV depending on the initial conditions, in particular the formation time. However, there are large differences in the predicted cross sections, which need to be addressed in future work.

Last I return to dilepton spectra, but in a double differential representation in mass and $m_T$. In Fig. 12 the same calculations already shown in the mass projection (Fig. 10) are compared to the $m_T$ spectra. In the mass range from 500 to 750 MeV/c$^2$ the models describe the data except for the lowest $m_T$, as expected from Fig. 10. At lower masses the models fall short at all $m_T$. It is interesting to point out that the data above $m_T \sim 1$ GeV/c$^2$ were used to determine the direct photon yield. If $qg$ Compton scattering would be consistently included in the models it would fill some of the difference at lower $m_T$, though probably at the lowest $m_T$ it would not account for all data. Another important consequence may be that the models then would likely overestimate the yield in mass range 500 to 700 MeV/c$^2$. Obviously more complete theoretical calculations are required. In the highest shown mass range the models predict widely different yields, most likely due to different contributions from hard scattering processes. Again this needs to be looked into.

To conclude this section I want to underline the importance of consistent model calculations that not only have a realistic description of the space time evolution and hadron spectra, but that also describe dilepton and photon emission simultaneously.
5. Summary and outlook

Dilepton data analysis of the PHENIX experiment has matured significantly over the past years. Experimental issues, most importantly the subtraction of pair background, are under control. Data from p+p collisions establish a precise reference to detect medium effects in Au+Au collisions. PHENIX has discovered such effects, namely a significant enhancement of dilepton production in mostly central Au+Au collisions. The enhancement covers the mass range from roughly 100 MeV to 750 MeV and is focused at low $m_T$. Most strikingly it exhibits a prominent soft contribution with $T_{eff}\sim 120$ MeV, which is independent of mass over the accessible range. PHENIX has also presented a first measurement of thermal photons indicating an initial temperature larger than 220 MeV.

Though much work on theoretical models is needed to make final conclusions some firm conclusions can already be made. Thermal radiation from the hadronic phase, mostly from $\pi\pi$-annihilation with collision broadening has emerged as the main contribution to dilepton enhancement observed at the SPS [2]. These contributions that obviously must exist also at RHIC energies remain insufficient to explain the PHENIX data. More complete calculations of dilepton radiation from the partonic phase need to be made. Model calculations of thermal real photon production is consistent with the data and hint towards initial temperatures larger than 300 MeV. However, big differences between various calculations remain.

PHENIX has just started their dilepton program, more data from Cu+Cu, p+p, and d+Au collisions are on tape and are being analyzed. During RHIC Run 9 the collaboration successfully commissioned the hadron blind detector (HBD) and we can look forward to precision Au+Au data from PHENIX from Run 10.

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References

[1] E. Shuryak Phys.Lett. 78B (1978) 150.
[2] R. Shahoyen, QM09 proceedings.
[3] R. Rapp and J. Wambach, Adv.Nucl.Phys. 25 (2000).
[4] S. Afanasiev et al. (PHENIX), arXiv:0706.3034 (2007).
[5] PHENIX archival paper in preparation (2009).
[6] A. Adare et al. (PHENIX), Phys.Lett. B670 (2009) 313.
[7] A. Adare et al. (PHENIX), Phys.Rev.Lett. 97 (2006) 252002.
[8] A. Adare et al. (PHENIX), Phys.Rev.Lett. 98 (2007) 172301.
[9] T. Dahms, Ph.D. Thesis, Stony Brook University (2008), arXiv:0810.3040 (2008).
[10] A. Adare et al. (PHENIX) Phys.Rev.Lett. 98 (2007) 232002.
[11] A. Adare et al. (PHENIX), arXiv:0801.4555 (2008).
[12] Y. Akiba (PHENIX), QM09 proceedings.
[13] L. E. Gordon and W. Vogelsang, Phys.Rev. D48 (1993) 3136. W. Vogelsang, private communication (2008).
[14] R. Rapp, Phys. Rev. C63 (2001) 054907; R. Rapp, nucl-th/0204003. W. Liu, R. Rapp, Nucl. Phys. A796 (2007) 101.
[15] E. L. Bratkovskaya, W. Cassing, O. Linnyk, Phys.Lett. B, in press arXiv:0805.3177 (2008).
[16] K. Dusling and I. Zahed, arXiv:0712.1982. K. Dusling Ph.D. thesis, Stony Brook University (2008).
[17] D. d’Enterria, D. Peressounko, Eur.Phys.J.C 46 (2006).