

Can the QGP be found using only an Electromagnetic Calorimeter?

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Abstract. Measurements using the finely segmented EM Calorimeter in PHENIX are presented. The issue of whether these are sufficient to claim discovery of the Quark Gluon Plasma is discussed.

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1. How to discover the Quark Gluon Plasma

The “gold-plated” signature for the discovery of the Quark Gluon Plasma and the proof of “deconfinement” is the suppression of J/Ψ due to “Debye screening” which dissociates the bound pair of $c - \bar{c}$ quarks. [1] The PHENIX experiment at RHIC is a special purpose detector [2] designed to observe this classic signature, and, more generally, to measure rare processes involving leptons and photons at the highest luminosities.

2. How the PHENIX detector was designed

The principles of the design of PHENIX are illustrated in Fig. 1. In order to detect electrons in hadron collisions, where the typical ratio of e^\pm/π^\pm is known to be of order of 10^{-4} for prompt electrons (from charm) at $23.5 \leq \sqrt{s} \leq 62.4$ GeV [4] (ISR energies), one must plan on a charged pion rejection of $> 10^5$. PHENIX decided to use a Ring Imaging Cerenkov counter (RICH) in combination with an Electromagnetic Calorimeter (EMCal) to achieve this rejection. There is also the issue of the huge background of e^\pm from internal and external conversion of the photons from π^0 decay or from direct photon production, which must be measured and understood to high precision. The EMCal is crucial for this purpose. The EMCal measures the energy of γ and e^\pm and reconstructs π^0 from 2 photons. It

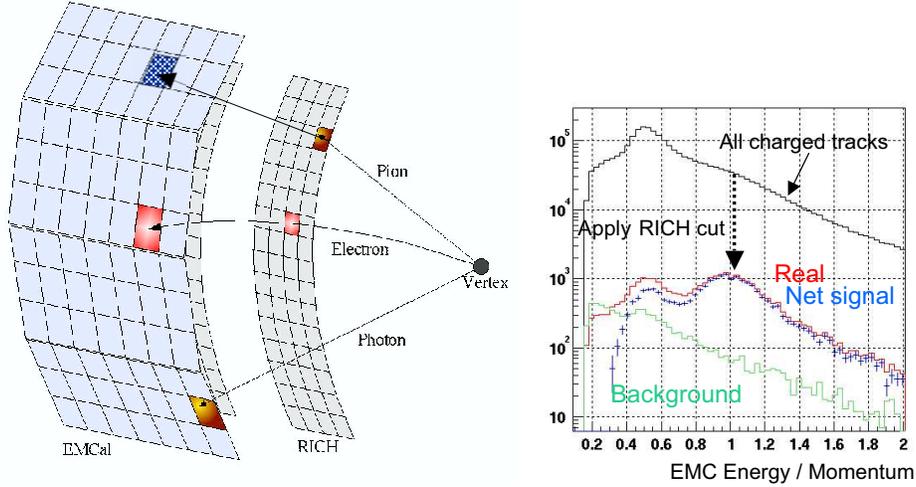


Fig. 1. (left) Schematic of π^\pm , e^\pm and γ in PHENIX, with ElectroMagnetic Calorimeter (EMCal) and Ring Imaging Cherenkov Counter (RICH). (right) Energy/momentum for all charged particles detected in the EMCal with and without a RICH signal.

measures a decent time of flight (TOF), 0.3 nanoseconds over 5 meters, allowing photon and charged particle identification. A high precision TOF over part of the aperture allows improved charged hadron identification. Electrons are identified by a count in the RICH and matching Energy and momentum (E/p), where the momentum is measured by track chambers in a magnetic field. Charged hadrons deposit only minimum ionization in the EMCal (~ 0.3 GeV), or higher if they interact, and don't count in the RICH (π^\pm threshold 4.7 GeV/c). Thus, requiring a RICH signal rejects all charged hadrons with $p < 4.7$ GeV/c, leaving only e^\pm as indicated by the $E/p = 1$ peak in Fig. 1-right. π^\pm can be identified above 4.7 GeV/c by a RICH signal together with an EMCal hit with minimum ionization or greater. It is amusing to realize that once you decide to measure electrons, you must make an excellent π^0 measurement to understand the background, and this implies a detector which can measure and identify almost all particles, as exemplified by the PHENIX central spectrometer.

Admittedly, in order to detect the QGP, there must be charged particle tracking to complement the EMCal and measure the momenta of charged hadrons and e^\pm . In the following, we discuss how an EMCal can be used to measure centrality, fluctuations, high p_T pions and direct photon production. Further discussion on J/Ψ and open charm detection in PHENIX using single e^\pm and e^+e^- pairs is given in a related article. [3]

3. Centrality Measurement and Fluctuations

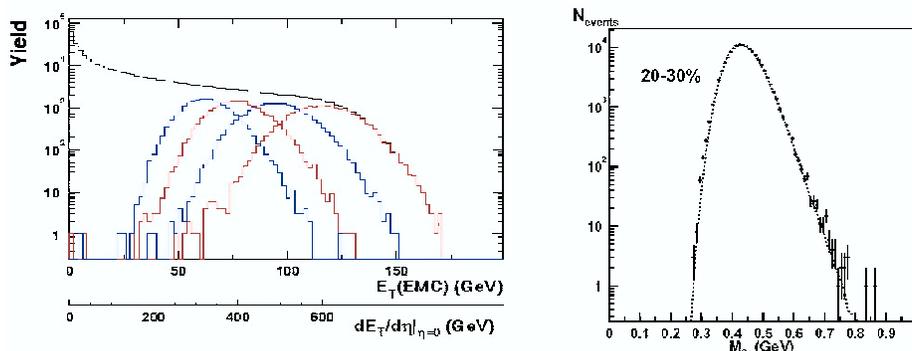


Fig. 2. (left) PHENIX E_T distribution in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV showing centrality selections of 0-5%, 5-10%, 10-15%, 15-20%. (right) Event-by-event average E_T /cluster in the EMCal for 20-30% centrality (data points), random baseline (dotted line).

E_T distributions at mid-rapidity (see Fig. 2-left), measured in either hadron or EM calorimeters, have traditionally been used as a measure of centrality in B+A collisions in terms of the upper percentiles of the distribution. [5] They also measure the Bjorken estimator of the energy density of the collision: [6]

$$\epsilon_{Bj} = \frac{1}{\tau_0 \pi R^2} \frac{dE_T}{dy} \quad , \quad (1)$$

which is $5.5 \text{ GeV}/\text{fm}^3$ for Fig. 2-left, well above the value of $1 \text{ GeV}/\text{fm}^3$ nominally required for QGP formation. Fluctuations can also be studied. For instance, is the shape of the upper edge of the centrality selected E_T distributions in Fig. 2-left random, or is it evidence of non-random fluctuations? The event-by-event distribution M_{eT} of the average E_T per cluster, which is closely related to E_T and also to M_{pT} , the event-by-event average p_T of charged particles, is shown in Fig. 2-right. [7] This measures the non-random fluctuations by comparison to a random baseline from mixed events. M_{pT} is defined:

$$M_{pT} = \overline{pT} = \frac{1}{n} \sum_{i=1}^n p_{T_i} = \frac{1}{n} E_{Tc} \quad , \quad (2)$$

where E_{Tc} is the analog of E_T for charged particles. PHENIX has shown that the non-random M_{pT} fluctuations are of the order of 1% [8] and are consistent with being the result of momentum correlations from jets. This places severely small limits on the critical fluctuations expected for a first order phase transition.

4. Hard-Scattering as a new probe of the QGP

One sure way to get a partonic probe into the dense nuclear matter produced in an A+A collision is to use the high p_T partons produced by hard-scattering. For p-p collisions in the RHIC energy range, hard-scattering is the dominant process of particle production with $p_T \geq 2$ GeV/c at mid-rapidity. Particles with $p_T \geq 2$ GeV/c are produced from states with two roughly back-to-back jets which are the result of scattering of constituents of the nucleons as described by QCD.

The high granularity of the individual EMCAL towers is $(\delta\eta \times \delta\phi) \sim (0.01 \times 0.01)$, which allows the two photons from a π^0 to be resolved from a single photon cluster for values of p_T up to 30 GeV/c, or higher. The performance of the EMCAL for detecting $\pi^0 \rightarrow \gamma + \gamma$ in Au+Au collisions is shown in Fig. 3-left. The π^0 cross section measurement from p-p collisions at $\sqrt{s} = 200$ GeV (Fig. 3-right) nicely agrees with NLO QCD predictions over the range $2.0 \leq p_T \leq 15$ GeV/c. [9]

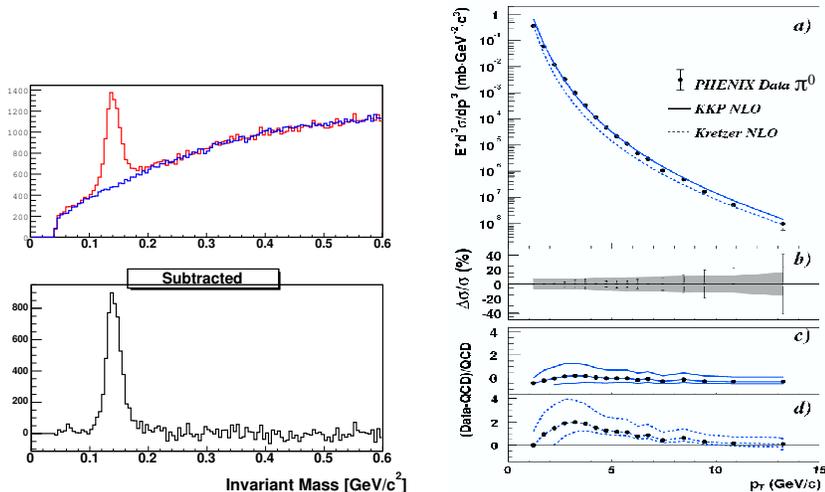


Fig. 3. (left) Pizero peak Au+Au minimum bias collisions for $4.5 \leq p_T \leq 5.0$ GeV/c. (right) PHENIX π^0 invariant cross section at mid-rapidity from p-p collisions at $\sqrt{s} = 200$ GeV, together with NLO QCD predictions.

4.1. Scaling hard-scattering from p-p to p+A and B+A collisions

Since hard-scattering is pointlike, with distance scale $1/p_T \leq 0.1$ fm, the cross section in p+A or B+A collisions, compared to p-p, is simply proportional to the relative number of possible pointlike encounters, or A (BA), for p+A ($B+A$) minimum bias collisions, and $T_{AB}(b)$, the overlap integral of the nuclear profile functions, as a function of impact parameter, b . In lepton scattering, where hard-scattering was discovered, [10] the cross section for μ -A collisions is indeed proportional to $A^{1.00}$ (Fig 4-left). [11] In p+A collisions, the cross section at a given p_T also scales

as a power law, $A^{\alpha(p_T)}$ (Fig 4-right), but the power $\alpha(p_T)$ is greater than 1! This is the famous ‘‘Cronin Effect’’. [12]

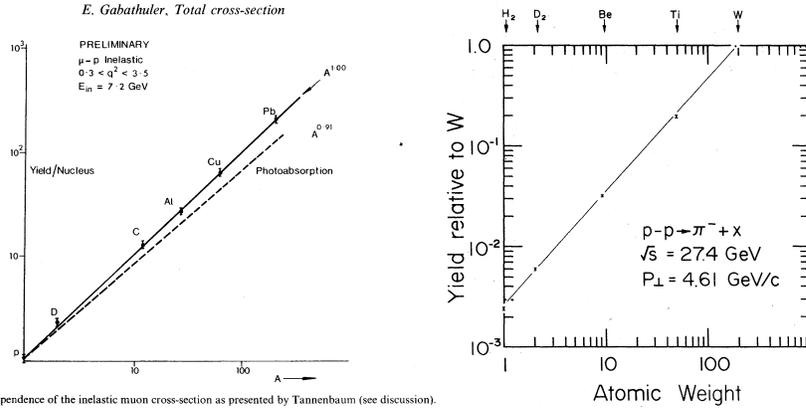


Fig. 14. The A dependence of the inelastic muon cross-section as presented by Tannenbaum (see discussion).

Fig. 4. A dependence of μ - A scattering (left) compared to p + A (right).

5. Measurements of high p_T π^0 and π^\pm production in d + Au and Au + Au collisions

I believe that the most spectacular discovery at RHIC so far is the suppression of high p_T π^0 in Au + Au collisions (Fig. 5-left). [13–15]

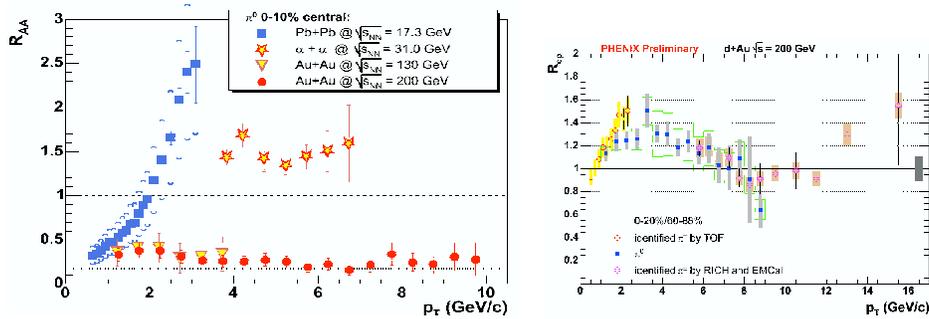


Fig. 5. (left) The nuclear modification factor R_{AA} for high p_T π^0 production in A + A collisions. (right) R_{CP} (point-like-scaled central/peripheral) for pions in d + Au collisions at RHIC showing a Cronin effect. [16]

In Au + Au central collisions at $\sqrt{s_{NN}} = 130$ GeV [13] and 200 GeV [14] the ratio, R_{AA} , of the Au + Au π^0 cross-section to the point-like-scaled p - p cross section is pretty much the same as a function of p_T for both 130 and 200 GeV, and in each case is much less than 1! The high p_T π^0 from central Au + Au collisions are suppressed by a factor of from 3-5 in the range $2 \leq 10$ GeV/c! This ‘‘anti-Cronin’’

effect is truly astounding and unique at RHIC. π^0 production in A+A collisions at lower $\sqrt{s_{NN}} \leq 31$ GeV and in p+A (or d+A) collisions, even at RHIC [17] (Fig. 5-right) all show a Cronin effect, an enhancement with respect to point-like-scaled p-p collisions. This implies that the suppression in Au+Au collisions at RHIC energies is due to final state interaction with the hot, dense and possibly deconfined medium produced, and is not due to an initial state effect such as gluon shadowing or coherence which would also show up in d+Au collisions.

5.1. The power of the power-law.

A power-law dependence is characteristic of hard-scattering. This is shown for both the Au+Au central and p-p data in Fig. 5-left. The invariant cross section behaves

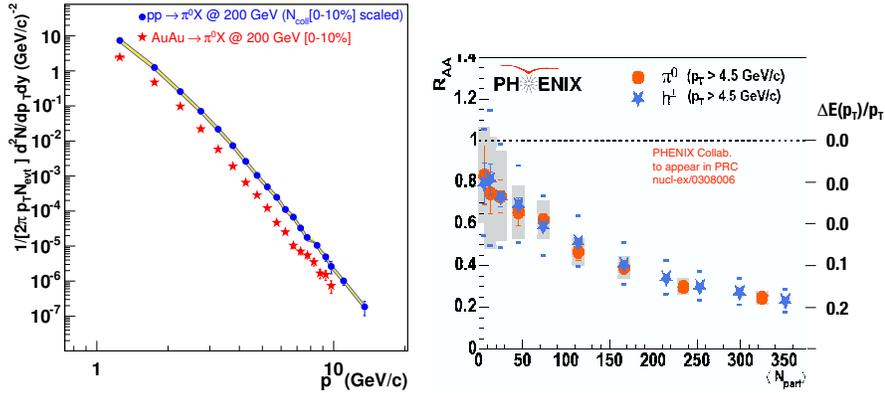


Fig. 6. (left) log-log plot of PHENIX π^0 p_T spectrum in central Au+Au collisions compared to scaled p-p data. (right) Centrality dependence of R_{AA} for $p_T \geq 4.5$ GeV/c with computed $\Delta E(p_T)/p_T$.

as a pure power, p_T^{-n} , for $p_T \geq 3$ GeV/c, with $n = 8.1 \pm 0.1$. It is easy to see that the medium effect in Au+Au collisions is equivalent to either a suppression of a factor R_{AA} at a given p_T or a shift in p_T of the Au+Au spectrum relative to the p-p spectrum. In fact the spectra are quite parallel, so the shift to match the spectra is a constant for all p_T , corresponding to a constant R_{AA} , or to a constant fractional shift $\Delta E(p_T)/p_T = 1 - R_{AA}(p_T)^{1/(n-1)}$ for $p_T \geq 4.5$ GeV/c, for all centralities. [18] (See Fig. 5-right.)

Another advantage of the power-law is that it makes the precise calculation of the photon spectrum from $\pi^0 \rightarrow \gamma + \gamma$ decay rather easy.

$$\text{If } \frac{dn_{\pi^0}}{p_T dp_T} \propto p_T^{-n} \quad \text{then} \quad \left. \frac{\gamma}{\pi^0} \right|_{\pi^0}(p_T) = 2/(n-1) \quad . \quad (3)$$

Since the photons from $\pi^0 \rightarrow \gamma + \gamma$, $\eta \rightarrow \gamma + \gamma$ and similar decays are the principal background to direct photon production, the importance of a precise estimate of this background can not be overstated.

6. Direct Photon production in Au+Au

The first measurement of direct photon production in Au+Au collisions at RHIC was shown by the PHENIX collaboration at Quark Matter 2004. [19] These photons originate from the ‘hard’ process $g + q \rightarrow \gamma + q$. There are lots of photons at RHIC. The problem is to subtract the background photons from π^0 and η decay. The simple (but accurate) approach in Eq. 3 gives, for $n = 8.1$, $\gamma|_{\pi^0}/\pi^0 \sim 1.2 \times 2/7.1 = 0.34$ where the factor 1.2 includes $\eta \rightarrow \gamma + \gamma$ (estimated). The validity of this simple approach is evident by comparison to the full calculation of γ/π^0 from known decays (Fig. 7-left).

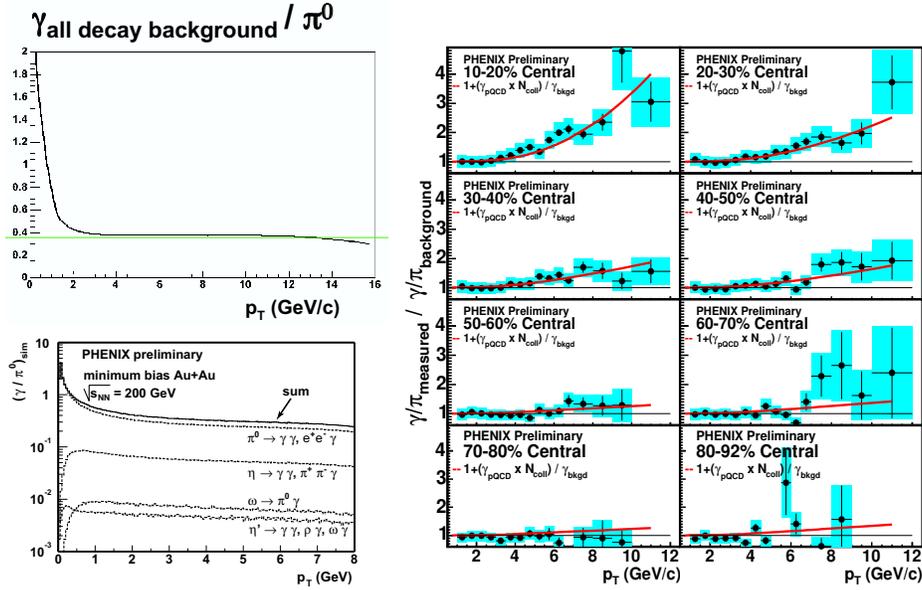


Fig. 7. (left)-(top) Calculation of background photon spectrum from known decays, expressed as $\gamma|_{\text{background}}/\pi^0$ compared to Eq. 3. (left)-(bottom) Individual components of the background. (right) PHENIX direct photon measurements relative to the calculated background for $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions, as a function of centrality (data points). The curves represent a pQCD calculation of direct photons in p-p collisions scaled to Au+Au assuming pure point-like (N_{coll}) scaling, with no suppression.

The direct photon measurements in Au+Au as a function of centrality follow pure point-like (N_{coll}) scaling relative to a pQCD calculation for p-p collisions, with no suppression, quite different from the π^0 measurements. This is good news because photons should not interact with the hot, dense medium. Ironically, the fact that the main source of background, the π^0 's, are suppressed in Au+Au collisions, while the direct photons are not, makes the measurement easier in Au+Au collisions than in p-p collisions.

7. Conclusions

It may very well be possible to find the QGP using only an EM Calorimeter. But it's better with e^\pm i.d. at the trigger level, and still better with μ^\pm , too. It is even better with full charged hadron identification. The only remaining question, since π^0 suppression is spectacular but is apparently not sensitive to deconfinement [18], is whether we have found the QGP at RHIC, or merely the densest, nuclear matter ever to have existed since the Big Bang?

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