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G. David, et al

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Physics Department/PO/2-182

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

DISCLAIMER

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G. David (for the PHENIX Collaboration)
BNL, Upton, NY 11973, USA

Direct photons are ideal tools to investigate kinematical and thermodynamical conditions of heavy ion collisions since they are emitted from all stages of the collision and once produced they leave the interaction region without further modification by the medium. The PHENIX experiment at RHIC has measured direct photon production in p+p and Au+Au collisions at 200 GeV over a wide transverse momentum (p_T) range. The p+p measurements allow a fundamental test of QCD, and serve as a baseline when we try to disentangle more complex mechanisms producing high p_T direct photons in Au+Au. As for thermal photons in Au+Au we overcome the difficulties due to the large background from hadronic decays by measuring "almost real" virtual photons which appear as low invariant mass e^+e^- pairs: a significant excess of direct photons is measured above the above next-to-leading order perturbative quantum chromodynamics calculations. Additional insights on the origin of direct photons can be gained with the study of the azimuthal anisotropy which benefits from the increased statistics and reaction plane resolution achieved in RHIC Year-7 data.

1. INTRODUCTION

Direct photons - defined as those not originating from (final state) hadron decays - are an important tool with unique capabilities to study both elementary particle and heavy ion collisions. By not interacting strongly they have a large mean free path and leave the interaction region unaltered even if they propagate through the hot, dense medium assumed to be formed in relativistic heavy ion collisions. The lowest order QCD processes generating photons - quark-antiquark annihilation ($q\bar{q} \rightarrow g\gamma$) and quark-gluon Compton scattering ($qg \rightarrow q\gamma$) - are reasonably well understood [1] thus photons are a sensitive probe of modifications of the parton distribution functions in nuclei (nPDFs). Furthermore, in p+p collisions at higher transverse momenta (p_T) the Compton process dominates, thus the photon "calibrates" the total energy of the opposing gluon jet (apart of the uncertainty stemming from the intrinsic k_T of partons). Setting the energy scale of the hard scattered parton (and the ensuing jet) is even more important in heavy ion collisions, where the partons lose a significant fraction of their energy while crossing the medium [2].

At higher order fragmentation (or Bremsstrahlung) photons contribute both in p+p and heavy ion collisions; the calculated rates in p+p are consistent with recent measurements but the uncertainties are large both on the theoretical and experimental side [3]. It is very important to understand all p+p processes as well as possible because in heavy ion collisions several new photon production mechanisms emerge or become significant, and often it is exactly the *difference* from p+p behavior that reveals the new physics. Case in point: the nuclear modification factor R_{AA}, the ratio of a cross-section measured in A+A collisions and the corresponding p+p cross-section scaled by the nuclear thickness function. If R_{AA} is different from unity, it invariably signals some new physics in A+A with respect to p+p collisions. If $R_{AA} = 1$ the interpretation is somewhat less clear: either the physics mechanisms producing photons are exactly the same as in p+p, or there might possibly be a "conspiracy" of mechanisms, some increasing, others decreasing R_{AA} but ultimately balancing each other. Also, one has to be careful when interpreting direct photon R_{AA}. For high p_T hadrons (thought to be mostly leading fragments of jets) scaling the p+p cross-sections with the nuclear thickness to obtain the expected A+A rates (colloquially "scaling with the number of binary nucleon-nucleon collisions" or "N_{coll} scaling") is legitimate due to the isospin symmetry of protons and neutrons in the nucleus. The same is not true for direct photons: due to the electromagnetic coupling the photon cross section is proportional to the sum Σe_q^2 of quark charges squared, different for p and n, causing a trivial deviation of R_{AA} from unity ("isospin effect" [4]) which may either mask or enhance other effects changing R_{AA}. In fact, the cleanest way to generate direct photon R_{AA} would be to compare to a properly scaled mixture of pp, pn and nn cross-sections at the same energy, which could (and in the author's private opinion, should) be measured at RHIC from d+d collisions, since the above three reactions could be tagged event-by-event.

While direct photons carry a plethora of (almost) unbiased information, measuring them is very challenging due to the large background from hadron decays. Substantial statistics and a thorough understanding of systematic errors are required. If in addition to the total direct photon yield one wants to *disentangle* the contributions from different physics sources (with minimal theoretical input and assumptions) the difficulties are even higher - but not insurmountable. Studying the emergence and evolution of new phenomena and at the same time tight control of the systematics is crucial. In specific, measuring various colliding systems (from p+p to the heaviest A+A) at different c.m.s. energies in the very same experiment goes a long way toward this goal. The flexibility of the accelerator and of the experiments at RHIC offers such an opportunity.

2. DIRECT PHOTONS AT RHIC - HIGH p_T AND THE THERMAL REGION

Direct photon cross-sections in $\sqrt{s} = 200$GeV p+p collisions at RHIC were first published in the limited $5 < p_T < 8$GeV/c range in [5], followed by a measurement in the $3 < p_T < 16$GeV/c range with considerably smaller systematic errors and detailed comparison to NLO pQCD calculations [3]. It was found that above $p_T > 5$GeV/c (where the systematic errors of the experiment and theory were comparable) the data are well described by the theory, including the fraction of isolated photons. This was welcome news after the “controversial situation” [1] of the past decade. Since RHIC collides polarized protons, a measurement of the polarized gluon structure functions is now within reach. The data also provide a measured - rather than calculated - baseline for the nuclear modification in heavy ion collisions (*modulo* the isospin-effect).

The first direct photon invariant yields up to $p_T = 13$GeV/c from $\sqrt{s_{NN}} = 200$GeV Au+Au collisions were published in [6], covering all collision centralities (impact parameter ranges) and in the same paper the direct photon R_{AA}, using an NLO pQCD reference and integrated above $p_T > 5$GeV/c was shown to be unity within errors for all centralities. This was a landmark result because it retroactively validated the concept of “N_{coll}-scaling” and R_{AA} itself in studying “jet-quenching” at high p_T with single inclusive hadron spectra [7, 8]. Although recent developments in theory and better data help to draw a more nuanced picture of how, where and when high p_T photons are produced (in addition to primordial hard scattering), the above conclusion is still sane, not the least thanks to the large differences between the effects: π^0-s are suppressed by a factor of 5, while direct photons (still *mostly* from hard scattering) are suppressed much less, or not at all.

More recent (and still preliminary) data on direct photon R_{AA} and comparisons to theoretical calculations are shown on Fig. 1. With the p_T range now extended to 20GeV/c photons appear to be somewhat suppressed. As mentioned before, some of this might be of trivial origin; the solid line predicts a 15% drop due to the isospin effect alone. Counteracting to this - particularly at medium p_T, *i.e.* in the $0.1 < x = 2p_T/\sqrt{s} < 0.2$ region - is the anti-shadowing (dash-dotted curve). On the other hand, if parton energy loss is added, direct photon production is suppressed in the entire range (band at the bottom of the figure).

While the energy loss in the medium suppresses the yield of high p_T particles, possibly including photons, the “jet-photon conversion” mechanism [9] may increase high p_T photon production. In this process a hard scattered quark (proto-jet) interacts with a gluon or antiquark of the medium. The collision has a collinear singularity thus the outcoming photon carries the full momentum of the original parton. Note that since antiquarks abund in the thermalized medium, $q\bar{q}$ annihilation is no longer suppressed with respect to Compton-scattering of gluons thus a new channel to direct photon production opens up.

An up-to-date overview of the known/assumed direct photon production mechanisms in heavy ion collisions is given in [10] and detailed, centrality-dependent calculations are shown in [11]. The tantalizing question is whether the contributions from the individual components can be disentangled experimentally? In other words: can the theory be tested? The answer is a tentative “yes” with a possible path laid out in [12] and briefly repeated here.

First, one has to realize that future, substantially larger data volumes not only decrease the statistical errors, but they also help to apply more sophisticated analysis techniques that reduce the systematic errors. Also, they allow meaningful analyses of multiple-differential quantities like azimuthal asymmetries of photon production. While such asymmetries are not expected from the primordial hard scattering, medium-related photon sources will exhibit them.

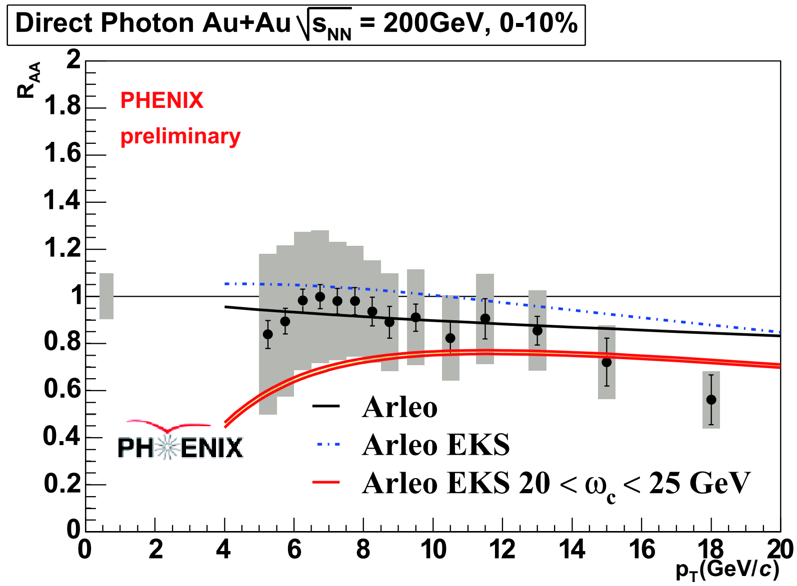

Figure 1: Direct photon R_{AA} in central (0-10%) $\sqrt{s_{NN}} = 200$GeV Au+Au collisions. The denominator is a fit to the PHENIX preliminary Run-5 p+p data. The theoretical curves are LO calculations from [4]. The solid line shows the pure isospin effect, the dash-dotted line shows the combined effect of isospin and (anti)shadowing (EKS), finally the band at the bottom combines isospin and antishadowing with photon quenching.

By now it is well established that due to the azimuthally asymmetric overlap geometry in all but the most central nucleus-nucleus collisions the pressure gradients and thus the momentum distributions of final state hadrons are asymmetric in azimuth ("flow"). The second Fourier-component (v_2) of the azimuthal distribution of momenta is positive for all hadrons, therefore, $v_2 > 0$ for all hadron decay photons as well (the background to the direct photon measurement). Also, $v_2 > 0$ for jet fragmentation photons. On the other hand medium-induced photons typically exhibit $v_2 < 0$, corresponding to the longer average pathlength of the parton in the medium. However, within this category jet-photon conversion photons are isolated whereas Bremsstrahlung photons are not. These properties might help to disentangle the different production mechanisms of direct photons.

Thermal radiation of photons from the quark-gluon plasma is expected to dominate in the $1 < p_T < 3$GeV/c region, where the measurement of (real) direct photons with classic calorimetry is nearly impossible due to the large hadron decay background. However, one can measure "quasi-real" virtual photons which manifest themselves as low mass e^+e^- pairs [13]. With this technique - applied for the first time in heavy ion collisions - the PHENIX experiment measured the fraction of direct photons in the total inclusive photon spectrum both in p+p and Au+Au collisions. The results are shown on Fig. 2 and compared to NLO pQCD calculations. In p+p the results are clearly consistent with the calculations (no new, unknown sources), while in Au+Au we observe a statistically significant, 10% excess at low p_T. Converting this excess into invariant yield and fitting it with an exponential we find [13] an inverse slope $T = 221 \pm 23(stat) \pm 18(sys)$MeV. Note that lattice QCD predicts a phase transition already at $\sim$170MeV, far below the value fitted to our data. Also, since the observed direct photon spectrum is the integral over the entire thermal history of the system, the above $T \sim 220$MeV estimate is almost certainly a lower bound only, and the initial temperature T_i of the system is much higher.

Acknowledgments

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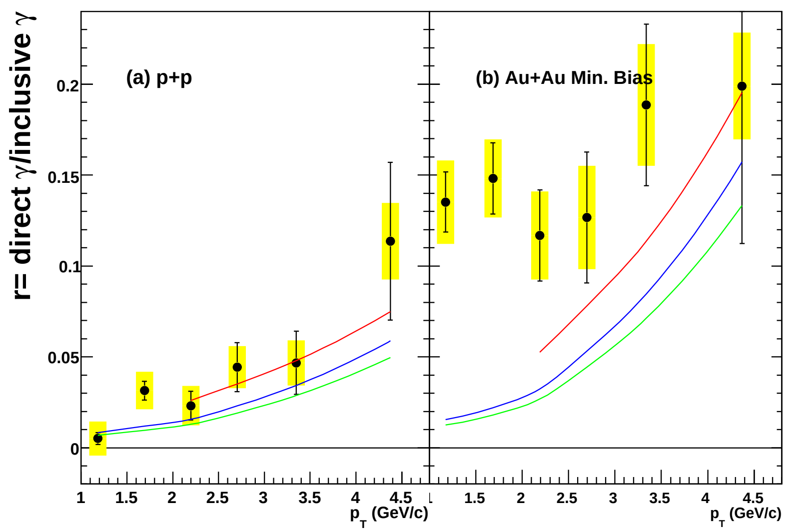

Figure 2: The fraction of the direct photon component as a function of p_T in (a) p+p and (b) Au+Au (min. bias). The error bars and the error band represent the statistical and systematic uncertainties, respectively. The curves are from a NLO pQCD calculation.

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