Observation of direct-photon collective flow in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

A. Adare,11 S. Afanasiev,27 C. Aidala,40 N.N. Ajitanand,57 Y. Akiba,51,52 H. Al-Bataineh,46 J. Alexander,57 K. Aoki,4,31 Y. Aramaki,10 E.T. Atomssa,34 R. Averbeck,58 T.C. Awes,47 B. Azmoun,5 V. Babintsev,22 M. Bai,4 G. Baksay,18 L. Baksay,18 K.N. Barish,8 B. Bassalleck,45 A.T. Baye,3 S. Bathe,6 V. Baublis,50 C. Baumann,41 A. Bazilevsky,5 S. Belikov,5,6 R. Belmont,62 R. Bennett,58 A. Berdnikov,54 Y. Berdnikov,54 A.A. Bickley,11 J.S. Bok,65 K. Boyle,58 M.L. Brooks,36 H. Buesching,5 V. Bumazhnov,22 G. Bunce,5,52 S. Buschyk,36 C.M. Camacho,36 S. Campbell 58 C.-H. Chen,58 C.Y. Chi,12 M. Chiu,5 I.J. Choi 65 R.K. Choudhury,3 P. Christiansen,38 T. Chlou,61 P. Chung,57 O. Chvala,6 V. Cianciolo,47 Z. Citron,58 B.A. Cole,12 M. Connors,58 P. Constantin,46 M. Csanád,16 T. Csörgő,36 T. Dahms,58 S. Dairaku,22 K. Das,19 A. Datta,40 G. David,5 A. Denisov,22 A. Deshpande,52,58 E.J. Desmond,5 O. Dietzsch,55 A. Dion,58 M. Donadelli,55 O. Draper,34 A. Drees,58 K.A. Drees,4 J.M. Durham,58 A. Durum,22 D. 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McEachern,36 N. Means,58 B. Meredith,23 Y. Miao,61 A.C. Mignerey,39 P. Mikeš,7,25 K. Miki,61 A. Milov,5 M. Mishra,2 J.T. Mitchell,5 A.K. Mohanty,3 Y. Morino,10 A. Morreale,6 D.P. Morrison,5 T.V. Moukhonova,32 J. Murata,53,51 A. Nagamitsu,29 J.L. Nagle,11 M. Naglis,64 M.I. Nagy,16 I. Nakagawa,51,52 Y. Nakamiya,21 T. Nakamura,51,29 K. Nakano,51,60 J. Newby,39 M. Nguyen,58 R. Noulcer,5 A.S. Nynan,32 E. O’Brien,5 S.X. Oda,10 C.A. Ogilvie,26 M. Oka,61 K. Okada,32 Y. Omuki,51 A. Oskarsson,38 M. Ouchida,21 K. Ozawa,10 R. Pak,5 V. Pant,5 V. Papavassilopoulos,46 I.H. Park,17 J. Park,56 S.K. Park,31 W.J. Park,31 S.F. Pate,46 H. Pei,26 J.-C. Peng,33 H. Pereira,14 V. Peresedov,27 D.Yu. Peressounko,32 C. Pinkenburg,5 R.P. Pisanı,5 M. Proissi,58 M.L. Purschke,52 A.K. Purwar,56 N. Qu,40 J. Rak,28 A. Rakotozafindraibe,34 I. Ravovich,64 K.F. Read,47,59 K. Reygers,41 V. Riabov,50 Y. Riabov,50 E. Richardson,39 D. Roach,62 G. Roche,37 S.D. Rolnick,6 M. Rosati,26 C.A. Rosen,11 S.S.E. Rosendahl,38 P. 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Vinogradov,32 M. Virtus,13 V. Vrba,25 E. Vznuzdzev,50 X.R. Wang,46 D. Watanabe,21 K. Watanabe,61 Y. Watanabe,51,52 F. Wei,26 R. Wei,57 J. Wessels,41 S.N. White,5 D. Winter,12 J.P. Wood,1 C.L. Woody,5 R.M. Wright,1 M. Wysocki,11 W. Xie,52 Y.L. Yamaguchi,10 K. Yamaura,21 R. Yang,23 A. Yanovitch,22 J. Ying,20 S. Yokkachi,51,52
Z. You,$^{49}$ G.R. Young,$^{47}$ I. Younus,$^{45}$ I.E. Yushmanov,$^{32}$ W.A. Zajc,$^{12}$ C. Zhang,$^{47}$ S. Zhou,$^{9}$ and L. Zolin$^{27}$

(PHENIX Collaboration)

$^1$Abilene Christian University, Abilene, Texas 79699, USA
$^2$Department of Physics, Banaras Hindu University, Varanasi 221005, India
$^3$Bhabha Atomic Research Centre, Bombay 400 085, India
$^4$Collider-Accelorator Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
$^5$Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
$^6$University of California - Riverside, Riverside, California 92521, USA
$^7$Charles University, Ovocný trh 5, Praha 1, 116 36, Prague, Czech Republic
$^8$Chonbuk National University, Jeonju, 561-756, Korea

$^9$Science and Technology on Nuclear Data Laboratory, China Institute of Atomic Energy, Beijing 102413, P. R. China

$^{10}$Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan

$^{11}$University of Colorado, Boulder, Colorado 80309, USA

$^{12}$Columbia University, New York, New York 10027 and Nevis Laboratories, Irvington, New York 10533, USA

$^{13}$Czech Technical University, Zikova 4, 166 36 Prague 6, Czech Republic

$^{14}$Département de Physique, Université Paris-Saclay, F-91191, Gif-sur-Yvette, France

$^{15}$Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary

$^{16}$ELTE, Eötvös Loránd University, H - 1117 Budapest, Püspökkörút 1/A, Hungary

$^{17}$Ewha Womans University, Seoul 120-750, Korea

$^{18}$Florida Institute of Technology, Melbourne, Florida 32901, USA

$^{19}$Florida State University, Tallahassee, Florida 32306, USA

$^{20}$Georgia State University, Atlanta, Georgia 30303, USA

$^{21}$Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan

$^{22}$IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia

$^{23}$University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

$^{24}$Institute for Nuclear Research of the Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia

$^{25}$Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic

$^{26}$Iowa State University, Ames, Iowa 50011, USA

$^{27}$Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia

$^{28}$Helsinki Institute of Physics and University of Jyväskylä, P.O.Box 35, FI-40014 Jyväskylä, Finland

$^{29}$KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan

$^{30}$KFKI Research Institute for Particle and Nuclear Physics of the Hungarian Academy of Sciences (MTA KFKI RMKI), H-1525 Budapest 114, POBox 49, Budapest, Hungary

$^{31}$Korea University, Seoul, 136-701, Korea

$^{32}$Russian Research Center “Kurchatov Institute”, Moscow, 123098 Russia

$^{33}$Kyoto University, Kyoto 606-8502, Japan

$^{34}$Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France

$^{35}$Lawrence Livermore National Laboratory, Livermore, California 94550, USA

$^{36}$Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

$^{37}$LPC, Université Blaise Pascal, CNRS-IN2P3, Clermont-Fd, 63177 Aubiere Cedex, France

$^{38}$Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden

$^{39}$University of Maryland, College Park, Maryland 20742, USA

$^{40}$Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003-9337, USA

$^{41}$Institut für Kernphysik, University of Muenster, D-48149 Muenster, Germany

$^{42}$Muhlenberg College, Allentown, Pennsylvania 18104-5586, USA

$^{43}$Myongji University, Yongin, Kyonggi-do 449-728, Korea

$^{44}$Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki 851-0193, Japan

$^{45}$University of New Mexico, Albuquerque, New Mexico 87131, USA

$^{46}$Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

$^{47}$IPN-Orsay, Université Paris Sud, CNRS-IN2P3, BP1, F-91406, Orsay, France

$^{48}$KFKI Research Institute for Particle and Nuclear Physics of the Hungarian Academy of Sciences (MTA KFKI RMKI), H-1525 Budapest 114, POBox 49, Budapest, Hungary

$^{49}$Saint Petersburg State Polytechnic University, St. Petersburg, 195251 Russia

$^{50}$PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region 188300, Russia

$^{51}$RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan

$^{52}$RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000, USA

$^{53}$Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan

$^{54}$Saint Petersburg State Polytechnical University, St. Petersburg, 195251 Russia

$^{55}$Universidade de São Paulo, Instituto de Física, Caixa Postal 66318, São Paulo, Brazil

$^{56}$Seoul National University, Seoul, Korea

$^{57}$Chemistry Department, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA

$^{58}$Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA

$^{59}$University of Tennessee, Knoxville, Tennessee 37996, USA

$^{60}$Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan
The second Fourier component $v_2$ of the azimuthal anisotropy with respect to the reaction plane was measured for direct photons at midrapidity and transverse momentum ($p_T$) of 1–13 GeV/c in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Previous measurements of this quantity for hadrons with $p_T < 6$ GeV/c indicate that the medium behaves like a nearly perfect fluid, while for $p_T > 6$ GeV/c a reduced anisotropy is interpreted in terms of a path-length dependence for parton energy loss. In this measurement with the PHENIX detector at the Relativistic Heavy Ion Collider we find that for $p_T > 4$ GeV/c the anisotropy for direct photons is consistent with zero, as expected if the dominant source of direct photons is initial hard scattering. However, in the $p_T < 4$ GeV/c region dominated by thermal photons, we find a substantial direct photon $v_2$ comparable to that of hadrons, whereas model calculations for thermal photons in this kinematic region significantly underpredict the observed $v_2$.

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Direct photons are produced in various processes during the entire space-time history of relativistic heavy ion collisions and, due to their small coupling, can leave the collision region without appreciable further interaction. This makes them a sensitive and direct probe of all stages of the medium, its transition to hadronic matter, and final de-energization and a means to distinguish between sources of direct photons. In this paper we consider the second Fourier component ($v_2$, often referred to as elliptic flow) of the event-by-event photon distribution in azimuth with respect to the reaction plane for minimum bias and selected centralities in Au+Au collisions.

At higher $p_T$ (> 4 GeV/c) there are four fundamental sources of direct photons, characterized by different $v_2$. Photons from initial hard scattering (predominantly from $qg \rightarrow q\gamma$ “gluon Compton scattering”) are isotropic and so $v_2 = 0$. Jet fragmentation photons have positive $v_2$ since the energy loss of the originating parton is smaller in the reaction plane. Jet-conversion photons where a hard scattered quark interacts with a thermal gluon in the medium and converts into a photon with almost equal $p_T$ have negative $v_2$, because the average pathlength of the parton in the medium (proportional to the conversion probability) is larger out of the reaction plane than within. Finally, Bremstrahlung photons are also emitted preferentially in the direction where the medium is thicker, leading to a negative $v_2$. Note that in this picture the azimuthal asymmetry of high $p_T$ photon production – while expressed in terms of $v_2$ – reflects the pure geometry of the medium, not its dynamics: it depends on the pathlength, not on the boost from the hydrodynamic pressure gradients.

The picture is quite different in the low $p_T$ range (1 $< p_T <$ 4 GeV/c) dominated by thermal photons, as first measured in [2], where bulk dynamics (expansion) plays an important role since it influences both the rate and azimuthal asymmetries of photon production [3, 4]. It is now established that collectivity – which already exists in the partonic phase (strongly interacting Quark-Gluon Plasma, sQGP) – persists after transition into the hadronic phase and the resulting azimuthal asymmetries in particle production can be described by near-ideal hydrodynamics. The expectation is that thermal radiation from both the sQGP and the hadronic phase will inherit the collective motion of the medium, i.e. will have a bona fide elliptic flow, positive $v_2$ at low $p_T$. The low $p_T$ behavior of direct photon $v_2$ puts constraints on the viscosity of the sQGP.

The PHENIX experiment has published the invariant yield as a function of $p_T$ for direct photons both via real photons and internal conversions of nearly real virtual photons [2, 5]. In the 1 $< p_T <$ 4 GeV/c region, a substantial excess of direct photons was observed relative to scaling of $p+p$ yields and has been interpreted in terms of thermal photon emission from the hot medium. An early attempt to infer $v_2$ of direct photons from a $\pi^0$ and inclusive photon $v_2$ measurement performed in a limited $p_T$ range has been published [6]. In this Letter we present measurements by the PHENIX experiment [7] of $v_2$ of $\pi^0$ and inclusive photons in a much extended transverse momentum ($p_T$) range (up to 13 GeV/c) in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions. Also, at low $p_T$ the fraction $R_\gamma$ of direct over inclusive photons is now measured with much higher precision [3] than before [8], therefore, for the first time a meaningful extraction of the direct photon $v_2$ itself is possible.
Data were taken in the 2007 run of the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. The analyzed sample includes ~ 3.0 x 10^9 minimum bias Au+Au collisions. Events were triggered by the Beam-Beam Counters (BBC), as described in [11], which comprise two arrays of Čerenkov counters covering 3.1 < |η| < 3.9 and 2π in azimuth in both beam directions (North and South). Event centrality was determined by the charge sum in the BBC.

The event-by-event reaction plane (RP) has been determined by two detectors, the first being the BBC itself. The RP resolution (effectively a dilution factor with which the observed v_2 is normalized to obtain the true v_2) is defined as \( \sigma_{\text{RP}} = |\langle \cos[2(\Phi_{\text{true}} - \Phi_{\text{RP}})] \rangle | \) and it is established by comparing event-by-event the RPs obtained separately in the North and South detectors. The resolution is highest in the 20-30% centrality bin where it reaches a value of 0.4. For the 2007 data taking period, a dedicated reaction plane detector (RXN) [12] was installed covering 1.0 < |η| < 2.8 and the full azimuth. The RXN is a highly segmented lead-scintillator sampling detector providing much better measurement (\( \sigma_{\text{RP}} \sim 0.7 \)) than the BBC, but it is closer to the central |η| < 0.35 pseudorapidity region where v_2 is measured, making it more sensitive to jet bias in those (rare) events where a high p_T particle is observed. The 0.7/0.4 = 1.75 improvement on the reaction plane resolution results is a 1.75-fold improvement on point-by-point uncertainty.

Inclusive photons were measured in the PHENIX electromagnetic calorimeter [13]. Particles were identified (PID) and hadrons were rejected by a shower shape cut and a veto on charged particles using the Pad Chambers [14]. The remaining sample is collected for each p_T range in histograms binned according to \( \Phi - \Phi_{\text{RP}} \) where \( \Phi_{\text{RP}} \) is the azimuth of the event-by-event reaction plane and established independently by the BBC and RXN. These distributions are then fit for each p_T range with \( N_0 \left[ 1 + 2 v_2 \cos(2(\Phi - \Phi_{\text{RP}})) \right] \) to extract the raw \( v_2^{\gamma, \text{meas}} \) coefficient for inclusive photons. As a cross-check of the fit value, another \( v_2^{\gamma, \text{meas}} \) is also calculated from the average cosine of the particles with respect to the reaction plane. While the PID eliminates virtually all hadrons above 6 GeV deposited energy (which might come from hadrons of any p_T above 6 GeV/c), a significant fraction of hadrons (up to 20% below 2 GeV deposited energy) survive the photon identification cuts. Since hadrons are known to have a large v_2 value, the observed \( v_2^{\gamma, \text{obs}} \) of inclusive photons is obtained after correcting for hadrons as

\[
v_2^{\gamma, \text{obs}} = \frac{v_2^{\gamma, \text{meas}} - (N_{\text{had}} / N_{\text{meas}}) v_2^{\text{had}}}{1 - N_{\text{had}} / N_{\text{meas}}},
\]

where \( v_2^{\text{had}} \) is the elliptic flow of hadrons and \( N_{\text{had}} / N_{\text{meas}} \) is the fraction of hadrons in the sample surviving the PID cuts, as estimated from GEANT simulations (20% at 2 GeV, 10% at 4 GeV and negligible above 6 GeV deposited energy). Finally the true \( v_2^{\gamma, \text{inc}} \) for inclusive photons is obtained by dividing by the reaction plane resolution \( \sigma_{\text{RP}} \).

A large fraction of inclusive photons comes from hadron decays, predominantly from \( \pi^0 \) (∼80%) and \( \eta \) (∼15%), with a small fraction coming from \( \rho, \omega \) and \( \eta' \) decays, but only the \( \pi^0 \) \( v_2 \) is directly measured. The measurement of neutral pions and their \( v_2 \) is described in detail in [4, 15]. We assume that \( \eta, \omega, \eta' \) follow the same \( K_E T \) scaling observed in hadrons [16] where \( K_E T = m_T - \mu \). Thus, \( v_2^{\pi^0} \) can be calculated for all hadrons from \( v_2^{\gamma} \).

The analyzed sample includes 3 pseudorapidity region where \( v_2 \) is established by comparing event-by-event the RPs obtained separately in the North and South detectors. The resolution is highest in the 20-30% centrality bin where it reaches a value of 0.4. For the 2007 data taking period, a dedicated reaction plane detector (RXN) [12] was installed covering 1.0 < |η| < 2.8 and the full azimuth. The RXN is a highly segmented lead-scintillator sampling detector providing much better measurement (\( \sigma_{\text{RP}} \sim 0.7 \)) than the BBC, but it is closer to the central |η| < 0.35 pseudorapidity region where v_2 is measured, making it more sensitive to jet bias in those (rare) events where a high p_T particle is observed. The 0.7/0.4 = 1.75 improvement on the reaction plane resolution results is a 1.75-fold improvement on point-by-point uncertainty.

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\[
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\]

where \( v_2^{\text{had}} \) is the elliptic flow of hadrons and \( N_{\text{had}} / N_{\text{meas}} \) is the fraction of hadrons in the sample surviving the PID cuts, as estimated from GEANT simulations (20% at 2 GeV, 10% at 4 GeV and negligible above 6 GeV deposited energy). Finally the true \( v_2^{\gamma, \text{inc}} \) for inclusive photons is obtained by dividing by the reaction plane resolution \( \sigma_{\text{RP}} \).

A large fraction of inclusive photons comes from hadron decays, predominantly from \( \pi^0 \) (∼80%) and \( \eta \) (∼15%), with a small fraction coming from \( \rho, \omega \) and \( \eta' \) decays, but only the \( \pi^0 \) \( v_2 \) is directly measured. The measurement of neutral pions and their \( v_2 \) is described in detail in [4, 15]. We assume that \( \eta, \omega, \eta' \) follow the same \( K_E T \) scaling observed in hadrons [16] where \( K_E T = m_T - \mu \). Thus, \( v_2^{\pi^0} \) can be calculated for all hadrons from \( v_2^{\gamma} \).

This cocktail is the input of a Monte Carlo simulation to calculate the total \( v_2^{\gamma, \text{bg}} \) due to photons from hadron decays. The direct photon \( v_2^{\gamma, \text{dir}} \) is then obtained using the \( R_\gamma(p_T) \) “direct photon excess ratio” as

\[
v_2^{\gamma, \text{dir}} = \frac{R_\gamma(p_T) v_2^{\gamma, \text{inc}} - v_2^{\gamma, \text{bg}}}{R_\gamma(p_T) - 1},
\]

where \( R_\gamma(p_T) = N_{\text{inc}}(p_T)/N_{\text{bg}}(p_T) \) with \( N_{\text{inc}} = N_{\text{meas}} - N_{\text{had}} \), the number of inclusive photons, while \( N_{\text{bg}}(p_T) \) is the number of photons attributed to hadron decay. Values of \( R_\gamma(p_T) \) above 5 GeV/c are taken from the real photon measurement with the PHENIX electromagnetic calorimeter [3], and below that from the more accurate, but p_T-range limited internal conversion measurement of direct photons [3].

**TABLE I**: Systematic uncertainties (\( \delta x/x \)) contributing to the direct photon \( v_2^{\gamma, \text{dir}} \) measurement for minimum-bias collisions over two p_T ranges.

| Contributing Source | 1-3 GeV/c | 10-16 GeV/c | Type |
|---------------------|----------|-------------|------|
| \( v_2^{\gamma, \text{inc}} \) remaining hadrons | 2.2% | N/A | B |
| \( v_2^{\gamma, \text{inc}} \) extraction method | 0.4% | 0.6% | B |
| \( v_2^{\gamma, \text{inc}} \) particle ID | 3.7% | 6.0% | B |
| \( v_2^{\gamma, \text{inc}} \) normalization | 0.4% | 7.2% | B |
| \( v_2^{\gamma, \text{inc}} \) shower merging | N/A | 4.0% | B |
| subtraction \( R_\gamma \) | 3.1% | 22% | B |
| common reaction plane | 6.3% | 6.3% | C |

Sources of systematic uncertainties for representative \( p_T \) values are listed in Table I along with their characterization: type A means point-by-point uncertainties which are uncorrelated with \( p_T \), type B means uncertainties that are correlated (with \( p_T \)) and type C is the overall normalization uncertainty, moving all points by the same fraction up or down. Since the \( v_2 \) measurement is a relative one (the azimuthal anisotropy is fit without the need to know the absolute normalization), the \( \pi^0 \) and
including photon $v_2$ measurements are largely immune to energy scale uncertainties which are typically the dominant source of uncertainty in an absolute (invariant yield) measurement. The uncertainties on $v_2$ are dominated by the common uncertainty on determining $\sigma_{RP}$ and by uncertainties on particle identification. Uncertainties from absolute yields enter indirectly via the hadron cocktail (normalization) and more directly at higher $p_T$ (where the real photon measurement is used) by the $R_v$ needed to establish the direct photon $v_2$. Note that due to the way $v_2^{\gamma,\text{dir}}$ is calculated, once $R_v$ is large, its relative error contributes to the error on $v_2^{\gamma,\text{dir}}$ less and less.

Figure 1 shows steps of the analysis using the minimum bias sample, as well as the differences between results obtained with BBC and RXN. The first $v_2$ of $\pi^0$ and inclusive photons ($v_2^{\pi^0}, v_2^{\gamma,\text{inc}}$) are measured, as described above (panels (a) and (b)). Then, using the $v_2^{\gamma,bg}$ of photons from hadronic decays and the $R_v$ direct photon excess ratio, we derive the $v_2^{\gamma,\text{dir}}$ of direct photons (panel (c)). Panel (d) shows the $R_v(p_T)$ values from the direct photon invariant yield measurements using internal conversion $[3]$ and real $[8]$ photons, with their respective uncertainties. Panel (e) shows the ratio of $v_2^{\gamma,\text{dir}}/v_2^{\pi^0}$. We observe substantial direct photon flow in the low $p_T$ region (c), commensurate with the hadron flow itself (e). However, in contrast to hadrons, the direct photon $v_2$ rapidly decreases with $p_T$; and starting with 5 GeV/c and above, it is consistent with zero (c). The rapid transition from high direct photon flow at 3 GeV/c to zero flow at 5 GeV/c is also demonstrated on panel (e), since the $\pi^0$ $v_2$ changes little in this region [4].

FIG. 1: (Color online) (a,b,c) $v_2$ in minimum bias collisions, using two different reaction plane detectors: (solid black circles) BBC and (solid red squares) RXN for (a) $\pi^0$, (b) inclusive photon, and (c) direct photon. (d) direct photon fraction $R_v$ for (solid black circles) virtual photons [3] and (open blue squares) real photons [3] and (e) ratio of direct photon to $\pi^0$ $v_2$ for (solid black circles) BBC and (solid red squares) RXN. The vertical error bars on each data point indicate statistical uncertainties and shaded (gray and cyan) and hatched (red) areas around the data points indicate sizes of systematic uncertainties.

A major issue in any azimuthal asymmetry measurement is the potential bias from where in pseudorapidity the (event-by-event) reaction plane is measured. At low $p_T$—where multiplicities are high and particle production is dominated by the bulk with genuine hydrodynamic behavior – there is no difference between the flow derived with BBC and RXN. However, at higher $p_T$ we observe that the $v_2$ values using BBC and RXN diverge, particularly for $\pi^0$ (panel (a) in Fig.1), less for inclusive photons. For direct photons (panel (c)) the two results are apparently consistent within their total errors, including the
error $\delta R_\gamma / R_\gamma$ (see Table II) but it should be noted that $R_\gamma$ is a common correction factor in the $v_2$ measurements with both reaction plane detectors.

Event substructure not related to bulk properties and expansion – most notably jets – can bias the reaction plane measurement, particularly at higher $p_T$ and lower multiplicity. Observation of a high $p_T$ particle practically guarantees the presence of a jet, which in turn modifies the event structure over a large $\eta$ range. The bias on the true event plane (with the bulk as its origin) is stronger if the overall multiplicity is small and if the $\eta$ gap between the central arm (where $v_2$ is measured) and the reaction plane detector is reduced. The bias in Fig. II is largest for $\pi^0$, since high $p_T$ hadrons are always jet fragments. Inclusive photons are a mixture of hadron decay photons, inheriting the bias seen in $\pi^0$ and the mostly unbiased direct photons, therefore, the difference between BBC and RXN is smaller. Finally, the bias is smallest (but nonzero) for direct photons, of which only a relatively small fraction (jet fragmentation photons) exhibit bias.

Figure 2 shows $v_2$ for minimum bias and two centralities as a function of transverse momentum for $\pi^0$, inclusive and direct photons. For reaction plane determination the BBC is used because it is farthest from midrapidity where $v_2$ is measured. Despite the fact that there is a significant direct (thermal) photon yield at low $p_T$ [5], the $\pi^0$ and inclusive photon $v_2$ is virtually identical. Note that the surprisingly large inclusive photon $v_2$ is confirmed by the (so far preliminary) results with a completely different analysis technique [17].

For direct photons at low $p_T$ we observe a pronounced positive $v_2$ signal, increasing with decreasing centrality and comparable to the $\pi^0$ flow, but then rapidly going toward zero at 5-6 GeV/$c$. Qualitatively this shape agrees with the prediction for very early thermalization times, 0.2-0.4 fm/$c$ in [18], 0.2 fm/$c$ and vanishing viscosity in [7], but both models severely underestimate the magnitude of the $v_2$. The model in [19] combines somewhat later thermalization time (0.6 fm/$c$) with partial chemical equilibrium in the hadronic phase, reproducing the shape, but missing the magnitude of the observed $v_2$ at low $p_T$. While such large direct photon $v_2$ in principle could be attributed to a dominant production mechanism at the later stage when bulk flow is already developed, simultaneously explaining the large values of $v_2$ at $\sim$2 GeV/$c$ and its vanishing above 5 GeV/$c$ remains a challenge to current theories.

Figure 3 shows the high $p_T$ integrated $v_2$ ($p_T > 6$ GeV/$c$) for $\pi^0$ and photons (inclusive and direct) as a function of centrality. The low $N_{\text{part}}$ behavior is strongly influenced by the location in pseudorapidity of the reaction plane detector. The $\pi^0$ $v_2$ is comparable to other hadrons and is higher than the inclusive photon $v_2$, which is diluted by direct photons. The two direct photon $v_2$ measurements (panel (c)) are consistent with zero (and each other) at all centralities within their total systematic errors. While zero $v_2$ would be expected if initial hard scattering is the dominant (sole considered) source of photons, it should be pointed out that the typical contribution from jet-conversion only would be $v_2 \sim -0.02$ and from fragmentation $v_2 \leq 0.01$ weighted with the fraction of photons coming from these specific processes [3, 7].

In conclusion, PHENIX has measured $v_2$ of $\pi^0$, inclusive and direct photons in the $1 < p_T < 13$ GeV/$c$ range for minimum bias and selected centralities in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions. At higher $p_T$ (> 6 GeV/$c$) the direct photon $v_2$ is consistent with zero at all centralities, as expected if the dominant source of photon production is initial hard scattering. However, the experimental uncertainties are currently about a factor of 2 higher than the predicted (small) positive and negative contributions from fragmentation and jet conversion photons, respectively. In the thermal region ($p_T < 4$ GeV/$c$), a positive direct photon $v_2$ is observed which is comparable in magnitude to the $\pi^0$ $v_2$ and consistent with early thermalization times and low viscosity, but its magnitude is much larger than current theories predict.

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∗ Deceased
† PHENIX Spokesperson: jacak@skipper.physics.sunysb.edu

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