Electromagnetic measurements in high-energy heavy-ion collisions

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Abstract. Electromagnetic measurements have been playing unique roles in the studies with high-energy heavy collisions. Many interesting results have been obtained in the recent RHIC experiments, which have been providing key information on the interpretation and understanding of the hot and dense nuclear matter created in the ultra-relativistic heavy ion collisions. In this article, some of the recent results are picked up, and implications of these results are discussed.

1. Introduction
Let me start with a little pedantic argument on the relations between electromagnetic probes and electromagnetic measurements. Electromagnetic probes are promptly produced leptons and photons without having intermediate long-lived composite states. Therefore, electromagnetic probes are penetrating probes by definition, which could provide direct information with minimum disturbance from when and where they are produced. Belonging to this category are; thermal and hard photons, and thermal and Drell-Yan lepton pairs.

Strictly speaking, all the other sources including leptonic and photonic decay of hadrons are background to the electromagnetic probes. It is, however, often the case that those ‘background’ sources are also the useful probes as well.

A good example is $J/\psi$. $J/\psi$, a charm and anti-charm bound state, is a hadronic composite with a long lifetime of $c\tau = 2264$ fm, and its yield has been considered to be a unique probe of deconfinement. Measurement of $J/\psi$ via lepton-pairs, therefore, should be considered as a purely technical matter.

Situation is similar for $\pi^0$, $\eta$, and D and B mesons. Photons from $\pi^0$ and $\eta$ are dominant background sources in view of measuring direct photons. High-$p_T$ $\pi^0$ and $\eta$, however, reconstructed from two photons are very powerful tools to study jet production in p-p collisions and its medium modifications in p(d)-A and A-A collisions, although these measurements are not covered in this article. Leptonic decay of charm and bottom is a dominant source of single leptons in the medium $p_T$ region in the collisions at the RHIC energies, and the leptons from decays of heavy quarks make it hard to access thermal and Drell-Yan pairs. Because of this dominance, however, heavy quark production and interactions with hot and dense media can be investigated by single leptons measured in p-p and A-A collisions.

The situation is a little different in case of light vector mesons, $\rho$, $\omega$ and $\phi$. Their lifetimes, $c\tau(\rho) = 1.3$ fm, $c\tau(\omega) = 23.3$ fm, and $c\tau(\phi) = 46.2$ fm, are comparable to the lifetime of hot
matter. Vector mesons measured with lepton-pairs may be considered as ‘pseudo-penetrating’ probes. A fraction of $\omega$ and $\phi$ would decay inside the medium. In case of $\rho$ mesons, lifetime will be shorter than the lifetime of the sources. The yield and line-shape measured via $ee$-channel could be significantly different from the one measured via hadronic decay channel, since the mesons decayed inside the medium can only be detected without severe disturbance via $ee$-channel.

In this article, selected results of electromagnetic measurements from the RHIC experiments are introduced. At first, photon measurements in the high $p_T$ region are picked up. Then, hot results on single lepton measurements are presented. Recent theoretical developments on $J/\psi$ production are referred, and experimental status is provided. Current situation on low-mass pair measurements are reviewed and near-future plan is provided. Brief summary and outlook is provided in the end.

Figure 1. Prediction on the yield of direct photons from various stages; initial pQCD (dotted), QGP (dot-dashed) and hadron gas (dashed), of the central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV.

Figure 2. The ratio of $\left(\frac{\gamma}{\pi^0}\right)_{\text{measured}}$ to $\left(\frac{\gamma}{\pi^0}\right)_{\text{background}}$ as a function of $p_T$ for several centrality bins of $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions. See text for details.

2. Direct photons

Direct photons come from various stages of collisions. They are in large divided into two categories; non-thermal and thermal. Non-thermal photons come from a hard process in the initial stage and from pre-equilibrium stage. Thermal photons are produced in the later stages; quark gluon plasma (QGP) phase and hadronic phase.

Although there are no explicit tags attached to photons where they are originated from, windows can be set so as to enrich photons from a certain stage. Figure 1 illustrates an expected photon yield from the three sources; a hadron gas phase, a QGP phase, and initial pQCD process[1]. Low-$p_T$ region below $\sim 1$ GeV/c is dominated by thermal photons from a hadron gas, and high-$p_T$ region above $\sim 3$ GeV/c is dominated by a pQCD hard process. A narrow window exist for photons from QGP phase in the $p_T$ region from 1 to 3 GeV/c. It is to be added here that signal to background ratio in this momentum region is expected to be in the order of several %.

2.1. Hard pQCD photons from Au-Au collisions

The PHENIX experiment successfully measured the photons in the high $p_T$ region for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV[2]. Figure 2 shows a double ratio of measured $\left(\frac{\gamma}{\pi^0}\right)_{\text{measured}}$
invariant yield ratio to the background decay ($\gamma/\pi^0$)$_{\text{Background}}$ ratio as a function of $p_T$ for minimum bias and five centralities. Solid lines are the predictions with the NLO pQCD calculations, where the hard photon yield is calculated for p-p collisions and multiplied by $N_{\text{coll}}$ assuming binary collision scaling. The shaded regions indicate the variation of the pQCD calculation for scale changes from $p_T/2$ to $2p_T$, plus $<N_{\text{coll}}>$ uncertainty.

Figure 3 shows the $R_{AA}$ for prompt photons (close circles) and $\pi^0$ (open circles) at $p_T > 6.0$ GeV/c as a function of number of participant nucleons, where $R_{AA}$ is the ratio of photon yield for Au-Au collisions scaled with $N_{\text{coll}}$ relative to that for p-p collisions. Difference in the behavior between prompt photons and $\pi^0$ is clearly demonstrated. From these results, we can clearly conclude that the initial state effect, that is, modification of parton distribution, is not large, and $\pi^0$ suppression is dominantly the final state effect.

2.2. Search for thermal photons and beyond
Although photons at high $p_T$ region are now getting under control, photon yield in the $p_T$ region below $\sim 4$ GeV/c does not have any significance primarily because of statistics and large systematic uncertainty. It remains to be a big challenge.

Recently, a new mechanism to produce photons in the intermediate $p_T$ region was introduced, where a photon is generated by an energetic quark via the pair-annihilation and gluon-Compton processes while passing through hot and dense medium[3, 4]. A related concept of modified photon bremsstrahlung of jets in the medium is also discussed[5]. There seems to be rich complexity in the photons in the intermediate momentum region.

3. Single lepton measurement
Only electrons are covered in this article. Single electrons come from many sources, which can be divided into two large categories; photonic and non-photonic. Photonic electrons are originated from photons and the typical sources are; Dalitz decay (internal conversion) of $\pi^0$, $\eta$, $\eta'$, $\omega$ and $\phi$, and external conversions of direct photons and decay mesons, $\pi^0$, $\eta$, and $\eta'$. Main sources of non-photonic electrons are; leptonic decay of D and B mesons, thermal pairs, lepton-pair decay of vector mesons, and Kaon decay $K_{e3} \rightarrow \pi^0 e\nu$.

3.1. Methods to extract the non-photonic components
There are two methods having been used to subtract a photonic component and extract a non-photonic one. One is a cocktail method, where all the background sources are cocktailed together to estimate the contributions using the Monte-Carlo simulations. The cocktail method was used in Ref. [6] for deducing single electron spectra in Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV.
Another is a converter method, which utilizes the data samples taken with and without an additional photon converter. The converter method was used in Ref. [7] for deducing non-photonic electrons in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Advantage of this method over the cocktail method is a smaller systematic uncertainty, since the photonic contribution can be estimated directly from the data samples with and without the converter.

![Figure 4](image1.png) **Figure 4.** Transverse momentum spectra of non-photonic single electrons for minimum-bias and central 10% $\sqrt{s_{NN}} = 130$ GeV Au + Au collisions.

![Figure 5](image2.png) **Figure 5.** Transverse momentum spectra of non-photonic single electrons for various centrality bins in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions.

### 3.2. Electron spectra and yield

Figure 4 shows a momentum spectra of non-photonic single electrons for minimum-bias and central 10% $\sqrt{s_{NN}} = 130$ GeV Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV[6]. As can be seen from the figure, major contribution comes from leptonic decay of charm and bottom quarks, as expected in the RHIC energies. Figure 5 shows invariant yields of non-photonic single electrons for several centrality bins in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV[7]. Shown with the solid lines are the $N_{\text{coll}}$ scaled momentum spectrum fitted for p-p collisions. Since the data points lie on the curves quite well, binary collision scaling seem to work quite well. To be more quantitative, $N_{\text{coll}}$ dependence is obtained assuming the following dependence; $N_{\text{Au-Au}}(p_T; b) = N_{\text{pp}}(p_T) \cdot N_{\text{coll}}^\alpha$. The best fitted value for electron yield integrated over $p_T$ from 0.8 to 4.0 GeV/c is, $\alpha = 0.938 \pm 0.075(\text{stat}) \pm 0.018(\text{sys})$.

### 3.3. Is charm coupled weakly?

The results seem to suggest that charm quarks are weakly coupled with hot and dense matter. Theorists have argued about “dead cone” effect in order to account for the small energy loss of heavy quarks[8, 9, 10].

### 3.3.1. Charm energy loss:

With higher statistics achieved using the cocktail method, detailed investigations in the high $p_T$ region became possible. Figure 6 shows a PHENIX preliminary $R_{AA}(p_T)$ as a function of $p_T$ for 0–10% central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Larger
hinderance is seen in the higher $p_T$ region, the magnitude of which is comparable to that of $\pi^0$. This is a challenge to theorists, and will force them to re-investigate the energy loss mechanism.

3.3.2. Elliptic anisotropy of non-photonic electron: Elliptic anisotropy has been utilized as a tool to investigate the hydrodynamical behavior of the system. According to hydrodynamical calculations, large anisotropy is a consequence of fast thermalization and subsequent near-perfect hydrodynamical space-time evolution.

The PHENIX experiment reported the $v_2$ for non-photonic electrons in the $p_T$ region below 1.5 GeV/c[11]. The result favors non-zero charm flow with a 90% confidence level, when compared with a model calculation which is based on a quark coalescence model assuming the anisotropy of a D meson is the sum of the anisotropy from a light quark and a charm quark: $v_2(D) = v_2(\text{light quark}) + v_2(\text{charm})$.

A recent result from the STAR experiment covers the higher $p_T$ region[12], and the PHENIX + STAR combined result as shown in Fig. 7 strongly favor the calculation with charm flow.

Again, this should be a good exercise to theorists.

3.3.3. Efforts in near future: Deduction of non-photonic electron is a complicated and difficult task. Since the results are so important, both PHENIX and STAR are working hard to re-visit this issue with the new analysis of Year-4 run. Year-4 run has much higher statistics, and full comparison between the cocktail method and the converter method will become possible. Higher statistics should also help to extend the $p_T$ region.

4. $J/\psi$ production in HI collisions
4.1. Experimental results at CERN-SPS
The history of experimental studies of $J/\psi$ at CERN-SPS was not straight-forward. Figure 8 shows the yield ratio of $J/\psi$ to Drell-Yan as a function of effective path length for various combinations of colliding systems, and provides a whole history at a glance[13]. When large suppression was observed in S+A collisions, it was considered to be what was predicted by
Matsui and Satz[14]. It turned out, however, that all the data points from S+A and p+A collisions lie on a common curve given by an empirical relation,

\[ N(L) = N(0) \cdot \exp(-\sigma_{\text{abs}} \rho L), \]

where \( \sigma_{\text{abs}} \) denoted the absorption cross section in nuclear medium, \( \rho \) is the nuclear density, and \( L \) denotes the path length. Large suppression strongly deviated from this trend, was finally observed in Pb+Pb collisions, which is considered to be a real consequence of deconfinement.

![Figure 8](image8.png)

**Figure 8.** \( J/\psi \) over Drell-Yan ratio as a function of effect path length \( L \) in p+A, S+U and Pb+Pb collisions at CERN-SPS.

![Figure 9](image9.png)

**Figure 9.** Spectral function of \( c - \bar{c} \) system for several temperature below and above \( T_C \), calculated using the maximum entropy method in the lattice-QCD calculations.

4.2. Recent theoretical progress

4.2.1. Lattice-QCD calculations In the theoretical studies, lattice-QCD calculation is used more frequently as a tool to investigate properties of particles or states in media. A well-known example is the temperature dependence of potential of \( c-\bar{c} \) system[15].

Recently, stability of \( J/\psi \) above \( T_C \) was studied by Asakawa and Hatsuda, using the maximum entropy method[16]. Figure 9 shows a spectral function of \( c-\bar{c} \) system at several different temperature, where the lowest peak corresponds to \( J/\psi \). The result indicates that the melting of \( J/\psi \) happens between \( T = 1.62T_C \) and \( 1.87T_C \). The result need to be treated properly when constructing a scenario of \( J/\psi \) suppression.

4.2.2. \( J/\psi \) enhancement due to recombination of charms With increase of number density of charm and anti-charm quarks, probability increases of forming \( J/\psi \)’s through recombination process. Probability is not high enough at the CERN-SPS energies, but may not be negligible at the RHIC energies. I was notified recently by Matsui that the idea of enhancement due to recombination is as old as the idea of suppression[17].
There are two branches of models, the one, categorized as statistical hadronization model, assumes the coalescence process only in the hadronization stage\cite{19, 20}, and the other, called kinetic formation model, adds $J/\psi$ formation in the QGP in addition to the coalescence in the hadronization stage\cite{21}.

4.3. Current experimental situation at RHIC

The PHENIX experiment published a result on central dependence of $J/\psi$ yield in Au+Au collisions\cite{18}. Data quality is very poor, and precise comparison with the various models are not possible. Much improved result from the Year-4 run are expected to appear soon for central electron pairs and forward muon pairs.

5. Continuum and low-mass vector mesons

Still missing at RHIC are the continuum and low-mass vector mesons. Importance of these measurements cannot be overemphasized. Continuum, together with thermal photons, would provide direct information on the thermal properties and degree of freedom of the evolving matter. Low-mass vector meson is a sensitive probe of the chiral restoration and/or medium modification.

In both cases, subtraction of overwhelming combinatorial background is the challenge. Even if high statistical data is accumulated and systematic error can be maintained minimum, significant quality reduction cannot be avoided by subtraction of huge background.

Figure 10. Invariant mass spectra of electron-positron pairs generated by a simulation, which indicate the magnitudes of signals and backgrounds in Au+Au collisions at RHIC.

5.1. Challenge to deduce combinatorials

Figure 10 shows invariant mass spectra of electron-pairs from a simulation which indicates the significant of combinatorial background in the low mass region in the PHENIX experiment for the Au+Au collisions.

Main source of combinatorial background is Dalitz pairs and external conversion of $\pi^0$. As was done properly in the CERES experiment at SPS, the combinatorial background can be reduced in principle, by utilizing the decay properties of $\pi^0$. Even after proper subtraction of the background, further complication is the large physics background from charm leptonic decay, as indicated in the figure. In the PHENIX experiment, an effort is being made to add Dalitz rejection capability, using a position sensitive Cherenkov detector called HBD (Hadron Blind Detector) placed in the near-field-free region near the beam pipe.
6. Summary and Outlook

Current status of electromagnetic measurements at RHIC was briefly overviewed. Mainly because of low yield and difficulty in measurement, the available results are rather limited at this moment, but it is expected that many results will be coming out soon from the data samples taken in RHIC Year-4 and Year-5 runs. The author is afraid that this article would become obsolete so quickly with a flood of new results.

In the end, remarks to some of electromagnetic measurements are provided.

**Direct photon:**
Successful detection of pQCD photons in Au-Au collisions is a big achievement, and the pQCD photon becomes the best reference of binary collision scaling. Measurement of photons in the low to intermediate \( p_T \) region is challenging but is quite important.

**Single electron:**
Charm and bottom are the dominant sources of single leptons, and total yield in the mid-rapidity region scales well with \( N_{\text{coll}} \). Recent results for \( v_2 \) and \( R_{\text{AA}} \) suggest that a charm quark flows and has large energy loss, as light quarks. These results need re-evaluation with the new data set from the Year-4 run. Exclusive measurements of mesons with positive vertex determination is strongly favorable.

**J/ψ:**
Good theoretical progresses have been made both in lattice-QCD and phenomenological calculations. New experimental results with good statistics are definitely waited for.

**Thermal pairs and low-mass vector mesons:**
Reduction of combinatorial background is definitely needed in order to gain accessibility to these physics quantities. The Hadron Blind Detector (HBD) seems to be the key device to serve for this purpose.

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