Transverse mass dependence of two-pion correlations
in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV

K. Adcox, S. S. Adler, N. N. Ajitanand, Y. Akiba, J. Alexander, L. Aphelcthe, Y. Ari, S. H. Aronson, R. Averbeek, T. C. Awes, K. N. Barish, P. D. Barnes, J. Barrette, B. Bassalleck, S. Bathe, V. Baublis, A. Bazilevsky, S. Belikov, F. G. Belfaia, S. T. Belyaev, M. J. Bennett, Y. Berdnikov, S. Botelho, M. L. Brooks, D. S. Brown, N. Bruner, D. Bucher, H. Buesching, V. Bunmazhnow, G. Bunce, J. Burward-Hoy, S. Butsyk, A. Carey, P. Chand, J. Chang, W. C. Chang, L. L. Chavez, S. Cheremchenko, C. Y. Chi, J. Chiba, M. Chin, R. K. Choudhury, T. Christ, T. Chui, M. Cho, Y. Cho, P. Chung, V. Cianciolo, B. A. Cole, D. G. D’Enterria, G. David, H. Delagrange, A. Denisov, A. Deshpande, J. Desmond, O. Dietzsch, B. V. Dinesh, A. Drees, A. Durum, K. Ebius, Y. V. Efremenko, K. El Chenai, A. Enokizono, H. Enyo, S. S. Esami, L. Ewell, T. Ferdousi, D. E. Fields, S. L. Fokin, Z. Fraenkel, A. Franz, A. D. Frawley, S. -Y. Fung, S. Garman, T. K. Ghosh, A. Glenn, A. L. Godoi, S. V. Greene, M. Grosse Perdekamp, S. K. Gupta, G. Guny, H. A. Gustafsson, J. S. Haggerty, H. Hamagaki, A. G. Hansen, H. Hara, E. P. Hartouni, R. Hayano, N. Hayashi, X. He, T. K. Hemmick, J. M. Heuser, M. Hibino, J. C. Hill, D. S. Ho, K. Homma, T. Hoong, A. Hoover, T. Ichihara, K. Imai, M. S. Ippolitov, M. Ishihara, B. V. Jacak, W. Y. Jiang, T. Jia, B. M. Johnson, S. C. Johnson, K. S. Joo, T. H. Kajita, G. K. Kang, M. Kann, S. S. Kapoor, S. Kelly, B. Khachaturov, A. Khazadeev, J. Kikuchi, D. J. Kim, H. J. Kim, S. Y. Kim, Y. G. Kim, W. W. Kinnison, E. Kistenev, A. Kiyomichi, C. Klein-Boeing, S. Klinkskie, L. Kochenda, V. Kochetkov, D. Koehler, T. Kohama, D. Kotchetkov, A. Kozlov, P. J. Kroon, K. Kurita, M. K. Kweon, Y. Kwon, G. S. Kyle, R. Lacey, J. G. Lajoie, J. Laulet, A. Lebedev, D. M. Lee, M. J. Leitch, X. H. Li, Z. Li, D. J. Lim, M. X. Liu, X. Liu, Z. Liu, C. F. Maguire, M. Mahon, Y. I. Makdisi, V. I. Manko, Y. Mao, S. K. Mark, S. Markacs, G. Martinez, M. D. Marx, A. Masaia, F. Mathatias, T. Matsumoto, P. L. McGaughey, M. Melnikov, M. Merschmeyer, F. Messer, M. Messer, Y. Mikaie, T. E. Miller, A. Milov, S. Mioduszewski, R. E. Mischke, G. C. Mishra, J. T. Mitchell, A. K. Mohanty, D. P. Morrison, J. M. Moss, F. Mühlbacher, M. Muniruzzaman, J. Murata, N. Nagamiya, Y. Nagasaka, J. L. Nagle, Y. Nakada, B. K. Nandi, J. Newby, L. Nikkinen, P. Nilsson, S. Nishimura, A. S. Nyanin, J. Nystrand, E. O'Brien, C. A. Ogilvie, H. Omlin, I. D. Ojha, M. Ono, V. Onuchin, A. Oskarsson, L. Österlund, K. Oyama, L. Paffrath, A. P. T. Palounek, V. S. Pantuev, V. Papavassiliou, S. F. Pate, T. Peitzmann, A. N. Petridis, C. Pinkenburg, R. P. Pisani, P. Pitukhin, F. Plasil, M. Pollack, K. Pope, M. L. Purschke, I. Ravovich, K. F. Read, K. S. Reyes, V. Riabov, S. Rosati, A. A. Rose, S. S. Ryu, N. Saito, A. Sakaguchi, T. Sakaguchi, H. Sako, T. Sakuma, V. Samsonov, T. C. Sangster, R. Sato, H. D. Sato, S. Sato, S. Sawada, B. R. Schleif, Y. Schutz, V. Semenov, R. Seto, T. K. Shea, I. Shein, T. A. Shibata, K. Shiagaki, T. Shima, Y. H. Shin, I. G. Sibiriak, D. Silvermyr, K. S. Sim, J. Simon-Gillo, C. P. Singh, V. Singh, M. Sivertz, A. Soldatov, R. A. Soltz, S. Sorensen, P. W. Stankus, N. Starinsky, P. Steinberg, E. Stenlund, A. Ster, S. P. Stolt, M. Sugak, T. Sugita, J. P. Sullivan, Y. Sumi, Z. Sun, M. Suzuki, E. M. Takagui, A. Taketani, M. Tanai, K. H. Tanaka, Y. Tanaka, E. Taniguchi, M. J. Tannenbaum, J. Thomas, J. B. Thomas, T. Thomas, W. Tian, J. Tojo, H. Torii, R. S. Townsend, I. Tserurya, H. Tsuruoka, A. A. Tsvetkov, S. K. Tuli, H. Tydesjö, N. Tynyrä, T. Ushiroya, H. W. van Hecke, C. Velissaris, J. Velkovskas, M. Velkovskaya, A. A. Vinogradov, M. A. Volkov, A. Vorobyov, E. Vznuzdaev, H. Wang, Y. Watanabe, S. N. White, C. Witzig, F. K. Wohn, C. L. Woody, W. Xie, K. Yagi, S. Yokkaichi, G. R. Young, I. E. Yushmanov, A. W. Zajc, Z. Zhang, S. Zhou (PHENIX Collaboration)

1 Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
2 Bhavati Atomic Research Centre, Bombay 400 085, India
3 Brookhaven National Laboratory, Upton, NY 11973-5000, USA
4 Department of Physics, Banaras Hindu University, Varanasi 221005, India
5 University of California - Riverside, Riverside, CA 92521, USA
6 China Institute of Atomic Energy (CIAE), Beijing, People's Republic of China
7 Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
8 Columbia University, New York, NY 10027 and Nevis Laboratories, Irvington, NY 10533, USA
9 Florida State University, Tallahassee, FL 32306, USA
10 Georgia State University, Atlanta, GA 30303, USA
Two-pion correlations in $\sqrt{s_{\text{NN}}} = 130$ GeV Au+Au collisions at RHIC have been measured over a broad range of pair transverse momentum $k_T$ by the PHENIX experiment at RHIC. The $k_T$ dependent transverse radii are similar to results from heavy ion collisions at $\sqrt{s_{\text{NN}}} = 4.1, 4.9,$ and 17.3 GeV, whereas the longitudinal radius increases monotonically with beam energy. The ratio of the outwards to sideways transverse radii $(R_{\text{out}}/R_{\text{side}})$ is consistent with unity and independent of $k_T$.

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The influence of Bose-Einstein statistics on the correlation of identical charged pions at low relative momentum was first used to probe the space-time structure of pion emission in $p\bar{p}$ annihilations [1] and has subsequently been applied to relativistic heavy-ion collisions from the Bevalac to RHIC [2–7] (see [8] for a recent review), and to a wide range of systems including $e^+e^-$ annihilations [9]. The correlation function is defined as the ratio of the two-particle probability distribution to the product of the single particle distributions. For a static source with no final state interactions, it is related to the Fourier transform with respect to $q = p_1 - p_2$ of the source distribution $\rho(\mathbf{r})$, $P(p_1, p_2)/P(p_1)P(p_2) = 1 + |\rho(q)|^2$ [1]. If the source is parameterized as a multi-dimensional Gaussian, the enhancement in the correlation function is a Gaussian, and the Gaussian widths are each inversely proportional to the source dimensions in the canonically conjugate spatial variables. The extracted source dimensions are commonly referred to as HBT radii, after a similar technique developed by Hanbury-Brown and Twiss to measure stellar radii [10]. For dynamic sources, such as rapidly expanding sources in heavy-ion collisions, the correlation function measures “lengths of homogeneity”, or the relative separations of the pions with low relative momentum. This leads to source radii which depend strongly on $k_T$, the mean transverse momentum of the

11 Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan
12 Institute for High Energy Physics (IHEP), Protvino, Russia
13 Iowa State University, Ames, IA 50011, USA
14 KEK, High Energy Accelerator Research Organization, Tsukuba-shi, Ibaraki-ken 305-0801, Japan
15 Korea University, Seoul, 136-701, Korea
16 Russian Research Center "Kurchatov Institute", Moscow, Russia
17 Kyoto University, Kyoto 606, Japan
18 Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
19 Los Alamos National Laboratory, Los Alamos, NM 87545, USA
20 Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden
21 McGill University, Montreal, Quebec H3A 2T8, Canada
22 Institut für Kernphysik, University of Münster, D-48149 Münster, Germany
23 Myongji University, Yongin, Kyonggi-do 449-728, Korea
24 Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki 851-0193, Japan
25 University of New Mexico, Albuquerque, NM 87131, USA
26 New Mexico State University, Las Cruces, NM 88003, USA
27 Chemistry Department, State University of New York - Stony Brook, Stony Brook, NY 11794, USA
28 Department of Physics and Astronomy, State University of New York - Stony Brook, Stony Brook, NY 11794, USA
29 Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
30 PNPI, Petersburg Nuclear Physics Institute, Gatchina, Russia
31 RIKEN (The Institute of Physical and Chemical Research), Wako, Saitama 351-0198, JAPAN
32 RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA
33 Universidade de São Paulo, Instituto de Física, Caixa Postal 66318, São Paulo CEP05315-970, Brazil
34 SUBATECH (École des Mines de Nantes, IN2P3/CNRS, Universite de Nantes) BP 20722 - 44307, Nantes-cedex 3, France
35 St. Petersburg State Technical University, St. Petersburg, Russia
36 University of Tennessee, Knoxville, TN 37996, USA
37 Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551, Japan
38 University of Tokyo, Tokyo, Japan
39 Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305, Japan
40 Vanderbilt University, Nashville, TN 37235, USA
41 Waseda University, Advanced Research Institute for Science and Engineering, 17 Kikui-cho, Shinjuku-ku, Tokyo 162-0044, Japan
42 Weizmann Institute, Rehovot 76100, Israel
43 Yonsei University, IPAP, Seoul 120-749, Korea
44 KFKI Research Institute for Particle and Nuclear Physics (RMKI), Budapest, Hungary

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pion pair $\frac{1}{2}-16$. If the dynamics are correctly modeled, then both the source geometry and rate of expansion can be deduced by measuring the $k_T$ dependence of the radii. The existence of a connection between HBT radii and heavy-ion source geometry is established by the dependence of the radii on system size $\frac{17}$, centrality $\frac{18}$, and reaction plane $\frac{19}$. Interest in Bose-Einstein correlations in heavy-ion collisions is driven by the expectation that HBT radii are sensitive to the large and/or long-lived sources which may accompany a QCD phase transition $\frac{12-13}$. Recent calculations predict that the greatest sensitivity to a long-lived source will come from measurements of the correlation function at high $k_T (\geq 0.3 \text{ GeV/c}) \frac{14-20}$.

We present new measurements from the PHENIX experiment on two-pion correlations in Au+Au collisions at $\sqrt{\text{SNN}} = 130 \text{ GeV}$ in the region $|\eta| < 0.35, 0.2 < k_T < 1.0$ GeV/c, significantly extending previous measurements by STAR $\frac{21}$ up to a mean-$k_T$ 0.63 GeV/c. The data are compared to theoretical predictions for RHIC and to HBT radii from lower energy collisions at the SPS and AGS. The $k_T$ dependence of the transverse radii is used to extract a geometrical transverse radius.

The PHENIX experiment has been described in detail elsewhere $\frac{21-23}$. For this analysis we utilize a subset of the detectors in PHENIX. We use the hadronic particle identification capabilities present in the west arm of the PHENIX spectrometer perpendicular to the beam direction $\frac{22}$ with polar and azimuthal ranges of $|\eta| < 0.35$ and $\pi/4$, respectively, during its first year of running. In this analysis, the vertex is determined with a zero degree calorimeter (ZDC) and a pair of Cerenkov beam-beam counters (BBC). Pattern recognition and momentum reconstruction rely on a drift chamber and a pad chamber which occupy the region between 2.0 and 2.5 meters from the beam axis. The momentum resolution from these detectors is $\delta p/p = 0.6\% \oplus 3.6\% p$. Particle velocity is determined from the differential time measurements of the BBC and the electromagnetic calorimeter (EMC) $\frac{23}$, with a combined rms resolution of 600 ps, coupled with the path length determined from pattern recognition. The momentum determination and particle identification method are similar to $\frac{22}$, except that the time of flight is measured by the EMC. A pion is defined as being within 1.5 standard deviations of the pion mass-squared peak but at least 2.5 standard deviations away from the kaon peak. After applying inter-detector association cuts the background from mis-associated EMC hits is $\sim 10\%$ as determined by a hit randomization technique. This background does not significantly distort the extracted radius in the correlation measurements, although it reduces the measured correlation strength ($\lambda$). We did not correct for this background in our correlation analysis.

A total of 493K events in the most central 30% of the cross section survive all offline cuts. This sample contains 3.1 million $\pi^+$ pairs and 3.3 million $\pi^-$ pairs in the analysis, and has a mean centrality of 10%.

The pion correlation function is determined from pairs of identical pions. The normalized probability of detecting two particles with relative momentum $\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2$ and average momentum $\mathbf{k} = (\mathbf{p}_1 + \mathbf{p}_2)/2$ is determined experimentally by the ratio of pairs from the same event ($A$) with those from different events ($B$): $C_2(\mathbf{q},\mathbf{k}) = A(\mathbf{q},\mathbf{k})/B(\mathbf{q},\mathbf{k})$. Pairs of particles within 2 cm of each other in the drift chamber are eliminated from the analysis in both the real and background samples. Pairs that share the same EMC cluster are also removed from both samples. Finally, all pairs in the mixed background sample are required to be from events with a reconstructed BBC collision vertex within 1 cm of each other.

We correct for the Coulomb interaction of the pairs in the correlation function by parameterizing the source as a Gaussian distribution in the pair center-of-mass frame and performing an iterative procedure $\frac{23}$ which accounts for the finite resolution of the detector. This procedure applied to the distribution of $\pi^+ - \pi^-$ pairs is in agreement with the data, although the statistics in the Run-1 opposite-signed analysis are not sufficient to independently determine the required Coulomb correction. Systematic studies of the Coulomb correction which vary both radius and magnitude within reasonable constraints produce variations in the final radii which never exceed 0.25 fm.

The relative momenta are projected into the variables $q_{\text{long}}, q_{\text{out}}$ along the beam direction, $q_{\text{side}}$ perpendicular to the transverse momentum of the pair $k_T = \frac{1}{2}(p_{\text{long}}+p_{\text{out}})$, and $q_{\text{side}}$, perpendicular to $q_{\text{long}}$ and $q_{\text{out}}$ $\frac{11-18}$. These variables are calculated in the longitudinal co-moving system (LCMS), obtained by a longitudinal boost from the lab frame to the frame in which the longitudinal pair velocity vanishes. This frame is commonly used for sources expected to be invariant under longitudinal boosts $\frac{20}$.

The fully corrected correlation function for $\pi^-$ pairs is shown in the top panels of Fig. $\frac{1}$. The large $q$ region of the correlation function has been normalized to 1 in the plots. The data are fit to a Gaussian parameterization of the source using a MINUIT based log-likelihood method $\frac{1}$.}

$$C_2 = 1 + \lambda \exp\left(-R_{\text{long}}^2 q_{\text{long}}^2 - R_{\text{side}}^2 q_{\text{side}}^2 - R_{\text{out}}^2 q_{\text{out}}^2\right)$$  

(0.1)

where $R_{\text{long}}, R_{\text{side}},$ and $R_{\text{out}}$ are the conjugate variables to $q_{\text{long}}, q_{\text{side}},$ and $q_{\text{out}}$, respectively. Errors quoted in the tables and figures are statistical only. Systematic errors come mainly from the Coulomb correction and dependence of the results on the two-track distance cuts. The combined systematic error for these effects, estimated by varying the cuts and corrections within reasonable bounds, is 8% for $R_{\text{long}}$, and $R_{\text{side}}$, and 4% for $R_{\text{out}}$. The
systematic error from residual correlations in the event-mixed background is 2%, yielding a total systematic error of \( \sim 8\% \) for \( R_{\text{long}} \) and \( R_{\text{side}} \) and \( \sim 4.5\% \) for \( R_{\text{out}} \).

The data set is subdivided into three \( k_T \) bins of equivalent statistics in order to study the momentum dependence of the correlation function. In Fig. 1, the radii for \( \pi^- \) pairs are shown to agree within statistical and systematic errors with previous measurements for overlapping \( k_T \) bins at this energy for the 12% most central events. For STAR, the mean pair centrality can be approximated by the geometric mean of 8%, which is slightly more central than the mean pair centrality of 10% for the PHENIX data. This figure also shows \( k_T \) dependent radii for mid-rapidity pions from central collisions for \( \sqrt{s_{\text{NN}}} = 17.3 \) GeV Pb+Pb [2] and for \( \sqrt{s_{\text{NN}}} = 4.9 \) and 4.1 GeV Au+Au [3]. For the transverse radii, \( R_{\text{out}} \) and \( R_{\text{side}} \), the variation with collision energy is generally smaller than the statistical and systematic errors of the individual data points. There is no evidence for a change in the low-\( k_T \) extrapolation of \( R_{\text{side}} \) with increasing \( \sqrt{s_{\text{NN}}} \) which would indicate a larger geometric source at higher energy. Nor is any change evident in \( R_{\text{out}} \) relative to \( R_{\text{side}} \) at high-\( k_T \), indicating a longer-lived source. This result is surprising given the factor of \( \sim 3 \) change in the total charged particle multiplicity per unit rapidity at mid-rapidity [25]. Only \( R_{\text{long}} \) exhibits a significant variation with collision energy. To quantify this difference, we fit the \( R_{\text{long}} \) dependence to \( A_f/\sqrt{k_T} \) [3] for the three sets of beam energies. The results are overlayed with the data in the bottom panel of Fig. 2 and yield \( A = 3.32 \pm 0.03, 3.05 \pm 0.06, \) and \( 2.19 \pm 0.05 \) fmGeV for \( \sqrt{s_{\text{NN}}} = 130, 17.3, \) and 4.9/4.1 GeV respectively.

Although a finite emission duration contributes to \( R_{\text{out}} \) but not to \( R_{\text{side}} \), dynamical correlations affect the two radii differently. A quantitative determination of the source lifetime can only be performed in the context of a dynamical model. The lower panel of Fig. 1 shows the \( k_T \) dependence of the ratio \( R_{\text{out}}/R_{\text{side}} \) for PHENIX and STAR along with recent calculations for a thermalized source which undergoes a first order phase transition at critical temperatures \( (T_c) \) of 160 and 200 MeV [2]. The rise in \( R_{\text{out}}/R_{\text{side}} \) which comes predominantly from a hadronic re-scattering phase is not present in the data, and the values of 1.6 \( (T_c = 160 \) MeV) and 2.2 \( (T_c = 200 \) MeV) at high \( k_T \) are excluded.

An additional consequence of strong dynamics occurs for sources in which the transverse expansion is relativistic. In this case, \( R_{\text{out}} \) measured in the LCMS frame is Lorentz contracted by the \( \gamma \) of the pion source velocity along the direction of \( q_{\text{out}} \) [30,31]. Current Lorentz invariant formulations of the correlation function [22,14] are insufficient to determine the source velocity due to transverse expansion, however, the pair center-of-mass system (PCMS) can be used to provide an upper limit on \( R_{\text{out}} \) [3]. The correlation function for \( \pi^- \) pairs in the PCMS frame is shown in the bottom panels of Fig. 1, and fit results for \( R_{\text{out}}^{\text{PCMS}} \) are listed in Table 1. As expected, \( R_{\text{side}} \) and \( R_{\text{long}} \) are equal to the corresponding LCMS parameters within errors.

Two analytic expressions have been used to describe \( R_{\text{side}} \) as a function of \( m_T = \sqrt{k_T^2 + m_T^2} \) for a transversely expanding source,

\[
R_{\text{side}}^2(m_T) = \frac{R_{\text{geom}}^2}{1 + \beta_T^2 (\frac{m_T}{R_{\text{geom}}})^2}, \tag{0.2}
\]

\[
R_{\text{side}}^2(m_T) = \frac{R_{\text{geom}}^2}{1 + \eta_T^2 (\frac{m_T}{R_{\text{geom}}})^2}. \tag{0.3}
\]

Eq. (0.2) is a first order approximation in \( \frac{m_T}{R_{\text{geom}}} \) for a longitudinal boost invariant source with finite temperature, \( T \), and expansion velocity, \( \beta_T = \beta T_{\text{geom}} \), where \( R_{\text{geom}} \) is the Gaussian transverse radius [4]. Eq. (0.3) includes an additional term in the approximation and the linear transverse expansion velocity is replaced by a transverse rapidity, \( \eta_T = \eta_T/R_{\text{geom}} \) [16]. For a transverse surface rapidity of \( \eta_T = 0.85 \) (\( \beta_T = 0.69 \)) and \( T = 125 \) MeV [33], a fit of Eq. (0.3) to the PHENIX \( R_{\text{side}} \) \( m_T \) dependence yields, \( R_{\text{geom}} = 8.1 \pm 0.3 \) fm with a \( \chi^2/\text{dof} = 9.6/6 \). To assess systematic errors the PHENIX data are also fit to Eq. (0.2), yielding \( R_{\text{geom}} = 6.7 \pm 0.2 \) fm and \( \chi^2/\text{dof} = 9.1/6 \), and the STAR data are fit to Eq. (0.3), yielding \( R_{\text{geom}} = 9.4 \pm 0.1 \) fm with \( \chi^2/\text{dof} = 21/6 \). These fits are shown in the top panel of Fig. 3. All values of \( R_{\text{geom}} \) are significantly larger than the comparable 1D rms radius for a Au nucleus [30] of \( \sqrt{A} \cdot \sqrt{A} \times 6.87 = 3.07 \) fm.

In conclusion, we have extended the measurement of two particle correlations for Au+Au collisions at \( \sqrt{s_{\text{NN}}} = 130 \) GeV to \( < k_T > = 0.63 \) GeV/c using the PHENIX detector at RHIC. Values of \( R_{\text{out}}^{\text{PCMS}} \) are used to constrain the Lorentz effects for a relativistic transverse expansion. Fitting \( R_{\text{side}}(k_T) \) to two analytic expressions for an expanding source yields a transverse geometric radius that is much larger than the comparable radius for Au. We find that \( R_{\text{long}}(k_T) \) increases monotonically with collision energy, yet no energy dependence is discernible in the \( k_T \) dependence of \( R_{\text{out}} \) and \( R_{\text{side}} \), and the ratio, \( R_{\text{out}}/R_{\text{side}} \), is consistent with unity and independent of \( k_T \). The results for the transverse radii are contrary to common expectations for a first order phase transition in Au+Au collisions at these energies, as demonstrated by the comparison to a typical hydrodynamic model with hadronic-rescattering. Therefore, we conclude that current concepts regarding the space-time evolution of the pion source inferred from two-pion correlations in Au+Au collisions at RHIC will need to be revised.

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∗ Deceased
† Not a participating Institution.

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FIG. 1. The three dimensional correlation function for π− pairs versus \( q_{\text{long}},q_{\text{side}}, \) and \( q_{\text{out}} \) in both the LCMS frame (top) and pair center-of-mass frame (bottom). The data are plotted versus one momentum difference variable while requiring the other two to be less than 40 MeV/c. The lines correspond to the fit to the entire distribution.

FIG. 2. HBT radii for pion pairs as a function of \( k_T \) measured at mid-rapidity for various energies from E895 (\( \sqrt{s_{NN}} = 4.1 \) GeV), E866 (\( \sqrt{s_{NN}} = 4.9 \) GeV), NA44, WA98 (\( \sqrt{s_{NN}} = 17.3 \) GeV), STAR, and PHENIX (\( \sqrt{s_{NN}} = 130 \) GeV). The bottom plot includes fits to \( a/\sqrt{m_T} \) for each energy region. The data are for π− results except for the NA44 results, which are for π+.

FIG. 3. The top panel shows the measured \( R_{\text{side}} \) from identical pions for STAR and PHENIX. The line solid line is a fit of Eq. [3] to the PHENIX data, and the dashed line is the same fit for Eq. [2]. The dot-dashed line is a fit of Eq. [3] to the STAR data. The bottom panel shows the ratio \( R_{\text{out}}/R_{\text{side}} \) as a function of \( k_T \) overlaid with theoretical predictions for a phase transition for two critical temperatures.

TABLE I. The \( k_T \) dependencies of the \( \pi^+ \) and \( \pi^- \) radii in the LCMS and PCMS frames. All momenta are in MeV and all radii are in fm. The errors are statistical only.

| \( k_T \) (MeV) | \( 200 \) – \( 400 \) | \( 400 \) – \( 550 \) | \( 550 \) – \( 1000 \) |
|-----------------|---------------|---------------|---------------|
| \( R_{\text{ave}} \) | 6.74 ± 0.31  | 6.42 ± 0.46  | 3.46 ± 0.46  |
| \( \lambda_{\text{LCMS}} \) | 0.423 ± 0.037 | 0.389 ± 0.039 | 0.287 ± 0.048 |
| \( \pi^+ \) | \( R_{\text{long}} \) | 6.01 ± 0.45  | 4.76 ± 0.35  | 2.97 ± 0.38  |
|               | \( R_{\text{side}} \) | 4.81 ± 0.30  | 3.74 ± 0.36  | 2.79 ± 0.37  |
|               | \( R_{\text{out}} \) | 4.78 ± 0.30  | 3.76 ± 0.26  | 2.59 ± 0.46  |
|               | \( R_{\text{PCMS}} \) | 11.35 ± 0.69 | 12.20 ± 1.02 | 8.60 ± 1.13  |

| \( \pi^- \) | \( R_{\text{ave}} \) | 6.00 ± 0.30  | 5.96 ± 0.41  | 4.58 ± 0.48  |
|             | \( \lambda_{\text{LCMS}} \) | 0.431 ± 0.079 | 0.405 ± 0.067 | 0.353 ± 0.062 |
| \( R_{\text{long}} \) | 5.69 ± 0.76  | 4.77 ± 0.49  | 3.76 ± 0.41  |
| \( R_{\text{side}} \) | 4.67 ± 0.38  | 4.13 ± 0.45  | 3.22 ± 0.35  |
| \( R_{\text{out}} \) | 4.69 ± 0.58  | 3.75 ± 0.40  | 2.81 ± 0.34  |
| \( R_{\text{PCMS}} \) | 11.27 ± 0.72 | 12.42 ± 1.18 | 11.89 ± 1.73 |