Electromagnetic Probes in PHENIX
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Abstract
Electromagnetic probes are arguably the most universal tools to study the different physics processes in high energy hadron and heavy ion collisions. In this paper we summarize recent measurements of real and virtual direct photons at central rapidity by the PHENIX experiment at RHIC in p+p, d+Au and Au+Au collisions. We also discuss the impact of the results and the constraints they put on theoretical models. At the end we report on the immediate as well as on the mid-term future of photon measurements in PHENIX.

Key words: direct photon, isolated photon, quark-gluon plasma, relativistic heavy ion collision
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1. Introduction

Electromagnetic probes are of crucial importance in relativistic heavy ion physics. They are real and virtual direct photons (where direct means that they are not produced in the decay of some final state hadron), and they are penetrating probes produced in virtually all subprocesses of relativistic heavy ion collisions. Equally important, once produced they escape unaltered even from a very dense medium because of their weak coupling ($\alpha_e << \alpha_s$). However, this very same property that makes them excellent “historians” of the entire collision makes both precise measurements and drawing of definitive conclusions challenging, since one has to disentangle contributions from different processes often with comparable rates in the same $p_T$ region.

In fact, for the experimenter difficulties start already by finding the direct photons themselves in the large background of photons from (final state) hadron decays like $\pi^0$, $\eta$, etc.. This can be especially hard in the low $p_T$ region; at higher $p_T$ it is somewhat easier due to the large suppression of hadrons observed in heavy ion collisions (Sec. 2). Interpretation of the results is challenging because the net signal is a convolution of photon spectra from a large variety of possible physics processes as different as initial hard scattering, a pure pQCD process, jet fragmentation, Bremsstrahlung, jet-photon conversion in the medium, and thermal radiation from the quark-gluon plasma (QGP) and/or a hot hadron gas.

Despite all these difficulties, photon physics made major inroads in the first few years of RHIC, both experimentally and theoretically - although not always in the areas originally anticipated. On one hand NLO pQCD calculations of photoproduction at central rapidities have been confirmed both in p+p and d+Au (Sec. 3), and we also have a better understanding of the ratio of photons from initial hard scattering and fragmentation in p+p. On the other hand one of the major pre-RHIC expectations was to relatively quickly establish the initial temperature $T_i$ after the collision from thermal radiation; data currently available (Sec. 4) are well described (within a factor of 2) by various models in which $T_i$...
ranges from 300 to 660 MeV - but this uncertainty is largely due to the unexpectedly fast thermalization (Sec 5). In Au+Au collisions the non-suppression of photons (Sec 4) became an independent validation of pQCD and of the concept of photons (Sec 5). In Au+Au collisions the non-suppression of largely due to the unexpectedly fast thermalization ranges from 300 to 660 MeV - but this uncertainty is assured π p KK set of fragmentation functions [8] up to 2. The “background”: neutral mesons calorimeters [4].

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in [5,6]. Note that the two detectors are fundamen-
tally different, as are their associated systematic errors, their data are analyzed separately, therefore, comparing their results is a strong, built-in consistency check in PHENIX. Electron pairs from virtual photons are identified by the tracking system, the Ring Imaging Cherenkov Detector (RICH) and the calorimeters [4].

2. The “background”: neutral mesons

Before discussing direct photons we should review briefly what is known about neutral meson (π⁰, η) production in different systems colliding at RHIC energies. In √s = 200GeV p+p collisions the measured π⁰ cross section [7] is well described by the KKP set of fragmentation functions [8] up to p_T = 13GeV/c (recent preliminary results from Run-5 ex-

\[
R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{T_{AA} \cdot d\sigma_{pp}/dp_T}
\]

where T_{AA} is the nuclear overlap function integrated over the relevant impact parameter range. The behavior of R_{AA} at high p_T (in the pQCD regime), in specific, its deviation from unity is a very important, albeit somewhat ambiguous indicator of the appearance of new, non-perturbative processes in nuclei. In d+Au collisions and at least at central rapidities R_{AA} for π⁰ is consistent with unity [9]. The situation is dramatically different in Au+Au collisions [10,11]: π⁰ production at midrapidity is suppressed by a factor of 5 with respect to T_{AA}-scaled pQCD expectations, and as seen of Fig. 1 the suppression is constant up to the highest p_T where identified hadrons have been measured so far at RHIC. Not only does this “jet quenching” constitute one of the earliest and most important discoveries at RHIC but it also makes the direct photon measurement somewhat easier at high p_T since the S/B is significantly improved. Furthermore, PHENIX has also shown that the suppression pattern is the same for η mesons [12], the second most important background for direct photons (Fig. 1). Finally, PHENIX also measured R_{AA} at √s_{NN} = 200GeV in Cu+Cu collisions, a system
much smaller than Au+Au. When mid-peripheral Au+Au collisions were compared to central Cu+Cu collisions (characterized by the same number of participants \(N_{\text{part}}\), i.e. by the same overlap volume albeit by very different geometry), the suppression pattern was the same. We should point out that this is true for the average, \(\phi\)-integrated \(R_{AA}\) only like the one shown on Fig. 1. If one studies \(R_{AA}\) as a function of the angle \(\Delta \phi\) with respect to the event-by-event reaction plane \([13]\) a significant angular anisotropy is observed (and attributed to the difference in average pathlength in the medium for quarks in or out of the reaction plane). So we fully expect that a comparison of the differential \(R_{AA}(\Delta \phi, p_T)\) in the symmetric central Cu+Cu and the \((N_{\text{part}}\)-equivalent) eccentric Au+Au systems will reveal differences and shed some more light on the nature of jet energy loss.

Hadron suppression in Au+Au and lack thereof in d+Au collisions together formed compelling evidence that a very high density matter has been formed at RHIC that strongly modifies jets created in the initial hard collisions and that - at least at central rapidities - these modifications are not due to a change of the (initial) parton distribution functions in a relativistic nucleus. However, from a purist’s point of view neither the hadron suppression nor conclusions drawn from it are on solid footing until the validity of the concept “scaling \(p+p\) cross-sections by \(T_{AA}\)” is proven with a penetrating probe. This happened by measuring \(R_{AA}\) for direct photons as also shown on Fig. 1: at and above \(\sim 5\text{GeV}/c\) the direct photon \(R_{AA}\) is consistent with unity.

3. Direct photons in p+p and d+Au collisions

In \(p+p\) collisions to leading order in \(\alpha_s\) direct photon production is dominated by gluon Compton-scattering \((q + g \rightarrow q + \gamma)\), and since RHIC is the world’s only polarized \(p+p\) collider it is a unique place to study (polarized) gluon structure functions. However, as pointed out in [6] photons emitted in parton fragmentation are also an important source of direct photons, particularly at low \(p_T\). In fact, calculations based upon CTEQ6 parton distribution functions and the GRV fragmentation function set predict that at \(\sqrt{s_{NN}} = 200\text{GeV}\) and at transverse momenta below \(3\text{GeV}/c\) more than half of photons will come from fragmentation. Note that this is the very same \(p_T\) region where in heavy ion collisions the thermal photon signal from the QGP, even if not dominant, might be sufficiently strong to be visible (Fig. 7 from [14]). Therefore, measurement and theoretical understanding of photon production in \(p+p\) is crucial both in its own right and as a baseline to interpret Au+Au data.

The PHENIX results from Run-3 on the inclusive direct photon yield (prompt and fragmentation) for \(\sqrt{s_{NN}} = 200\text{GeV} \ p+p \) and \(d+Au\) collisions is shown on Fig. 2 along with NLO pQCD calculations performed with three different renormalization scales \([15]\). At the bottom the data/theory ratios are plotted: for both systems the agreement is quite good, although not as spectacular as for pions in \(p+p\) \([16]\).

Low multiplicities in \(p+p\) collisions allow PHENIX to tag isolated photons by requiring that

![Fig. 2. Inclusive direct photon yield measured in \(\sqrt{s_{NN}}\) \(p+p\) (open triangles) and \(d+Au\) (solid circles) collisions and compared to NLO pQCD calculations.](image-url)
the energy deposited in a cone around the photon is small compared to the photon energy itself [6]. Those isolated photons come mostly from primordial hard scattering (as opposed to fragmentation). The ratio of isolated/inclusive direct photons has been measured as well as calculated and it is a sensitive test of the photon fragmentation functions [6] although one has to be careful to reproduce the acceptance bias of the experiment in the theoretical calculation. At $p_T = 7\text{GeV/c}$ and above, i.e. in the region where contribution from fragmentation is small, the measurement agrees with the calculation quite well; at small $p_T$ improved experimental techniques are needed to make meaningful comparisons.

4. Direct photons in Au+Au collisions

Based upon the $\sqrt{s_{NN}} = 200\text{GeV}$ Au+Au data from Run-2 PHENIX already published [17] centrality dependent invariant photon yields and photon excess double ratios up to $p_T = 14\text{GeV/c}$ and found - within sizeable systematic errors - that at high transverse momenta ($p_T > 5 - 6\text{GeV/c}$) the data agree well with NLO pQCD predictions scaled by $T_{AA}$. (The widely used photon excess ratio is the ratio $N_{\text{inc}}/N_{\text{had}}$ of the inclusive photons to photons from hadron decays, with values above 1 indicating the presence of direct photons. For technical reasons it is often plotted as the "excess double ratio" $N_{\text{inc}}/N_{\text{fit}}$, because it eliminates some of the systematic errors.)

The much larger dataset in Run-4 allowed PHENIX to extend the $p_T$ range up to 18 GeV/c and to reduce the errors at medium $p_T$ where several new photon production mechanisms (beyond pQCD) have been suggested recently including photons from jet-plasma interactions. The preliminary results from Run-4 on Fig. 3 show combined results from the PHENIX PbSc and PbGl up to $14\text{GeV/c}$ (where the two analyses are completely consistent, see Sec. 1) and the results are compared to $T_{AA}$-scaled NLO pQCD calculations; the overall agreement is very good.

A more detailed look to the most central collisions is given on Fig. 4 where results for the two calorimeters are plotted separately and up to 18GeV/c along with $T_{AA}$-scaled NLO pQCD alone, with contributions from the QGP and hadron gas and with in-medium jet modifications. Note that in this particular model a very short thermalization time and high initial temperature are assumed ($\tau_0 = 0.15\text{fm/c}$ and $T_i = 590\text{MeV}$, respectively); as shown later on Fig. 7 they are not the only possible choice to describe the PHENIX data. Also, while strictly speaking the PbSc and PbGl results agree within errors even above $p_T = 14\text{GeV/c}$, there is an apparent "deficit" in the PbSc with respect to both the PbGl and pQCD; the ongoing analysis of the full Run-4 dataset should clarify this situation very soon. The errors at medium $p_T$ (5-10GeV/c) are already smaller than in the published Run-2 data [17] but the trend that almost all points are above $T_{AA}$-scaled pQCD survives - a tantalizing hint of additional photon sources like jet-photon conversion, which can be further explored investigating azimuthal asymmetries in the photon distribution (Sec. 6). We discuss the low $p_T$ region (1-5GeV/c) in the context of the internal conversion measurement (Sec. 5).

5. Internal conversion photons in Au+Au collisions

A very promising approach to measure low-$p_T$ direct photons is to utilize low-mass electron pairs from "internal conversions", a technique first applied in heavy-ion collisions recently by PHENIX [18]. The basic idea is that any process
producing a real photon can also produce a virtual one of very low mass [19], subsequently decaying into an \( e^+e^- \) pair. This direct photon signal competes, of course, with dielectrons from Dalitz decays of \( \pi^0, \eta, \) etc. The rate and mass distributions of dielectrons are described both for the low-mass direct photons and the Dalitz decays by the Kroll-Wada formula [19],

\[
\frac{1}{N_{\gamma}} \frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi} \sqrt{1 - \frac{4m_{\pi}^2}{m_{ee}^2}} \left( 1 + \frac{2m_{\pi}^2}{m_{ee}^2} \right) \frac{1}{m_{ee}} \left| F(m_{ee})^2 \right| (1 - \frac{m_{ee}^2}{M^2})^3,
\]

where the form factor, \( F \), is unity for real photons. Note that the phase space for Dalitz decays is limited by the mass of the parent meson \( (m_{ee} < M_{\pi^0,\eta,\omega}) \), while for direct photons it is not \( (m_{ee} \sim p_T) \). Therefore, the measurement becomes relatively clean for \( p_T > 1 \) GeV/c, which is still in the low-\( p_T \) realm where the “traditional” calorimeter measurement has serious difficulties. The method is illustrated on Fig. 5, described in detail in [18] and the resulting photon excess ratios are shown as solid circles on Fig. 6. The systematic errors are much smaller for the internal conversion measurement (solid circles) than for the traditional calorimeter measurement (open circles) but the statistical errors become large for \( p_T > 4 \) GeV/c. Tantalizingly, the low \( p_T \) region is consistent with a 10% photon excess over the hadronic background (and with the traditional measurement), but before drawing conclusions about a thermalized source the same measurement has to be repeated in p+p to establish the baseline. Also, since internal conversion is a very small probability process the method would greatly benefit from at least an order of magnitude increase of the available dataset (Sec. 7).

Using the inclusive photon yields from the calorimeter measurement [17] the excess ratio on Fig. 6 can be translated into a direct photon yield and compared to theory as shown on Fig. 7. Partial contributions are calculated in [14,20] and the solid curve is the sum of all subprocesses; it describes the data very well. Remarkably, this calculation uses an expanding fireball with \( \tau_0 = 0.33 \) fm/c and \( T_i = 370 \) MeV, double the formation time and only 2/3 of the temperature conjectured in [21] and applied on Fig. 4. In fact, five different models with thermalization times in the range 0.15-0.5 fm/c and initial temperatures between 300 MeV and 660 MeV describe the data within a factor of 2. But even with these uncertainties a very important lesson has already been learned: while pre-RHIC expectations put the thermalization time to \( \sim 1 \) fm/c, in turned out to be much shorter and the need to find the mechanism of this unexpectedly rapid thermalization triggered a large amount of theoretical work recently.

6. Azimuthal asymmetries in direct photon production

We have seen in Fig. 6 that the overall yields of high-\( p_T \) photons (integrated over azimuth) scale...
Fig. 6. Nuclear modification factor $R_{AA}$ in central Au+Au collisions ($\sqrt{s_{NN}} = 200\text{GeV}$) for $\pi^0$, $\eta$ and direct photons, compared to a GL V calculation with $dN_g/dy = 1200$ gluon density. The mesons - independent of their mass - are suppressed by a factor of 5 with respect to their yield in p+p scaled with the nuclear thickness $T_{AB}$, whereas the direct photons are not suppressed.

**Fig. 7.** Predictions for direct photon spectra combining pQCD initial, jet-plasma interactions [20] as well as thermal radiation [14], compared to preliminary PHENIX data. The lines labeled "Th-Th" and "HG" correspond to the usual thermal radiation from QGP and hadron gas, respectively.

Fig. 8. Nuclear modification factor $R_{AA}$ in central Au+Au collisions ($\sqrt{s_{NN}} = 200\text{GeV}$) for $\pi^0$, $\eta$ and direct photons, compared to a GLV calculation with $dN_g/dy = 1200$ gluon density. The mesons - independent of their mass - are suppressed by a factor of 5 with respect to their yield in p+p scaled with the nuclear thickness $T_{AB}$, whereas the direct photons are not suppressed.

with $T_{AA}$ and are well described by pQCD (within current experimental and theoretical uncertainties). However, this global agreement may mask more subtle effects and it is even possible that the agreement is only accidental, due to cancellations of processes that enhance and others that quench the photon yield. An important step toward clarification is to study azimuthal asymmetries of photon distributions, specifically their elliptic flow ($v_2$). If (and since) the photons from the initial scattering do not interact with the medium, their $v_2$ is expected to be zero. However, initial hard scattering is far from being the only source of photons in Au+Au collisions. Photons may also originate from jet partons scattering off thermal partons (jet-thermal interactions) or from Brehmsstrahlung off a quark. These photons are expected to exhibit a negative $v_2$ [22,23], since more material is traversed out-of-plane (which is the major axis in coordinate space), with a strong $p_T$ dependence. On the other hand, photons from thermal radiation should reflect the dynamical evolution of the hot and dense matter thus carrying a positive $v_2$.

A first measurement of photon elliptic flow is shown in Fig. 8 taken from Ref. [24]. The measurement is quite delicate due to the large background from $\pi^0$ decay-photons that inherit their parent’s
v_2$. The measured $v_2$ of inclusive photons is consistent with $v_2$ of photons from hadronic decays, i.e., a zero net direct photon flow - but the error bars are appreciable and the direct-to-inclusive photon ratio is very small at low $p_T$. The quality of the data currently available is not sufficient to prove or disprove theoretical predictions [22,23], not even the sign of the net flow. Much higher statistics can help remedy the situation, at least at higher $p_T$: although the net direct photon flow is predicted to decrease, the statistical errors will also become smaller and, equally important, the direct-to-inclusive photon ratio increases dramatically. But even at high $p_T$ the net flow will be a competition between processes with $v_2 > 0$ and $v_2 < 0$. New analysis techniques may be able to disentangle (at least statistically) isolated and non-isolated direct photons in heavy-ion collisions. Jet-photon conversions produce mostly isolated photons [22] with $v_2 < 0$ and the magnitude of this flow depends strongly both on $p_T$ and the energy-loss mechanism of jets in heavy-ion collisions. Therefore, a measurement of the $v_2$ for isolated photons may give an independent constraint on energy-loss models.

7. Outlook

One of the fundamental questions in the pQCD phase transition is whether chiral symmetry is (partially?) restored and in this context to measure the in-medium modification of the light vector meson ($\rho, \omega, \phi$) spectral functions. In PHENIX this can be done in the $e^+e^-$ channel, and “proof of principle” results have been shown earlier [25]. However, suffering from an $\sim 1/500$ signal/background ratio - combinatorics from $\pi^0$ Dalitz-decays and photon conversions - they are not precise enough to make a meaningful statement on broadening or dropping of vector meson masses. A hadron-blind detector (HBD), already foreseen in the original PHENIX design and actually installed September 2006 for Run 7 will remedy this situation, as illustrated by the simulations shown on Fig. 9. This novel detector, described in [26] is a windowless Cherenkov detector operated with pure CF$_4$ in a proximity focus configuration with a CsI photocathode and a triple GEM detector with pad readout, and improves the signal to background ratio to $\sim 1/10$.

The remaining background from open charm will be measured in PHENIX separately with a Silicon Vertex Detector (SVTX), which will measure the heavy-flavor displaced vertex with a 40$\mu$m resolution of the distance of closest approach, the specification driven by $ct$ of 123 and 462$\mu$m for $D^0$ and $B^0$ decays, respectively. The SVTX will have a central barrel and two endcap detectors, thus covering both central and forward rapidities, providing inner tracking with full azimuthal coverage and up to $|\eta| < 2.4$. This, in particular, will enable the measurement of correlated $e\mu$ invariant-mass spectra and thus provide for a stand-alone determination of the correlated open-charm (and -bottom) component in the dilepton spectra.

Photons, $\pi^0$ and $\eta$ mesons can be measured well at mid-rapidity in PHENIX, but the pseudorapidity coverage of the electromagnetic calorimeter (along with the current “central arm”) is limited to $|\eta| < 0.35$. This makes full jet reconstruction very difficult. Also, several measurements made at large rapidities in d+Au collisions suggest that in the low Bjorken-$x$ domain gluons might be saturated and
the CGC-model properly describes the results, including hadron suppression at large rapidities in d+Au (as opposed to no suppression as observed at y = 0). If the suppression at large y is indeed a consequence of gluon saturation (initial state), photons should also be suppressed there — an important test feasible only with a calorimeter at large rapidities. The limited acceptance of the central arm also makes the crucial \( \gamma \)-jet measurements very difficult. To remedy the situation PHENIX already added a high resolution Muon Piston Calorimeter (MPC) to 3 < \( \eta \) < 4 and proposed to add a calorimeter replacing the current copper nosecones of the magnet and covering 1 < |\( \eta \)| < 3. The longitudinally segmented Nose-Cone Calorimeter (NCC) will allow for distinction between electromagnetic and hadronic showers. Jet physics and energy-loss studies using both photon-tagged jets and leading \( \pi^0 \)'s will be possible with the NCC, far away from central rapidity. It will also be very useful in studying heavy quarkonia enabling for instance the measurement of \( \chi_c \rightarrow \gamma J/\psi \) and possibly the \( \chi_b \rightarrow \gamma Y \) states in conjunction with the existing muon spectrometer. It is also an important addition to the spin program in measuring the (polarized) gluon structure functions at low \( x \).

8. Summary

In this paper we reported on recent measurements of direct photons by the PHENIX experiment at RHIC at central rapidity. Invariant yields in p+p collisions are well described by NLO pQCD calculations, as are the d+Au results if the calculations are scaled with the nuclear thickness function. In Au+Au the high transverse momentum region is well reproduced by (the \( T_{AA} \)-scaled) NLO pQCD; at medium transverse momenta additional, medium-induced production mechanisms are possible although so far they are neither confirmed nor ruled out by measurements of the azimuthal anisotropy of photons. At low \( p_T \) the Au+Au data are consistent with a 10% direct photons excess whose origin will be constrained by a similar measurement in p+p. The hadron-blind detector currently installed in PHENIX will give access to high quality data on low mass vector mesons. Current and mid-term upgrades will extend the photon and jet measurements to 1 < |\( \eta \)| < 4.

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