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Highlights from PHENIX: I

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Abstract
This contribution highlights recent results from the PHENIX Collaboration at RHIC. It covers global variables, flow and 2-particle correlations. A second contribution in this issue, by T C Awes (2008 *J. Phys. G: Nucl. Part. Phys.* **35** 104007), covers PHENIX results on heavy quarks, leptons and photons.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL) in Upton, NY has just finished its eighth year of operation. The PHENIX Collaboration with its to-date 476 scientists from 67 institutions and 14 Nations has collected in the recent d–Au and p–p run a record 577 TB of data and 275 billions events. The Run-8 d–Au sample represents a 30 times increase over the Run-3 data set despite the addition of new detectors which are described in section 2 in more detail. These large data samples allow us to probe the properties of the new matter with precision measurements of the distributions and systematic study of their dependence on colliding system, centrality, rapidity or even the reaction plane. RHIC also increased its luminosity by a better understanding of the machine and new techniques such as stochastic cooling.

RHIC is likely to be the most versatile heavy ion collider in the world and has collided in its first eight years four different species at six different beam energies. Table 1 shows a summary of these first eight years of PHENIX data taking.

The different collision systems vary from simple p–p and d–Au, where cold nuclear effects should be visible, serving as a baseline and via proper scaling as a comparison to the collisions of heavier ions, e.g. Cu–Cu and Au–Au. These comparisons should enhance the difference of scaled p–p collisions to the properties of the produced dense medium. In 2003, all four RHIC experiments published white papers [1] to summarize their findings which led to the announcement that a new phase of matter had been found [2].

[1] A list of members of the PHENIX Collaboration can be found at the end of this issue.

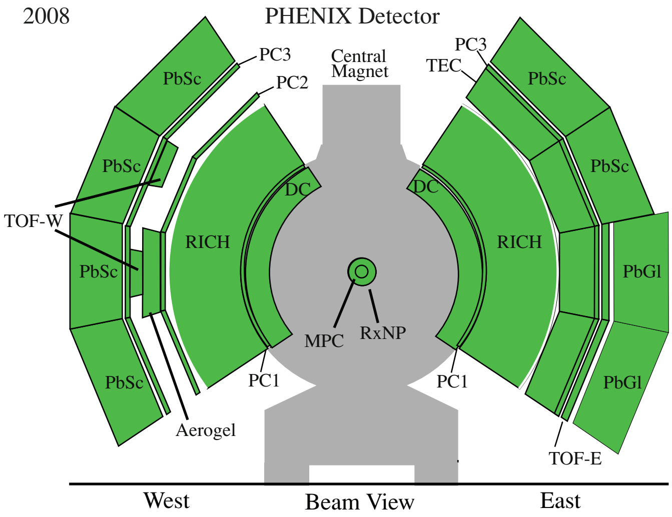

Figure 1. View of the PHENIX detector in beam direction.

Table 1. Summary of the first eight years of RHIC running for the PHENIX experiment.

	Year	Species	$\sqrt{s}$ (GeV)	$\int L\,dt$	N_{tot} (sampled)	Data size
Run-1	2000	Au–Au	130	1 μb^{-1}	10 M	3 TB
Run-2	2001/2002	Au–Au	200	24 μb^{-1}	170 M	10 TB
		Au–Au	19		<1 M	
		p–p	200	0.15 pb^{-1}	3.7 B	20 TB
Run-3	2002/2003	d–Au	200	2.74 nb^{-1}	5.5 B	46 TB
		p–p	200	0.35 pb^{-1}	6.6 B	35 TB
Run-4	2003/2004	Au–Au	200	241 μb^{-1}	1.5 B	270 TB
		Au–Au	62.4	9 μb^{-1}	58 M	10 TB
Run-5	2005	Cu–Cu	200	3 nb^{-1}	8.6 B	173 TB
		Cu–Cu	62.4	0.19 nb^{-1}	0.4 B	48 TB
		Cu–Cu	22.4	2.7 μb^{-1}	9 M	1 TB
		p–p	200	3.8 pb^{-1}	85 B	262 TB
Run-6	2006	p–p	200	10.7 pb^{-1}	233 B	310 TB
		p–p	62.4	0.1 pb^{-1}	28 B	25 TB
Run-7	2007	Au–Au	200	813 μb^{-1}	5.1 B	650 TB
Run-8	2007/2008	d–Au	200	80 nb^{-1}	160 B	437 TB
		p–p	200	5.2 pb^{-1}	115 B	118 TB
		Au–Au	9.2			few k

2. New PHENIX detector subsystems

Figures 1 and 2 show the PHENIX detector in the 2007/2008 configuration. It consists of four spectrometer arms with three main magnets: two arms at mid-rapidity (East and West)

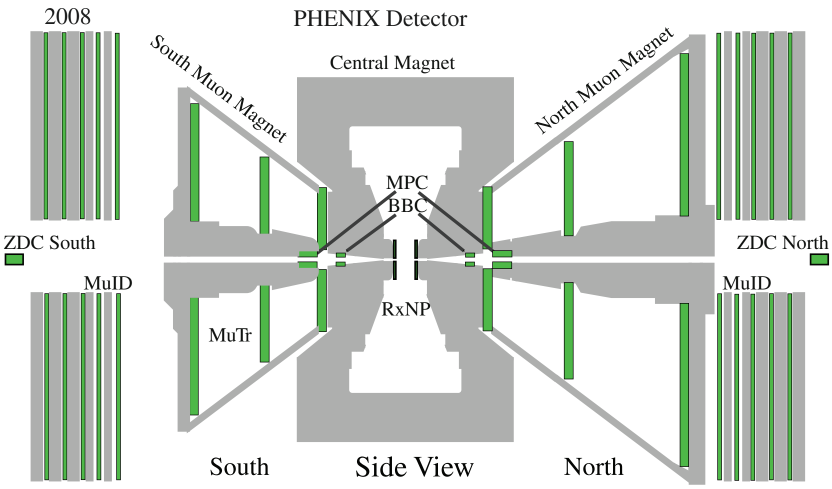

Figure 2. View of the PHENIX detector in side-view.

with tracking, particle identification (PID) detectors and calorimeters for hadron, electron and photon detection and two muon arms in the forward angles (North and South). Details can be found in [3].

Several new detectors had been added over the past few years to improve PID, the measurement of the reaction plane (RP) and π^0 identification at forward angles.

A time-of-flight (TOF-W) detector, based on multi-gap resistive plate chambers (MRPC) [4], was added to the PHENIX West central arm detector in 2007 to extend the PID to higher momenta, i.e. above 2–3 GeV/c. Before the PID in the PHENIX West arm relied on a combination of a gas ring image Cherenkov (RICH) vessel, an aerogel detector ($n = 1.0114$), and the electromagnetic calorimeter (EMCal) which left a gap in the pion-to-kaon separation between 3 and 5 GeV/c. One octant of these MRPCs with pad readout was installed and achieving a 75 ps time resolution, 85 ps overall with the beam–beam counter (BBC), the interaction and TOF start detector, resolution folded in. Several new results based on this detector have been presented at this conference [5, 6].

For a few years PHENIX will use the new reaction plane detector (RxNP) [7] to further improve the RP measurement and to improve triggering at lower energies when the BBC and zero-degree calorimeters (ZDC) are not efficient enough. The RxNP consists of 2 × 2 rings with 12 scintillator counters each, read out by 2 × 24 photomultipliers. It covers the pseudorapidity windows $\eta = 1.0 \rightarrow 1.5, 1.5 \rightarrow 2.8$.

Seeking to extend the detector coverage into the forward direction, PHENIX installed 412 $PbWO_4$ crystals into the forward tips, $3.1 < |\eta| < 3.7$, of each magnet piston in the North and South muon magnets. The main goal for the muon piston calorimeter (MPC) [8], as it is called, is the reconstruction of π^0 and the search for spin asymmetries in p–p collisions. In heavy-ion running, when the overall multiplicity is too high, it improves the measurement of the event reaction plane.

A detector which had a first engineering run in 2007 is the hadron blind detector (HBD) [9, 10]. It is a windowless Cherenkov detector using pure CF_4 with a triple GEM readout, where the top most layer is coated with cesium iodide (CsI) to convert the Cherenkov photons into photo-electrons which are in turn amplified by the GEM with a gain of $\sim 5 \times 10^3$.

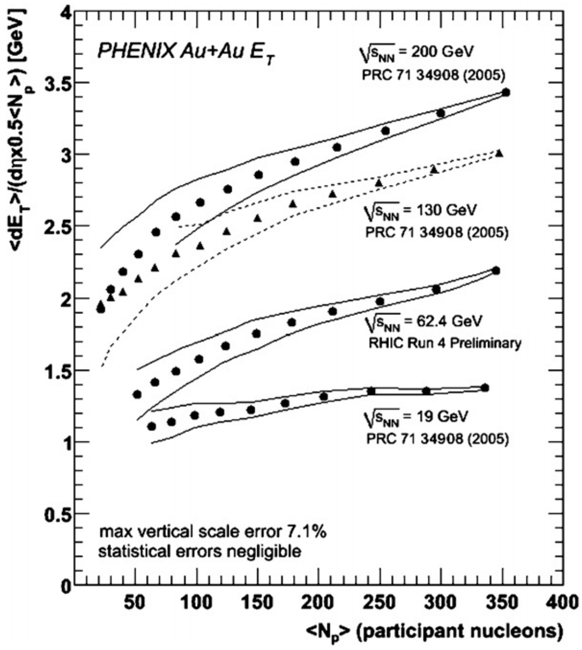

Figure 3. Transverse energy versus number of participating nucleons in Au–Au collisions.

The HBD will be important in coming years for the measurement of low mass electron pairs from the decay of light vector mesons (ρ, ω and ϕ).

In the coming years PHENIX plans to install a silicon vertex tracking system, see [11], a forward silicon–tungsten calorimeter, and a muon trigger based on resistive plate chambers.

3. Global observables

Presentations at Quark Matter 1987 in Nordkirchen [12], more than 20 years ago, concentrated on the first measurements of global observables like event multiplicity, transverse momentum and energy distributions to understand if the levels of energy densities reached were sufficient to form a QGP. More than ten years later, in 2000, further detailed measurements lead to the announcement [13] that a new state of matter had been observed.

PHENIX had published measurements of the total transverse energy, E_T, for $\sqrt{s} = 200$, 130 and 13.9 GeV/c previously [14, 15]. Figure 3 summarizes these measurements for Au–Au collisions as a function of participating nucleons and adds the distribution for the fourth beam energy. E_T increases with increasing number of participants and grows faster with higher beam energy. Concentrating on the most central collisions, figure 4 shows $\mathrm{d}E_T/(\mathrm{d}\eta\, 0.5N_p)$ as a function of $\sqrt{s}$ for several measurements including the new PHENIX datapoint at $\sqrt{s} = 62.4$ GeV/c. The measurement falls well in line with the previous observed linear dependence of the scaled E_T with the log of $\sqrt{s}$.

Detailed studies of charged particle multiplicities in smaller and smaller rapidity windows are accessible with the large datasets. In this volume PHENIX presents fluctuation studies in overall multiplicities and particle ratios [16]. Deviations from a monotonic behavior in these

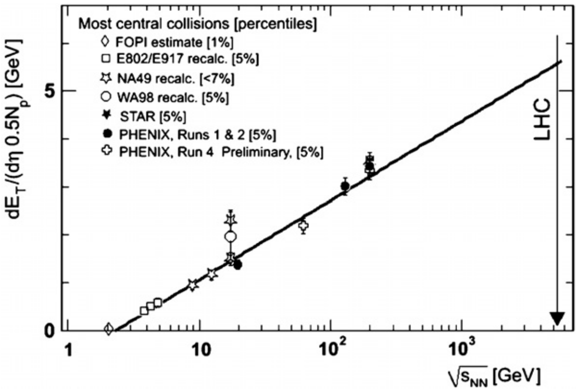

Figure 4. Transverse energy versus $\sqrt{s}$ for central Au–Au collisions.

ratios should indicate a possible phase transition or critical change in the medium. In the current data nothing unusual was found.

A long proven approach to studying the dynamics of a heavy-ion collision is a Hanbury-Brown and Twiss, HBT, analysis [17, 18]. PHENIX presented first results in reconstructing the shape and dynamical evolution of the particle emitting source by a three-dimensional source imaging technique [19].

Another method of estimating the source size is to measure the coalescence parameter, B_2, for deuterons [6, 20]. Using the above-mentioned TOF-W detector PHENIX could extend the existing (anti-) deuteron measurements to higher p_T and multiple centrality bins. Expressing the coalescence probability, B_2^{-1}, is a measure of the source radius. It increases linearly with the number of participating nucleons in the collision, and the extracted radius parameter is compatible with HBT results on pion pairs.

4. Flow

A most surprising observation at RHIC was the strong elliptic flow, which leads to the conclusion that the medium we are studying does not behave like a hot gas but rather like a strongly coupled liquid. When colliding at intermediate impact parameters the overlap region between the two nuclei is elliptically shaped in the transverse plane. This spacial anisotropy creates a pressure gradient which translates into a momentum anisotropy in the final particle stage. Experimentally, this is measured via the ϕ angular distribution of the particles with respect to the reaction plane angle, Ψ_R, of the event which is defined by the beam direction and the distance vector of the center of the two nuclei [21], and a Fourier decomposition:

$$E\frac{\mathrm{d}^3N}{\mathrm{d}p^3} = \frac{1}{2\pi}\frac{\mathrm{d}N}{p_T\,\mathrm{d}p_T\,\mathrm{d}y}\left[1+\sum_{n=1}^{\infty}2v_n(p_T, y)\cos(n\phi)\right]. \tag{1}$$

Because of the symmetry $\phi \leftrightarrow -\phi$ in the collision geometry, sine terms do not appear in the above expansion. Also the odd-order anisotropic flows of particles at midrapidity vanish in collisions with equal mass nuclei as a result of the additional symmetry $\phi \leftrightarrow \phi + \pi$.

The second coefficient in the Fourier transform, v_2, is usually the largest and has been studied by all RHIC experiments. It has been observed that the v_2 of all studied particles scales as $v_2/n_q \sim KE_T/n_q$, where n_q is the number of quarks in the particle and $KE_T = m_T - m_0$ is

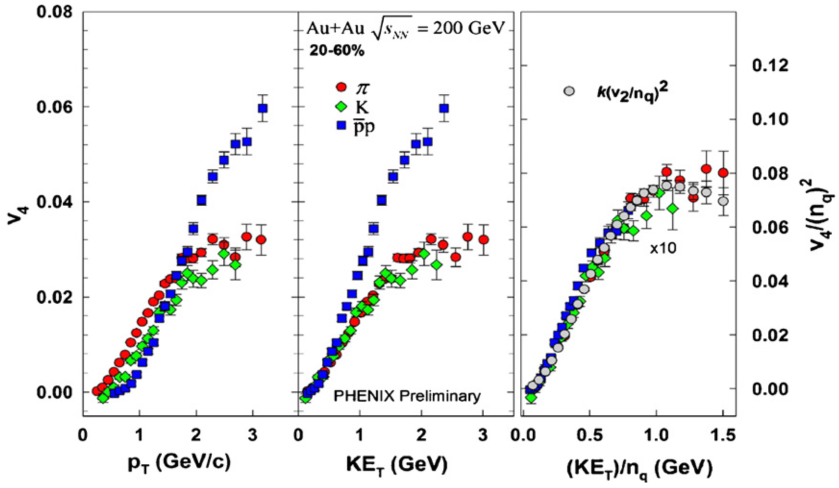

Figure 5. v_4 as a function of p_T, KE_T and KE_T/n_q.

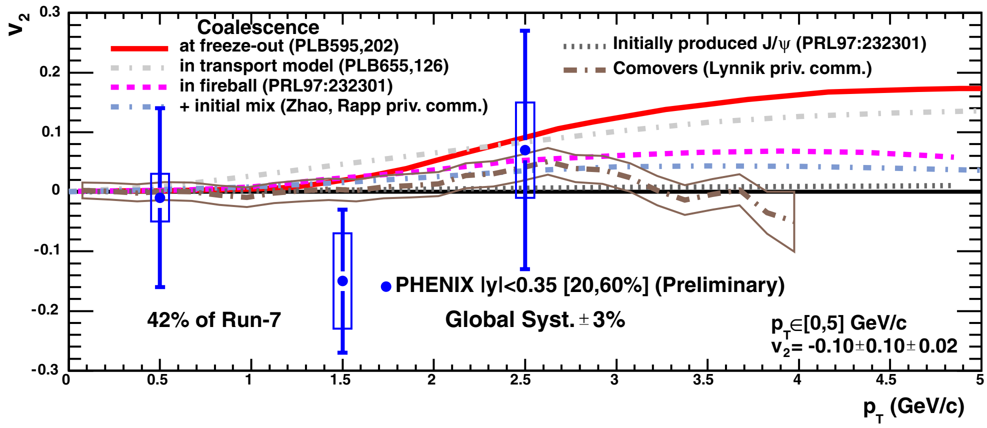

Figure 6. v_2 for $J/\Psi \rightarrow e^+e^-$ measured at mid-radidity in Au–Au collisions with the PHENIX central arm detectors. The lines indicate theoretical predictions as indicated in the figure.

the transverse kinetic energy. This scaling was observed up to $KE_T \approx 1$ GeV/c, an indication that hydrodynamical description of the data was valid [22]. New data from PHENIX [5] indicate that this is not valid above 1 GeV/c that corresponds to $p_T \approx 3$ GeV/c for a proton, the region where hard scattering becomes important.

The next higher term v_4 is an important measure if a ideal hydrodynamical description is applicable in this momentum range. If valid, v_4 should follow the same scaling in KE_T as v_2, but should be scaled with n_q^2 and more importantly be equivalent to $v_2^2 n_q^{-2}$ as demonstrated in the right panel of figure 5.

Figure 6 shows the first data on the v_2 of $J/\Psi \rightarrow e^+e^-$ in heavy-ion collisions. The preliminary result of $v_2 = -0.10 \pm 0.10 \pm 0.02$ is compatible with 0, but only 42% of the data are analyzed so far. The lines in figure 6 represent theoretical predictions as indicated. A PHENIX result on $J/\Psi \rightarrow \mu^+\mu^-$ is to be presented soon, see [23] for more details.

Instead of a Fourier transform of the angular particle distribution with respect to the reaction plane, a cumulant technique [24, 25] can also be used to extract the anisotropic

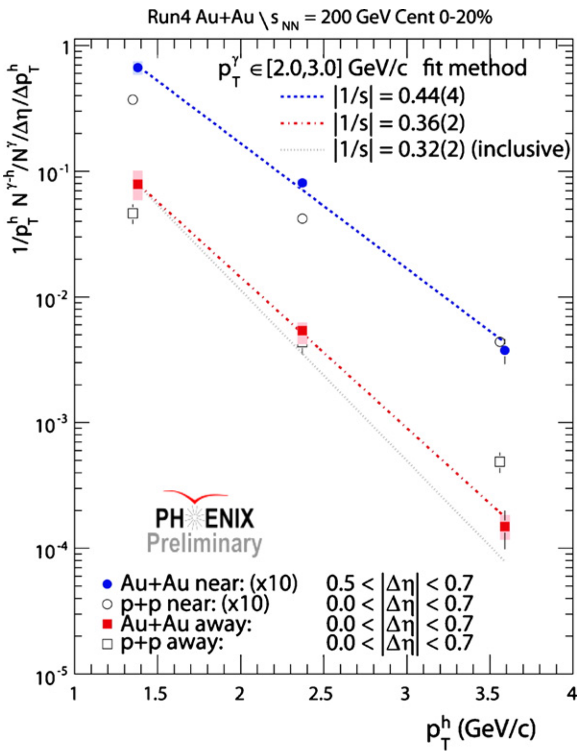

Figure 7. Near (squares) and awayside (circles) transverse momentum spectra for Au–Au (filled) and p–p (open) collisions for different rapidity regions for the near- and away-side jets. The lines represent fits to the datapoints, with the solid line indicating the fit to an inclusive p_T distribution.

flow strength. The detectors used for the RP determination in PHENIX have a large enough rapidity gap to the tracking and PID detectors that non-flow effects are not important. A direct comparison should then indicate where non-flow effects set in. The cumulant v_2 starts to diverge from the RP v_2 at $p_T \approx 3.5\text{GeV}/c$, indicating that non-flow effects, e.g. jets from hard scattering, become important. Incidentally, it is also the region where the KE_T/n_q scaling starts to fail.

5. Jets

PHENIX has studied the properties of jets at 200 and 62.4 GeV/c for p–p, d–Au, Cu–Cu and Au–Au collisions [26–32].

Jets resulting from a hard scattering of partons are impossible to reconstruct in heavy-ion collisions because of the high background. Therefore these studies are done by 2 and 2+1 azimuthal correlations of a high-p_T particle, assumed to be the leading particle of one jet-arm and all other particles assumed to be from the same jet or the recoil. The correlation functions have to be corrected for background and flow, which in itself is an angular correlation.

It has been observed in p–p and peripheral A–A collisions that opposite the trigger particle jet (near-side) a slightly wide correlated distribution emerges (away side). In central A–A collisions the momentum spectra for the away side soften and the angular distribution widens even more. Several explanations for these effects have been presented at this conference. Figure 7 shows a PHENIX comparison of the momentum distribution for two pseudo-rapidity,

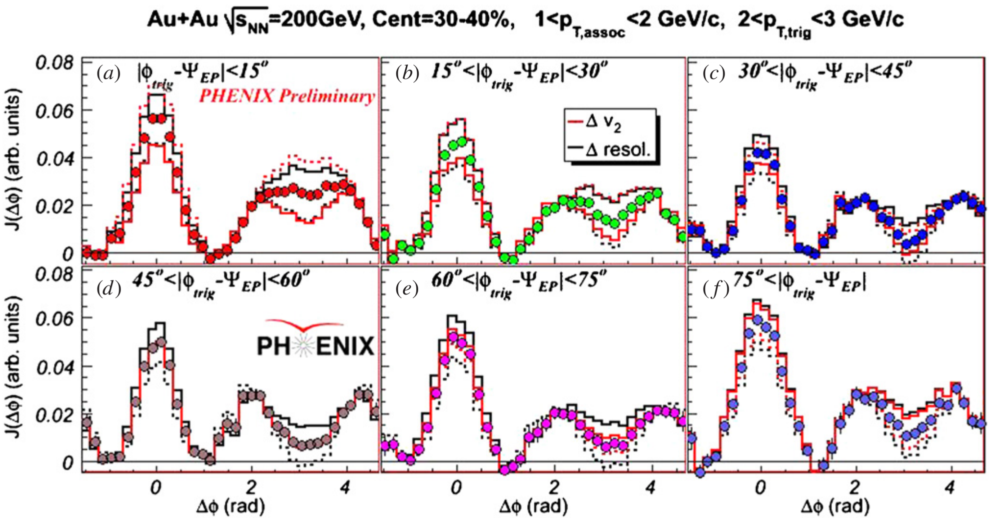

Figure 8. Jet correlation functions for Au–Au collisions, panels represent 15° slices from 0 to 90° away from the reaction plane.

η, regions of the near and away side in p–p and Au–Au collisions. The momentum spectra for Au–Au collisions on the near side, but away from the main jet (upper, blue, solid points), and the away side (lower, red, solid points) are softer compared to p–p (open points) and close to the inclusive spectra (lines). This indicates that the momentum distributions of these particles have been softened by passing through the medium.

If the particle distributions and momenta are affected by their passage through the collision medium then the distributions when measured along the long versus the short axis of the collisions ellipsoid should be different. Figure 8 shows preliminary PHENIX results on a two-particle correlation function where the data are binned in angular regions with respect to the reaction plane. Even so the v_2 dominated systematic error is large, a clear change in the shape of the distributions is visible.

6. Summary

PHENIX has collected a vast sample of data from p–p to Au–Au collisions at various energies. The data show that we have created a dense medium which affects the momenta and angular distributions of the produced particles. On the other hand it shows a strongly coupled flow which affects all produced particles, even heavy quarks. PHENIX has shown multiple new and more detailed results at this conference and will with its current and future detector subsystems continue to uncover the details of this ‘perfect liquid’.

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