Production of $\phi$ mesons at mid-rapidity in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC

S.S. Adler,5 S. Afanasiev,17 C. Aidala,5 N.N. Ajitanand,43 Y. Akiba,20,38 J. Alexander,43 R. Amiri,12 L. Apecce,45 S.H. Aronson,5 R. Averbeck,44 T.C. Awes,35 R. Aymont,44 V. Babintsev,15 A. Baldisseri,10 K.N. Barish,6 P.D. Barnes,27 B. Bassalleck,33 S. Bathe,30 S. Batsoulis,9 V. Baublis,37 A. Bazilevsky,39,15 S. Belikov,16 Y. Berndikov,34 S. Bhagavatula,16 J.G. Boissevain,27 H. Borel,10 S. Borenstein,25 M.L. Brooks,27 D.S. Brown,34 N. Bruner,33 D. Bucher,30 H. Buesching,30 V. Bumazhnov,15 G. Bunea,5,39 J.M. Burward-Hoy,26,44 S. Butsly,44 X. Camard,45 J.-S. Chai,18 P. Chand,4 W.C. Chang,2 S. Chernichenko,15 C.Y. Chi,9 J. Chiba,20 M. Chiu,9 I.J. Choi,52 J. Choi,19 R.K. Choudhury,4 T. Chujo,5 V. Cianciolo,35 Y. Coligo,19 B.A. Cole,9 P. Constant,16 D.G. d'Enterria,45 G. David,5 H. Delagrave,45 A. Denisov,15 A. Deshpande,39 E.J. Desmond,5 O. Dietzsch,41 O. Draper,25 A. Drees,44 R. du Rietz,29 A. Durum,15 D. Dutta,4 Y.V. Efremenko,35 K. El Chenawi,49 A. Enokizono,14 H. En’yo,38,39 S. Esumi,48 L. Ewell,5 D.E. Fields,33,39 F. Fleuret,25 S.L. Fokin,23 B.D. Fox,39 Z. Fraenkel,51 J.E. Franz,9 A. Franz,5 A.D. Frawley,12 S.-Y. Fung,6 S. Garman,29 T.K. Ghosh,49 A. Glenn,46 G. Gogiberidze,46 M. Goin,25 J. Gosset,10 Y. Goto,39 R. Granier de Cassagnac,25 N. Grau,16 S.V. Greene,49 M. Grose Perdekamp,39 W. Gury,5 H.-A. Gustafsson,29 T. Hachiya,14 J.S. Haggerty,5 H. Hamagaki,8 A.G. Hansen,27 E.P. Hartouni,26 M. Harvey,5 R. Hayano,8 X. He,13 M. Heffner,26 T.K. Hemmick,44 J.M. Heuser,44 M. Hibino,50 J.C. Hill,16 W. Holzgo,43 K. Homma,14 B. Hong,22 A. Hoover,34 T. Ichihara,38,39 V.V. Ikonnikov,23 K. Inami,24,38 D. Isehower,1 M. Ishihara,38 M. Issah,43 A. Isupov,17 B.V. Jacak,54 W.Y. Jang,22 Y. Jeong,19 J. Jia,44 O. Jinnouchi,38 B.M. Johnson,5 S.C. Johnsen,26 K.S. Joo,31 D. Jouan,36 S. Kameta,8,30 N. Kanihara,47,38 J.H. Kang,52 S.S. Kapoor,1 K. Katou,39 S. Kelif,9 B. Khachaturov,51 A. Khanzadeev,37 J. Kikuchi,50 H.D. Kim,31 D.J. Kim,52 D.W. Kim,39 E. Kim,42 G.-B. Kim,25 H.J. Kim,52 E. Kisten,5 K. Aiyomi,39 K. Kiyohama,39 C. Klein-Bosings,30 H. Kobayashi,38,39 L. Kouchend,37 V. Kochetkov,15 D. Koehler,33 T. Kohama,14 M. Kopytine,44 D. Kotechetkov,6 A. Kozlov,51 P.J. Kroom,3 C.H. Kuberg,1,27 K. Kurita,39 Y. Kuroki,48 M.J. Kweon,22 Y. Kwo,52 G.S. Kylle,34 R. Lacey,43 V. Ladygin,17 J.G. Lajoie,16 A. Lebedev,16,23 S. Leckey,44 D.M. Lee,27 S. Lee,19 M.J. Leitch,27 X.H. Li,6 H. Lim,42 A. Litvinkov,17 M.X. Liu,27 Y. Liu,39 C.P. Maguire,49 Y.I. Makdisi,5 A. Malakhov,17 V.I. Manko,23 Y. Mao,7,38 G. Martinez,45 M.D. Marx,44 H. Masui,48 F. Matathias,44 T. Matsumoto,8,50 P.L. McGaughy,27 E. Melnikov,15 F. Messer,49 Y. Mieke,48 J. Milan,43 T.E. Miller,49 A. Milov,51 S. Mioduszewski,5 R.E. Mischke,27 G.C. Misra,13 J.T. Mitchell,5 A.K. Mohanty,4 D.P. Morrison,5 J.M. Moss,27 F. Mühlbacher,44 D. Mukhopadhyay,51 M. Muniruzzaman,6 J. Murata,38,39 S. Nagamiya,50 J.L. Nagle,9 T. Nakamura,14 B.K. Nandi,6 M. Nara,48 J. Newby,46 P. Nilsson,29 A.S. Nyanin,29 N. Nystrand,29 E. O'Brien,5 C.A. Ogilvie,16 H. Ohnishi,5,38 I.D. Ojha,49,3 K. Okada,38 M. Ono,48 V. Onuchin,15 A. Oskarsson,29 I. Otterlund,26 K. Oyama,8 K. Ozawa,8 D. Pal,51 A.P.T. Palounek,27 V.S. Pantuev,34 V. Papavassiliou,34 J. Park,42 A. Parmar,33 S.F. Pate,34 T. Peitzmann,30 J.-C. Peng,27 V. Peresedov,17 C. Pinkenburg,5 R.P. Pisani,8 F. Plasil,35 M.L. Purschke,5 A.K. Purwar,44 J. Rak,16 I. Rabinovich,51 K.F. Read,35,46 M. Reuter,44 K. Reygers,30 V. Riabov,37,40 Y. Riabov,37 G. Roche,28 A. Romana,25 M. Rosati,46 P. Rosnet,28 S.S. Ryu,52 M.E. Sadler,1 N. Saito,38,39 T. Sakaguchi,8,50 M. Sakai,22 S. Sakai,49 V. Samsonov,37 L. Sanfratello,33 R. Santo,30 H.D. Sato,24,38 S. Sato,54 S. Sawada,20 Y. Schutz,45 V. Semenov,15 R. Seto,6 M.R. Shaw,1,27 T.K. Shea,5 T.-A. Shibata,47,38 K. Shigaki,14,20 T. Shinya,27 C.L. Silva,41 D. Silverman,27,29 K.S. Sim,22 C.P. Singh,3 V. Singh,3 M. Sivertz,5 A.Soldatov,15 R.A. Solte,26 W.E. Sondheim,27 S.P. Sorensen,46 I.V. Sourikov,5 F. Staley,10 P.W. Stankus,35 E. Stenlund,29 M. Stepanov,34 A. Ster,21 S.P. Stoll,5 T. Sugitate,14 J.P. Sullivan,27 E.M. Takagui,41 A. Taketani,38,39 M. Tamai,50 K.H. Tanaka,20 Y. Tanaka,32 K. Tanida,38,39 M.J. Tannenbaum,5 P. Tarján,11 J.D. Tepe,1,27 T.L. Thomas,33 J. Tojo,24,38 F. Torii,24,38 R.S. Towell,1 I. Tserruya,51 H. Tsunetaka,48 S.K. Tuli,3 H. Tydesjö,26 N. Tyurin,15 H.W. van Hecke,27 J. Velkovskaya,5,44 M. Velkovsky,54 L. Villatte,46 A.A. Vinogradov,23 M.A. Volkov,23 E. Vznuzdaev,37 X.R. Wang,13 Y. Watanabe,38,39 S.N. White,5 F.K. Wohlen,16 C.L. Woody,5 W. Xie,5 Y. Yang,7 A. Yanovich,51 S. Yokai,38,39 G.R. Young,35 E.Y. Yushanov,23 W.A. Zajac,9 C. Zhang,9 S. Zhou,7 S.J. Zhou,51 and L. Zolin17

(PHENIX Collaboration)

1Abilene Christian University, Abilene, TX 79699, USA
2Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
3Department of Physics, Banaras Hindu University, Varanasi 221005, India
4Bhabha Atomic Research Centre, Bombay 400 085, India
5Brookhaven National Laboratory, Upton, NY 11973-5000, USA
6University of California - Riverside, Riverside, CA 92521, USA
7China Institute of Atomic Energy (CIAE), Beijing, People's Republic of China
We present the results of φ meson production in the $K^+K^-$ decay channel from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as measured at mid-rapidity by the PHENIX detector at RHIC. Precision resonance centroid and width values are extracted as a function of collision centrality. No significant variation from the PDG accepted values is observed, contrary to some model predictions. The $\phi$ transverse mass spectra are fitted with a linear exponential function for which the derived inverse slope parameter is seen to be constant as a function of centrality. However, when these data are fitted by a hydrodynamic model the result is that the centrality-dependent freeze–out temperature and the expansion velocity values are consistent with the values previously derived from fitting identified charged hadron data. As a function of transverse momentum the collisions scaled peripheral–to–central yield ratio $R_{CP}$ for the $\phi$ is comparable to that of pions rather than that of protons. This result lends support to theoretical models which distinguish between baryons and mesons instead of particle mass for explaining the anomalous (anti)proton yield.

PACS numbers: 25.75.Dw
I. INTRODUCTION

Relativistic heavy-ion experiments have a goal of producing matter at extreme temperatures and energy densities such that conditions are favorable for the transition to a deconfined state of quarks and gluons, the Quark Gluon Plasma (QGP). Theoretical calculations predict that the temperatures and energy densities which can be reached at the Brookhaven National Laboratory’s Relativistic Heavy Ion Collider (RHIC) will exceed those needed for the formation of the QGP [1, 2, 3].

The production and decay of the $\phi$ meson have long been recognized as an important probe for the state of matter produced in relativistic heavy ion (RHI) collisions [4–13, 14, 15, 16, 17, 18, 19, 20, 21]. In $pp$ collisions the creation of the $\phi$ is suppressed according to the Okubo-Zweig-Iizuka rule [22]. Hence, if there is an enhancement of the $\phi$ yield in RHI collisions relative to $pp$ collisions, this could be evidence of non-conventional production mechanisms such as strange quark coalescence via the formation and subsequent hadronization of the QGP. The fact that the $\phi$ yield is undistorted by feed-down from higher mass resonances makes it an attractive probe in this respect.

The decay modes of the $\phi$, specifically the dilepton channels ($e^+e^-$ or $\mu^+\mu^-$) and the $K^+K^-$ channel, will probe the final state differently should the decay take place in the presence of the QGP-mixed or the completely hadronized phase. The dileptons will have insignificant interactions with the medium, while the kaons can scatter until freeze-out. The lifetime of the $\phi$ in vacuum is large ($\approx 45$ fm/$c$) compared to say a $10$ fm sized interaction region. However, several theoretical calculations [13, 21, 23] predict that the $\phi$ mass and width could be significantly modified in either the hot or the cold nuclear medium. These medium induced effects could be manifested through measured shifts in the mass centroid of the resonance or changes in the resonance width. Also predicted are changes in the relative branching ratio between kaon and lepton pairs, with respect to the Particle Data Group (PDG [24]).

The production mechanism of strangeness in heavy ion collisions can be investigated through the measurement of the particle yields. In this paper, we study system size dependence by analyzing centrality selected data. A comparison between different systems can be made by normalizing to the number of participant pairs. The expectation is that for production dominated by soft processes, the yields scale as the number of participants. We compare the centrality dependence of strange and non-strange particle yields in order to reveal the possible flavor dependence.

An additional important question is whether the $\phi$ mesons participate in radial flow together with the other hadrons, or if they freeze-out earlier, as might be true if the small vacuum cross sections of the $\phi$ with hadrons persist in the fireball. Previous measurements have yielded contradictory results [25, 26]. One of the important advantages of RHIC experiments is the capability to examine the momentum spectrum as a function of centrality for a variety of hadrons which should yield important additional information on the radial flow issue. A spectral shape analysis including a simultaneous treatment of the $\phi$ and the more abundant hadrons ($\pi$, $K$, $p$) will be presented here.

At high $p_T$, hadrons are primarily produced from the fragmentation of hard-scattered partons. One of the most exciting results from RHIC was the discovery of hadron suppression in central Au+Au collisions [27, 28] where this suppression is absent in d+Au collisions [29]. Surprisingly, it was also discovered that proton and anti-proton production at intermediate $p_T$ (1.5–4.5 GeV/$c$) scales with the number of binary nucleon-nucleon collisions ($N_{coll}$) as would be expected for hard-scattering in the absence of any nuclear modification [30]. In fact, the intermediate $p_T$ anti-proton to pion ratios were found to exceed by a factor of 3 the values expected from parton fragmentation [30, 31]. These experimental results lead to the conclusion that protons and pions have different production mechanisms at intermediate $p_T$ [30]. One possible explanation invokes parton recombination from the QGP [32, 33, 34, 35]. A measurement of the nuclear modification factor for the $\phi$ meson, which has a mass comparable to the proton but carries only two quarks, is crucial for understanding the hadron production at intermediate $p_T$. In this work we have measured the nuclear modification factor through the ratio $R_{CP}$ of central to peripheral yields scaled by their respective $N_{coll}$ value.

To put our results into perspective, we begin by describing the currently available $\phi$ data obtained in RHI collisions. The production of $\phi$ mesons has been studied systematically at ever increasing $\sqrt{s}$ from the AGS to RHIC. The E802 collaboration made the first observation of the $\phi$ in fixed target central collisions of $14.6A$ GeV Si+Au ($\sqrt{s_{NN}} = 5.39$ GeV) via the $K^+K^-$ channel [36]. They obtained a ratio $N_\phi/N_{K^-} = 11.6\%$, roughly consistent with the ratio obtained in $pp$ data over a wide range of $\sqrt{s}$ [37]. The analysis of the E802 rapidity distributions indicated that the $\phi$ production scaled with the product of the $K^+$ and $K^-$ separate yields, and that there was either significant rescattering of the $\phi$ after production or the production itself came after rescattering of the colliding participants.

Also at the AGS the E917 experiment has reported another $\phi$ measurement with $11.7A$ GeV Au+Au ($\sqrt{s_{NN}} = 4.87$ GeV) in the rapidity range $1.2 < y < 1.6$ in five centrality bins [38]. The observed yield of the $\phi$ increased towards more central collisions with a distinctly faster than linear dependence on the number of participants. The yield increase of the $\phi$ in central collisions was stronger than that of the $\pi$ since the $N_\phi/N_\pi$ ratio in-
increased in central collisions. However, the $N_\pi/N_{K^+}$ and $N_\phi/N_{K^+}$ ratios were constant as a function of centrality.

At the SPS the NA49 experiment has measured $\phi$ production in $pp$, $pp$, and Pb+Pb collisions with $E_{\text{beam}}=158$ A GeV ($\sqrt{s_{NN}}=17.5$ GeV) in the rapidity range $3.0 < y < 3.8$ [33]. Relative to the $pp$ yields, these data showed that the ratio of the $\phi$ yield to the $\pi$ yield in central Pb+Pb collisions was enhanced by a factor $3.0 \pm 0.7$. Another SPS collaboration, NA38/NA50, has measured the $\phi$ in the $\mu^+\mu^-$ channel [40, 41], for which the extracted effective temperature and $dN/dy$ differ from those obtained in the $K^+K^-$ channel in the same systems. The yield difference between the two SPS experiments has been calculated to be factors of 2–4 [42], with the NA38/NA50 result being higher.

The first measurement of the $\phi$ meson at RHIC was reported by the STAR collaboration [43], in the collisions of Au+Au at $\sqrt{s_{NN}}=130$ GeV at three centralities, 0–11%, 11–26%, and 26–85% in the rapidity range $-0.5 < y < +0.5$. The extracted temperature $T$ and the ratio $N_\phi/N_\pi$ did not vary with centrality.

One may summarize the current state of knowledge of $\phi$ production in heavy ion collisions by stating that the topic remains highly unexplored territory. The heavy-ion measurements do indicate that the observed $\phi$ yield is not a simple linear superposition of nucleon-nucleon collisions. Rather the data imply the influence of some collective effects. Whether those effects are induced by cold and/or hot nuclear matter, there do not yet exist definitive measurements. Moreover, there has not been so far precise enough heavy-ion data which can address the question of the change in the $\phi$ mass or its width in the cold nuclear or the hot QGP medium. And except for one experiment measuring the dimuon channel, there is a scarcity of useful quantitative information in heavy ion collisions concerning the $\phi$ decay into dileptons.

In this paper we report on a measurement of the $\phi$ yield at mid-rapidity in collisions of Au+Au beams from RHIC at $\sqrt{s_{NN}}=200$ GeV as measured in the $K^+K^-$ channel by the PHENIX detector. The paper is organized as follows. In Section II we give a short review of the PHENIX detector configuration. In Section III we describe the data analysis procedure. Section IV presents and discusses the results. The first precision measurements of $\phi$ mass and width values obtained in relativistic heavy ion collisions as a function of centrality are given in Section IV–A. Absolute yields as a function of $p_T$ for three centrality bins are shown in Section IV–B. The centrality dependence of yields and ratios are studied in Section IV–D. In Section IV–D the spectra shapes are interpreted in the framework of a hydrodynamical model and the freeze-out conditions are extracted. Finally, the nuclear modification factor $R_{CP}$ for the $\phi$ is obtained and compared to those of pions and protons in Section IV–E.

II. PHENIX DETECTOR

The PHENIX detector consists of two spectrometer arms at near zero rapidity, two forward rapidity muon spectrometers, and three global event characterization detectors. The central arm spectrometers, shown schematically in Fig. 1, are located East and West of the beam line with $\pi/2$ radian azimuthal coverage each. These spectrometers are designed to detect photons, electrons, and charged hadrons. The $\phi$ data for this paper were obtained with the central arm detector subsystems which provide high resolution particle identification and momentum reconstruction. A complete description of the PHENIX apparatus has been published elsewhere [44, 45, 46, 47, 48, 49]. We present a brief review of the relevant detector subsystems in the following sections.

A. Global Detectors

The global detectors furnish the start time signals, collision vertex measurements, and interaction centrality. The centrality for events in the Au+Au collisions is determined [50] by combining the data from two subsystems: the Zero Degree Calorimeters (ZDC) [48] and the Beam-Beam Counters (BBC) [47]. The ZDC are hadronic calorimeters located 18 m downstream and upstream of the interaction point along the beam line. These calorimeters detect the energy carried by spectator neutrons. The BBC are Čerenkov telescopes placed $\pm 1.4 m$ the center of the beam collision region in the pseudo-rapidity region $3.0 < |\eta| < 3.9$. The correlation between the ZDC energy sum and the charge sum recorded in the BBC determines the centrality of the collision event. The BBC data also determine the longitudinal collision coordinate ($z_{\text{vertex}}$) and the start time for the time-of-flight measurements.

B. Central Arm Detectors

The central arm spectrometers [49] in PHENIX provide charged particle tracking and particle identification. This analysis was done with the East arm spectrometer. The $\phi \rightarrow K^+K^-$ decay kinematics are such that the PHENIX detector has negligible acceptance for the very low $p_T$ $\phi$ particles which would decay into East-West kaon pairs. The data included information from the drift chamber (DC), the pad chambers (PC1 and PC3), the high resolution time-of-flight wall (TOF), and the electromagnetic calorimeter (EMCal) lead-scintillator detectors (PbSc), as depicted in Fig. 1.

Pattern recognition and tracking of the charged particles are accomplished using the DC information by a combinatorial Hough transform method [51]. The DC
subsystem is located at an average radial distance of 2.2 m from the beam line. It is a projective tracking detector providing high precision measurements in the azimuthal XYZ plane, which are combined with the XYZ single spatial point measurement from the PC1 located at 2.45 m. These data, together with the BBC $z_{\text{vertex}}$ information, are sufficient to determine the track’s initial momentum vector whose magnitude is obtained with a resolution $\delta p/p \approx 0.7\% \oplus 1.0\% \times p$ (GeV/c). The first term in this expression is due to the multiple scattering before the DC and the second term is the angular resolution of the DC. Based on identified mass measurements obtained with the TOF subsystem, the absolute momentum scale is known to $\pm 0.7\%$.

Tracks obtained from the DC/PC1 detectors are projected to the PC3, TOF, and PbSc detectors where associations can be made. The high resolution TOF subsystem provides one set of mass measurements while the PbSc detectors provide a geometrically independent set of mass measurements. The TOF wall is positioned 5.06 m from the beam line and consists of 960 scintillator slats oriented along the azimuthal direction. It is designed to cover $|\eta| < 0.35$ and $\Delta \phi = \pi/4$ in azimuthal angle.

The PbSc detector, covering half of the East arm and entire West arm, can also be used for hadron timing measurements. The present analysis uses the PbSc modules in the East Arm which are located at 5.1 m in radial distance from the beam line and cover a $\Delta \phi = \pi/4$ azimuthal range. This detector is constructed as separate towers of dimension 5.25 x 5.25 x 37 cm$^3$, in an alternating lead-scintillator sandwich type structure (“shish-kebob”), approximately 18 radiation lengths in depth. As illustrated in Fig. 1 the TOF and the PbSc sectors are completely non-overlapping.

### III. DATA ANALYSIS

In this section, we describe the event and track selection, particle identification, the details of $K^+K^-$ pair reconstruction, and the corrections for geometrical acceptance, particle decay in flight, multiple scattering, and detector occupancy factors, all of which couple into deriving the $\phi$ meson spectra.

#### A. Event Selection

The events selected for this analysis were based on the PHENIX minimum-bias trigger provided by the beam-beam counters (BBC) and zero-degree calorimeters (ZDC). As noted previously, the centrality of each Au + Au collision event was determined by correlating the BBC charge sum and the ZDC total energy [50]. The PHENIX minimum-bias data sample included 92.2% of the 6.9 barn Au + Au total inelastic cross section [29]. This analysis used 20 million minimum-bias events with a vertex position within $|z_{\text{vertex}}| < 30$ cm.

To study the centrality dependent physics, we divided these events into different centrality bins. For the $\phi$ meson line shape analysis, we used five centrality bins: 0–10%, 10–20%, 20–40%, 40–60% and 60–92%. The transverse mass ($m_T$) spectra were reconstructed for three centrality bins: 0–10%, 10–40% and 40–92%. These bin divisions were chosen to have approximately equal statistical significance for their respective data points. The centrality of collisions is additionally characterized by the average number of participants ($< N_{\text{part}} >$) and the average number of binary nucleon–nucleon collisions ($< N_{\text{coll}} >$). These two global quantities, shown in Table I as a function of centrality, are derived from a Glauber model calculation [29].

| Centrality (%) | $< N_{\text{part}} >$  | $< N_{\text{coll}} >$  |
|----------------|-------------------------|-------------------------|
| 0 - 10         | 325.2 ± 3.3             | 955.4 ± 93.6            |
| 10 - 20        | 234.6 ± 4.7             | 602.6 ± 59.3            |
| 20 - 40        | 140.4 ± 4.9             | 296.8 ± 31.1            |
| 10 - 40        | 171.8 ± 4.8             | 398.7 ± 40.5            |
| 40 - 60        | 59.9 ± 3.5              | 90.6 ± 11.8             |
| 60 - 92        | 14.5 ± 2.5              | 14.5 ± 4.0              |
| 40 - 92        | 32.0 ± 2.9              | 45.2 ± 7.3              |
| Min. bias      | 109.1 ± 4.1             | 257.8 ± 25.4            |
B. Track Selection

Only tracks with valid information from the DC and the PC1 were used for the analysis. These tracks were then confirmed by matching the projected and associated hit information at the TOF wall for the TOF analysis, or at the PC3 and the EMCal for the PbSc analysis. The differences between the actual azimuthal and longitudinal hit coordinates compared to the projected hit coordinates were determined. These tracking coordinate residuals were converted to standard deviation residuals by a momentum dependent function which computed the expected residual coordinate value. On this basis, a $3\sigma$ track matching cut was used to accept track associations. Lastly, for the TOF wall, an energy loss cut is applied on the analog signal height from the scintillator slat. This cut has been described in a previous publication $^{50}$.

C. Particle Identification

As mentioned earlier, the PHENIX central arm spectrometer utilizes the high resolution TOF wall and PbSc modules for hadron mass identification. The kaons in the TOF wall were identified via reconstructed momentum combined with a time of flight measurement. The timing resolution of this subsystem is $\sigma \approx 115$ ps. A momentum range of 0.3–2.0 GeV/c was selected in order to compute the mass distributions $^1$. Fig. 2 shows the mass-squared distribution of all tracks passing through the TOF module for six different momentum bins. The kaons were identified by applying a $2\sigma$ mass–squared cut, which is shown by the shaded region in each plot.

The particle identification with the electromagnetic calorimeter modules is sensitive to the fact that the electromagnetic and hadronic interactions produce quite different patterns of energy sharing between calorimeter towers $^{52}$. As a consequence, the hadron timing properties of the PbSc depend on the energy deposited on the central tower of the cluster, particle momentum, particle type, charge, angle of incident of the track, etc. The PbSc hadronic timing response was corrected for these effects and we obtained an overall timing resolution of $\sigma \approx 450$ ps which is sufficient to enable a clear $\pi/K$ separation within $0.3 < p$ (GeV/c) < 1.0 using a $2\sigma$ mass–squared selection criterion. In Fig. 3 the mass-squared distributions are plotted for four different momentum slices for all tracks passing through PC3 and PbSc. The identified kaons are also shown in the figure by the $2\sigma$ width shaded histograms superimposed on the $M^2$ distributions for all tracks in different momentum bins.

D. $K^+K^-$ Invariant Mass spectra and $\phi$ Signal Extraction

All identified $K^+$ and $K^-$ tracks in a given event were combined to form the invariant pair mass distributions. Three different pair combinations were used. These are

a) Both $K^+$ and $K^-$ identified by the TOF detector (TOF–TOF combination),

b) $K^+$ identified with TOF and $K^-$ identified with PbSc (TOF–PbSc combination), and

c) Both $K^+$ and $K^-$ identified with PbSc detector (PbSc–PbSc combination).

We did not use the $K^+$ from PbSc and $K^-$ from TOF in the b) combination. This is due to the fact that the PHENIX central arm geometry, in the presence of a 0.8 T-m magnetic field, does not have any acceptance for such pairs below an invariant mass of 1.06 GeV/c$^2$ in the TOF–PbSc combination.

A large combinatorial background is inherent to the $K^+K^-$ pair invariant mass distribution. The combinatorial background was estimated by an event mixing method in which all $K^+$ tracks from one event were

\[ M^2 = \frac{p^2}{c^2 (\frac{c^2}{L^2} - 1)}, \]

where $p$ is the momentum, $t$ is the time of flight, $c$ is the speed of light, and $L$ is the length of the path traversed by the track from vertex to the detector.

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1 The mass-squared for each track is defined as, $M^2 = \frac{p^2}{c^2 (\frac{c^2}{L^2} - 1)}$, where $p$ is the momentum, $t$ is the time of flight, $c$ is the speed of light, and $L$ is the length of the path traversed by the track from vertex to the detector.
FIG. 3: Mass-squared distribution of all selected tracks passing through the PbSc for four momentum bins. The identified kaons within $2\sigma$ mass-squared boundaries at the different momentum bins are shown by the shaded region on each plot.

combined with $K^-$ tracks of ten other events within the same centrality and vertex class. The mixed event technique reproduces the shape of the unlike sign combinatorial background. Finally, the size of the combinatorial background is obtained by normalizing the mixed event invariant mass spectra to $2\sqrt{N_{++}N_{--}}$ where $N_{++}$ and $N_{--}$ represent the measured yields in $K^+K^+$ and $K^-K^-$ mass distributions respectively. This normalization is derived analytically starting from the assumption that the number of $K^\pm$ tracks per event follows a Poisson distribution. A complete derivation of this is given in Appendix A.

The ability of this event mixing method to reproduce correctly the shape of the combinatorial background distribution was confirmed by constructing, in a similar way, the mixed–event like-sign spectrum and comparing it to the same–event like-sign pair distribution. The assumption is that the like-sign pair distributions are purely combinatoric. For the three detector combinations TOF–TOF, TOF–PbSc and PbSc–PbSc, the ratio of the measured and combinatorial like-sign invariant mass distributions were found to be consistent with 1.0 as a function of the pair mass within statistical errors for all centrality bins. As an example, in Fig. 1 we plot the measured and combinatorial $++$ and $--$ invariant mass distributions and their ratios for the TOF–PbSc combination as a function of the invariant mass of $K^+K^+$ and $K^-K^-$ pairs for minimum-bias events. As can be seen from the figures, these ratios are equal to the expected value of 1.0 within the statistical fluctuations.

The systematic uncertainty associated with this normalization procedure was estimated to vary between 0.5–2% for the different centralities in the different detector combinations. When we added all data together to derive the $\phi$ spectrum, the range of the systematic uncertainty reduced to 0.7–1.0%.

Finally, the $\phi$ meson signal was obtained by subtracting the combinatorial background from the measured unlike-sign invariant mass spectrum. An example of the $K^+K^-$ invariant mass spectrum for the TOF–PbSc combination is shown in Fig. 4 where we plotted the measured and scaled mixed event invariant mass distributions for minimum-bias events. The lower panel of the figure shows the subtracted mass spectrum. The corrected yield of the $\phi$ mesons from the experimental data is then determined by integrating the subtracted invariant mass spectrum within a mass window of $\pm$ 5 MeV/$c^2$ about the measured $\phi$ mass centroid. This narrow mass window was used as it provided a better signal-to-background ratio compared with a wider window. Since we will show that there is no significant centrality dependence of the intrinsic width, then the extracted yields as a function of centrality are not being biased by the use of a constant integration window. The systematic effect of the mass integration window itself on the corrected yield was studied by varying the stated integration limit and found to contribute 2.6–3.2%, depending on centrality, to the total systematic uncertainty in the integrated yield.

**E. Acceptance, Decay and Multiple Scattering Corrections**

The $\phi$ meson yields were corrected for the geometrical acceptance of the detectors, in-flight kaon decay, multiple scattering effects, and nuclear interactions with materials in the detector using the PISA software package which is a GEANT-based Monte Carlo detector simulation of the PHENIX detector. The simulation was carried out by generating 34 million single $\phi$ mesons in a $\pm$0.6 rapidity interval with an exponential transverse momentum distribution

$$dN/dp_T = p_T \exp(-m_T/(t_{fo} + \beta^2 M_\phi))$$

with $t_{fo} = 157$ MeV and $\beta = 0.4$, i.e. an effective slope of $T = 320$ MeV in the range $0 < p_T < 10$ GeV/$c$. The generated $\phi$ mesons were then propagated through the simulation package. In this simulation, the BBC, DC, PC, TOF and PbSc detector responses were tuned to match the real data by including their dead areas and by matching their track associations and mass–squared resolutions. That is, the track association and mass–squared cut boundaries in the Monte Carlo analysis were parameterized to match the real data. The $K^+K^-$ pair acceptance efficiency as a function of transverse mass was calculated as
FIG. 4: $K^+K^+$ [(a) and (a')] and $K^-K^-$ [(b) and (b')] invariant mass spectra and ratio of real to mixed event spectra, respectively, for the TOF–PbSc combination.

$$\epsilon(m_T) = \frac{N^\text{reconstructed}(m_T)}{N^\text{generated}(m_T)} \tag{2}$$

The calculated acceptance efficiencies for the TOF–TOF, TOF–PbSc and PbSc–PbSc combinations are shown in Fig. 6 as a function of $m_T$. The points in the figure are located at the center of the bins. In the actual $m_T$ spectra, the proper bin centroids were used. The figure shows that the TOF detector (closed circles) has low acceptance for the low momentum kaon pairs due to their large opening angles. On the other hand, the TOF covers the largest $m_T$ range for the $\phi$ particles. As a result, the TOF efficiency function increases towards higher transverse mass. In contrast, the TOF–PbSc (open squares) and PbSc–PbSc (closed triangles) combinations offer better low pair momentum acceptance than the TOF. However, the high momentum kaon identification limit in the PbSc leads to the efficiency function decreasing at the highest transverse mass values. The systematic error associated with the acceptance correction factor originates from
i) tuning of detector alignments and mass–squared parameters in the Monte Carlo with reference to the real data (∼3%), and

ii) systematics in the fiducial geometries in the data and the Monte Carlo (∼12%).

F. Detector Occupancy Correction

The high multiplicity environment in the heavy ion collisions produces multiple hits in a detector cell such as in the slats of the TOF or in the towers of the PbSc. These occupancy effects reduce the track reconstruction efficiency in central collisions compared to that in peripheral collisions, and these occupancy dependent effects need to be accounted for in calculating the invariant yields. The multiplicity dependent efficiency ($\epsilon_{\text{occupancy}}$) factors were calculated by embedding simulated $K^+K^-$ pairs into real data events. This study was done for different centrality bins from 0 to 92% in steps of 10%. We calculated the multiplicity dependent efficiencies for TOF–TOF, TOF–PbSc and PbSc–PbSc pairs separately. The systematic uncertainty associated with the embedding procedure was estimated for the three centrality bins used in the yield determinations, namely 0 - 10%, 10 - 40% and 40 - 92%. The systematic errors, calculated by estimating the occupancy efficiency corrections for different track confirming criteria, were found to vary from 7% to 10% for the three centrality bins used here, independent of the pair momenta. Fig. 7 shows the $\epsilon_{\text{Occupancy}}$ factors as a function of collision centrality for the $K^+K^-$ pairs both identified in the TOF detector. The occupancy dependent efficiency factors were found to be independent of the transverse momenta of the pairs.
IV. RESULTS AND DISCUSSION

In this section, we present and discuss the results of our measurements, which consist of: 1) the $\phi$ line shape analysis, 2) the transverse mass spectra analysis, 3) the integrated yields and ratios analysis, 4) hydrodynamical fits to $\pi^\pm$, $K^\pm$, $p$, $\bar{p}$ and $\phi$ transverse momentum spectra, and 5) the centrality dependence of the yields and nuclear modification factor $R_{CP}$ as compared to that of pions and (anti)protons.

A. Line Shape Analysis

The invariant mass spectra of the $\phi$ mesons are obtained by subtracting the combinatorial backgrounds from the same event $K^+K^-$ mass spectra. The details of the combinatorial background analysis were described in section III D. For the best statistical precision, we combine data from TOF and PbSc detectors to analyze the $\phi$ mass centroids and widths at the five different centrality bins.

Fig. 8 shows the minimum-bias $\phi \rightarrow K^+K^-$ invariant mass spectrum for the PHENIX data. The subtracted $\phi$ mass spectrum (lower panel), containing approximately 5100 $\phi$ in the fit region, is fitted with a relativistic Breit-Wigner (RBW) mass distribution function \[F_{RBW}(M)\] convolved with a Gaussian experimental mass resolution function. Using Monte Carlo studies based on the experimentally measured single kaon momentum resolution, the experimental $\phi$ mass resolution is calculated to be 1.0 MeV/$c^2$. This pair mass resolution value is found to be almost constant across the kinematic region of acceptance.

The errors on the data points in Fig. 8 reflect the statistical errors only. The systematic errors associated with the mass centroid and width measurements originate from the magnetic field uncertainties in the kaon momentum determination and the combinatorial background normalization procedure. The minimum-bias line shape parameters (centroid and width) derived in our analysis are listed in Table II. The fitted minimum bias $\phi$ mass centroid and width are consistent at the one standard deviation (1$\sigma$) level with the PDG values\(^2\), taking into account both systematic and statistical errors.

We investigated the centrality dependence of the $\phi$ meson line shapes. For each centrality bin, we again fitted the $\phi$ mass spectrum with the RBW function convolved with a Gaussian experimental $\phi$ mass resolution. The results are presented in Fig. 8. The left panel of the figure shows the centrality dependence of the fitted centroids.

\[\text{TABLE II: } \phi \text{ meson mass centroid and width for the minimum-bias } Au + Au \text{ collisions at } \sqrt{s_{NN}} = 200 \text{ GeV. The corresponding PDG values are } M_\phi = 1.019456 \text{ GeV}/c^2, \Gamma_\phi = 4.26 \text{ MeV}/c^2.\]

| Parameter       | Value                                      |
|-----------------|--------------------------------------------|
| Centroid (GeV/$c^2$) | $1.01877 \pm 0.00014 \text{ (stat) } \pm 0.00085 \text{ (syst.)}$ |
| Width (MeV/$c^2$)     | $4.24 \pm 0.45 \text{ (stat) } \pm 0.55_{0.51} \text{ (syst.)}$ |

The upper and lower 1$\sigma$ systematic error limits are indicated. The dotted line shows the PDG mass centroid. The solid line indicates the result obtained with a one-parameter constant fit through the measured data points. These results lead to two immediate conclusions. First, to within less than 1 MeV/$c^2$ there is no observed centrality dependence of the $\phi$ meson mass centroid, and second, the fitted centroids at all centralities are consistent with the PDG value within the statistical and systematic uncertainties of our measurements.

The $\phi$ mass widths, as shown in the right panel of the figure, are studied as a function of the centrality. The

\(^2\) The PDG value for the $\phi$ mass centroid is 1019.456 $\pm$ 0.020 MeV/$c^2$, and for the $\phi$ width the value is 4.26 $\pm$ 0.05 MeV/$c^2$. \[2\]
error bar on each point shows the statistical error while the bands on the points indicate the systematic errors. The dotted line shows the PDG \(\phi\) mass width. The solid line shows the results of the constant fit assumption to the data points. Again, within the random and systematic error limits shown, there is no convincing evidence of a variation of the \(\phi\) width as a function of centrality.

The topic of medium effects on meson masses has been actively investigated in the recent literature. The predictions are that for both cold and hot nuclear matter there could be a decrease of the \(\phi\) mass value by a few MeV/c\(^2\) or even tens of MeV/c\(^2\). Even more dramatically the width could increase by several multiples above the PDG value of 4.26 MeV/c\(^2\). A sample of such predictions is given in Table III. However, one of the models considers the \(\phi \rightarrow K^+K^-\) channel largely insensitive to medium effects since the kaons are “unlikely to escape without reacting further, thus destroying any useful information possessed about the \(\phi\)”. In this sense the \(\phi \rightarrow K^+K^-\) is inherently biased in that only \(\phi\) decays which are unaffected by the medium changes, for example those produced peripherally, can be detected.

It is sometimes thought that since the vacuum \(c\tau\) of the \(\phi\) is \(\approx 45\) fm/c there will be only limited sensitivity to medium effects in any case. However, if the resonance width were to actually increase by several times, as indicated in Table III, then the \(c\tau\) would then approach or be even substantially less than 10 fm/c, which is a size compatible with the expected collision volume. The dramatic width changes predicted in either cold or hot nuclear matter might be visible, at least in the dilepton channel if not also the \(K^+K^-\) channel, as a function of centrality.

The present mass centroid and width data, which are integrated over the available \(m_T\) range, rule out any major changes with respect to the PDG values. Specifically, the one parameter fit result of 3.97 \(\pm\) 0.34 MeV/c\(^2\) obtained here excludes at the 99% confidence level a width value of 4.75 MeV/c\(^2\) or greater. Possibly at the lowest \(m_T\) values where the \(\phi\) would remain longer in the collision volume, or with the availability of more finely binned centralities, there could be visible evidence of in medium effects. However, the current data sample is insufficient to explore these possibilities.

It seems clear from the current set of the theoretical models that an observed change in the \(\phi\) width would not be itself indicative of a QGP formation. One would first have to constrain the cold nuclear medium effects on the \(\phi\) as could be obtained in \(d+Au\) collisions, or by comparing peripheral \(Au+Au\) collision data results with central collision data. It is also important to measure the \(\phi\) mass in the dilepton \(e^+e^-\) channel. That channel should be more sensitive to the \(\phi\) which are produced deeper or earlier in the collision volume.

### B. Spectral Shapes Analysis

At low \(m_T\), the spectral shapes carry information about the kinetic freeze-out conditions. Since the centrality dependence reveals the effect of the system size on the fireball evolution it becomes desirable to study the centrality dependence of the spectral shapes. Transverse mass spectra were obtained in three centrality bins corresponding to 0–10%, 10–40% and 40–92% of the total geometrical cross-section. We count the same event \(K^+K^-\) pairs within a defined mass window \((\pm 5\) MeV/c\(^2\) with respect to the \(\phi\) mass centroid) and estimate the number of combinatorial background pairs within that window. In each centrality bin, the data are divided into different \(m_T\) bins. The invariant mass spectrum for the same events and the background distributions are obtained for each of these \(m_T\) bins. Finally, the background is subtracted from the same event invariant mass spectrum within the aforementioned \(\pm 5\) MeV/c\(^2\) \(\phi\) mass window to determine the number of reconstructed \(\phi\) mesons within that \(m_T\) bin. The reconstruction of the \(\phi\) in the Monte Carlo simulation takes into account the effect of the \(\phi\) mass window size.

The \(\phi\) mesons are reconstructed using kaons identified in the TOF and the PbSc detectors. Three detector combinations: TOF–TOF, TOF–PbSc, and PbSc–PbSc are used to obtain three independent transverse mass spectra. Fig. shows the minimum-bias \(m_T\) spectra for the above three combinations. The combined result, which is the sum of the three combinations is also included. For better visibility of the data points, TOF–TOF, TOF–PbSc and PbSc–PbSc spectra are scaled by a factor of 0.5, 0.1 and 0.05, respectively. The \(m_T\) spectrum obtained from the PHENIX detector is fitted with the exponential function:

\[
\frac{1}{2\pi m_T \text{d}m_T \text{d}y} \frac{\text{d}^2N}{\text{d}m_T \text{d}y} = \frac{\text{d}N/\text{d}y}{2\pi T(T + M_\phi)} e^{-(m_T - m_\phi)/T}
\]

where \(\text{d}N/\text{d}y\) and the inverse slope \(T\) are returned as two fitting parameters. The lines drawn through the TOF–TOF, TOF–PbSc and PbSc–PbSc spectra represent the same fit, but scaled with the same scaling factors as the data points. Comparison of the individual spectra to the fit obtained from the combined spectrum demonstrates the consistency between the different measurements, which have different systematic uncertainties. The TOF–TOF, TOF–PbSc and PbSc–PbSc spectra are also independently fitted using Eq. (3). The resulting \(\text{d}N/\text{d}y\) and \(T\) are tabulated in Table IV. Both statistical and systematic errors are quoted. The systematic errors on \(\text{d}N/\text{d}y\) and \(T\) in the full dataset from all sources is shown in Appendix C. We also fitted the TOF–
FIG. 9: Centrality dependence of the φ mass centroid (left) and φ intrinsic width (right), where the $N_{\text{part}}$ to Centrality correspondence is given in Table III. For the mass centroid plot, the 1σ systematic error limits on the data points are shown by the two continuous bands. The dotted line shows the PDG centroid value (1.019456 GeV/c$^2$). The solid line indicates the centroid value obtained from a one parameter fit assumption. For the width plot the systematic errors on the RBW widths are indicated as bands on each data point. Similarly the dotted line shows the PDG width value (4.26 MeV/c$^2$), and the solid line shows a one parameter fit result for the measured data points.

TOF and TOF–PbSc data over the smaller $m_T$ range of the PbSc–PbSc data and obtained consistent sets of $dN/dy$ and $T$ values from that check.

Fig. 10 and Table IV indicate that the three different analyses with different systematic uncertainties give consistent results. This allowed us to combine the results and make use of the maximum available statistics in each $m_T$ bin. This combined spectrum was used to obtain the physics results discussed in the next sections.

Fig. 11 shows $m_T$ spectra of the φ mesons in 0–10%, 10–40%, 40–92% and minimum bias centrality classes. The data points representing the invariant yield as a function of transverse momentum are given in Appendix B. Each spectrum is fitted with an $m_T$-exponential function Eq. (3). The φ yield per unit of rapidity ($dN/dy$) and inverse-slope ($T$) obtained from the fits are shown in Table V and summarized in Fig. 12 and Fig. 13.

C. Yields and ratios

Hadron yields and ratios carry information about the chemical properties of the system. The yields of strange

---

3 The STAR experiment at RHIC has recently reported its analysis of the $\phi \rightarrow K^+ K^-$ data for Au+Au at $\sqrt{s_{NN}} = 200$ GeV\[66\]. The analyses for PHENIX and STAR have one common centrality bin, 0–10%, for which the extracted $dN/dy$ are not in agreement. The STAR value is $6.65 \pm 0.35 (\text{stat}) \pm 0.73 (\text{sys})$, compared with the PHENIX value $3.94 \pm 0.60 (\text{stat}) \pm 0.62 (\text{sys})$. The discrepancy persists even if one eliminates the four lowest $m_T$ data points from the STAR data set in order to fit over the same $m_T$ range for both the STAR and the PHENIX data. There is not a discrepancy between the quoted inverse slope parameters.
TABLE III: Theoretical Predictions for Changes in the $\phi$ Resonance

| Authors                  | Models                  | Environment   | Predictions                                      |
|--------------------------|-------------------------|---------------|--------------------------------------------------|
| Caberara and Vacas [23]  | Chiral SU(3)            | Cold hadronic | $M_\phi \to 1.011$ GeV $\Gamma_\phi \to 30$ MeV/c$^2$ |
| Pal, Ko, and Lin [13]    | AMPT                    | Hot hadronic  | $M_\phi \to 0.95$ GeV/c$^2$ at twice normal nuclear density ($\rho_0$) $\Gamma_\phi \to 45$ MeV/c$^2$ at $2\rho_0$ Suppression of $\phi \to K^+K^-$ relative to $\phi \to e^+e^-$ |
| Oset and Ramos [21]      | Kaon mass renormalization | Cold hadronic | $M_\phi$ unchanged $\Gamma_\phi \to 45$ MeV/c$^2$ |
| Smith and Haglin [20]    | One boson exchange      | Hot hadronic  | $M_\phi$ unchanged $\Gamma_\phi \to 22$ MeV/c$^2$ |
| Blaizot and Galain [12]  | Nambu-Jona-Lasino       | Hot hadronic  | $M_\phi \to 2M_K$ at $T \approx T_{critical}$ $\Gamma_\phi$ reduced by a factor of 6 $\phi \to K^+K^-$ disappears |
| Bi and Rafelski [14]     | Bag Model               | Hot hadronic  | $M_\phi \to 1.029$ GeV/c$^2$ at $T \approx T_{critical}$ $\Gamma_\phi \to 10$ MeV/c$^2$ |

TABLE IV: Minimum-bias $dN/dy$ and $T$ for different subsystem combinations. The statistical and systematic errors are shown after the first and second ± signs, respectively.

| Subsystem combination | TOF-TOF | TOF-PbSc | PbSc-PbSc | Full Data Set |
|-----------------------|---------|----------|-----------|---------------|
| $dN/dy$               | 1.16 ± 0.17 ± 0.19 | 1.37 ± 0.15 ± 0.22 | 1.47 ± 0.26 ± 0.27 | 1.34 ± 0.09 ± 0.21 |
| $T$(MeV)              | 380 ± 18 ± 22 | 385 ± 34 ± 28 | 311 ± 47 ± 65 | 366 ± 11 ± 18 |

FIG. 10: Minimum-bias $m_T$ spectra of the measured $\phi$ mesons for three different PHENIX subsystem combinations, with scale factors as indicated. The combined spectrum is fitted with an exponential function in $m_T$, Eq. (3). The lines drawn through the individual spectra (TOF-TOF, TOF-PbSc and PbSc-PbSc) represent the same fit parameters as in the minimum-bias case. Statistical error bars are shown.

FIG. 11: $m_T$ spectra of $\phi$ mesons for 0–10%, 10–40%, 40–92% and minimum-bias (0–92%) centrality classes, with scale factors as indicated. Each spectrum is fitted with an exponential function in $m_T$, Eq. (3), with the fit parameters listed in Table V. Statistical error bars are shown.

particles have been of particular interest as they help in understanding the strangeness enhancement in heavy ion collisions and the equilibration of strangeness. It is important to study these phenomena as a function of system size. Centrality selected data can be particularly useful in this respect. Here we present the yield of the $\phi$ mesons at mid-rapidity as a function of centrality and compare this yield to the yields of other hadrons and the results
TABLE V: $dN/dy$ and $T$ for different centrality bins.

| Centrality (%) | $dN/dy$ (stat) ± (syst) | $T$ (MeV) (stat) ± (syst) |
|----------------|-------------------------|--------------------------|
| 0 – 10%        | 3.94 ± 0.60 (stat) ± 0.62 (syst) | 376 ± 24 (stat) ± 20 (syst) |
| 10 – 40%       | 2.22 ± 0.18 (stat) ± 0.35 (syst) | 360 ± 13 (stat) ± 23 (syst) |
| 40 – 92%       | 0.32 ± 0.03 (stat) ± 0.05 (syst) | 359 ± 15 (stat) ± 16 (syst) |
| Minimum Bias   | 1.34 ± 0.09 (stat) ± 0.21 (syst) | 366 ± 11 (stat) ± 18 (syst) |

from lower energy heavy ion collisions. The $dN/dy$ of $\phi$ (shown in Fig. 12) is found to increase steadily with the number of participants ($N_{\text{part}}$) (left) whereas the $dN/dy$ per participant pairs increases slightly from peripheral to mid-central events and saturates after that (right). The error bars indicate the statistical errors. The shaded boxes on each data point are the systematic errors.

![FIG. 12: Centrality dependence of $\phi$ yield at mid-rapidity. The value of $dN/dy$ increases steadily with the number of participants ($N_{\text{part}}$) (left) whereas the $dN/dy$ per participant pairs increases slightly from peripheral to mid-central events and saturates after that (right). The error bars indicate the statistical errors. The shaded boxes on each data point are the systematic errors.](image)

We now consider the ratio of strange to non-strange particles in order to understand the extent and mechanism of the strangeness enhancement in heavy ion collisions. The ratios $K^+/\pi^+$ and $K^-/\pi^-$, are shown in Fig. 14(a)–(b). Both ratios show an increase of $\approx 60\%$ from peripheral to central collisions. Most of this increase is for $N_{\text{part}} < 100$. Only a mild increase or saturation is observed from mid-central to the top centrality bin.

![FIG. 13: Centrality dependence of the inverse slope, $T$.](image)
colliding energies. The figure indicates two aspects of $\phi$ meson production at various energies. First, as we go from AGS to SPS to RHIC, the $\phi$ meson yield per participant increases by an order of magnitude overall. Secondly, at the AGS energy, we find a steady increase of $\phi$ production per participant pair from peripheral to central collisions. It is worth mentioning that the NA50 experiment \cite{25} at CERN SPS reported an increase in fiducial $\phi$ yield (in $\mu^+\mu^-$ decay channel) per participant from peripheral to central collisions although the yield per participant showed saturation within error for the top centrality bins. The yield of $\phi$ mesons at RHIC, on the contrary, is found to be almost independent of centrality.

To investigate further the mechanism of $\phi$ enhancement with increase in collision energy, we study the two ratios $\phi/\pi$ and $\phi/K^-$ as a function of collision energy as illustrated in Fig. 16. The $\phi/\pi$ ratio is found to increase with the collision energy from AGS to RHIC. The $\phi/K^-$ ratio, on the other hand, remains almost constant within error bar with increasing collision energy.

\section*{D. Hydrodynamical Model Fits to the Spectral Shape Data}

From the $\phi$ spectral data shown in the preceding sections, we can conclude that the transverse mass distributions are well described by an exponential distribution and are quite similar for all the centralities. There is little, if any, centrality dependence of the inverse slope parameter in the measured centrality bins, as shown in Fig. 13. The exponential behavior is expected for particle production from a thermal source.

If the system develops collective motion, particles experience a velocity boost resulting in an additional transverse kinetic energy component. This motivates the use of the transverse kinetic energy, \textit{i.e.} transverse mass minus the particle rest mass, for studying flow effects. Traditionally, the CERN experiments \cite{57,58} have used simple exponential fits to the transverse kinetic energy dis-
tributions and often quote just one number, the inverse slope $T$, to characterize the spectra. These fits are usually done in the the range ($m_T - m_0 < 1$ GeV/c$^2$) in order to minimize the contribution from hard processes.

The results of such fits, obtained from previously published PHENIX $\pi^\pm, K^\pm, p$ and $\bar{p}$ data, are shown in Fig. 17. The slope parameters show a clear mass dependence, as expected from radial flow. The mass dependence increases from peripheral to central collisions indicating stronger collectivity in the more central events. The $\phi$ meson has mass similar to that of the proton. Hence we expect that if the $\phi$ participates in the collective flow then its inverse slope will be affected by this motion. For protons, the slope parameter changes significantly from peripheral to central collisions. As just noted, the $\phi$ inverse slopes shows no such centrality dependence. An important difference between the results obtained for $p, \bar{p}$ and $\phi$ is that the former have been fitted within a limited low-$m_T$ range ($m_T - m_0 < 1$ GeV/c$^2$) as motivated above. In the case of the $\phi$ the full measured range has been used for the fit due to having limited data at low-$m_T$. As shown in Fig. 17 the three data points below 1 GeV/c$^2$ are consistent with the fit over the entire $m_T$ range.

![FIG. 17: Mass and centrality dependence of inverse slope parameters $T$ in $m_T$ spectra for positive (left) and negative (right) particles in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The fit ranges are 0.2 – 1.0 GeV/c$^2$ for pions, protons, and anti-protons in $m_T - m_0$. Figure taken from reference 54.](image)

The detailed study of the higher statistics (anti)proton spectra indicated that (anti)proton spectra cannot be described by a single exponential in $m_T - m_0$, if the full measured range is considered. Although easy to visualize, the one-parameter inverse slope analysis proves to be too simplistic as a way to infer the kinetic properties of the system. In particular, the degree to which the $\phi$ mesons participate in the collective expansion will be shown (see Fig. 22) to be obscured in this simple approach.

A more sophisticated approach to this problem is to compare the particle spectra to a functional form which describes a boosted thermal source, based on relativistic hydrodynamics. This is a two-parameter model, termed the “blast-wave” model, in which the surface radial flow velocity ($\beta_T$) and the freeze-out temperature ($T_{fo}$) are extracted from the invariant cross section data according to the equation

$$\frac{dN}{m_T \, dm_T} \propto \int_0^R f(r) \, r \, dr \, m_T \, I_0 \left( \frac{m_T \, \sinh \rho}{T_{fo}} \right) K_1 \left( \frac{m_T \, \cosh \rho}{T_{fo}} \right),$$

where $I_0$ and $K_1$ represent modified Bessel functions with $\rho$ being the transverse boost which depends on the radial position according to

$$\rho = \tanh^{-1}(\beta_T) \cdot r/R.$$

Here the parameter $R$ is the maximum radius of the expanding source at freeze-out. The function $f(r)$ represents the density which is taken to be uniform in this calculation.

To study the parameter correlations, we make a grid of $(T_{fo}, \beta_T)$ pairs and then for each pair we perform a chi-squared minimization for each particle type. We use a linear velocity profile and constant particle density distribution. The first fit attempt is performed simultaneously for the six particle species $\pi^\pm, K^\pm$, and the $p, \bar{p}$ in the range ($m_T - m_0 < 1.0$ GeV/c$^2$).

The experimental data for $p$ and $\bar{p}$ have been corrected for $\Lambda$ and $\bar{\Lambda}$ decays. However, the invariant yields of $\pi^\pm$ and $K^\pm$ include feed-down from the decay of resonances and weak decays. To take this into account we add the decay of mesonic ($\rho, \eta, \omega, K^*...$) and baryonic ($\Delta, \Lambda, \Sigma...$) resonances as follows:

1) Generate resonances with the transverse momentum distribution determined by each combination of $T_{fo}$ and $\beta_T$.  
2) Simulate the decays using a Monte Carlo approach and obtain $\pi^\pm$ and $K^\pm$ distributions.  
3) Merge all particles, where the particle abundance is calculated with chemical parameters $T_{ch} = 177$ MeV, $\mu_B = 29$ MeV.

The two-parameter $T_{fo}$ vs $\beta_T$ fit results obtained in this analysis for the most central bin are shown in Fig. 18. Shown in the lower panel of the figure are the $\chi^2$ contour levels obtained from fitting each particle spectrum separately. We observe that the parameters $T_{fo}$ and $\beta_T$ are anti-correlated, the different particles have different preferred parameter space and different sensitivity to the parameters. For example, the contours for the heavier particles are more sensitive to the flow velocity than to the kinetic freeze-out temperature. The minimum valleys in the contours for the six particle species do overlap at a single common point at the $2\sigma$ level. To find the values of the parameters at this overlap point, a simultaneous fit for the six single particle spectra $(\pi^\pm, K^\pm, \text{and } p, \bar{p})$ was done which converges to a best fit value of
$T_{f_0} = 108.9^{+2.6}_{-2.4}$ MeV and $\beta_T = 0.771^{+0.003}_{-0.004}$. Using these parameters, we obtain the transverse momentum shapes shown in Fig. 19 where we also include the prediction for the $\phi$ spectrum shape which was not part of the original fit. The shape of the $\phi$ spectrum is reproduced well.

For the two other centrality bins in this study, 10–40% and 40–92%, we show the best fit hydrodynamical results in Fig. 20 and Fig. 21 respectively. Again we see that the $\phi$ transverse momentum shapes are reproduced by the same flow parameters which fit the identified hadron data at the same centrality bins.

For a second hydrodynamical fit attempt, we include the $\phi$ transverse momentum 0–10% centrality data along with the previously identified hadron data as part of the $\chi^2$ minimization search. The flow parameters derived with the $\phi$ data included are numerically consistent with the flow parameters derived previously without the $\phi$ data being included.

The two-dimensional grid search best fit values for the blast–wave parameterization as a function of centrality are tabulated in Table VI. The radial average expansion velocity $<\beta_T>$ is also given in this table. For the range of centralities studied here, the expansion velocity parameter is seen to decrease moderately for more peripheral collisions while the kinetic freeze-out temperature increases more significantly, approximately 40%. If one takes these parameters literally, then the more peripheral collisions are subject to decreased radial flow while correspondingly the particles are decoupling kinetically from each other at temperatures close to the chemical freeze-out temperature. This is a physically reasonable scenario given fewer participants in the initial expansion phase.

It should be pointed out that our present $\phi$ transverse momentum range does not extend below 0.8 GeV/c. The spectral shapes at low-$m_T$, especially for the heavier particles, are mostly sensitive to the expansion velocity. In the range of our $\phi$ measurement, it is more appropriate to consider the asymptotic behavior of the spectral shapes, which for $m_T >> m_o$ is given by [59]:

$$T_{\phi} = T_{f_0} \sqrt{(1 + \beta_T)/(1 - \beta_T)}$$

(6)

Here, $T_{\phi}$ is the slope parameter obtained using $m_T$ exponential fit, as in Eq. (3). It is interesting to note that the measured asymptotic slopes do not seem to depend on centrality, although both $T_{f_0}$ and $\beta_T$ show a clear centrality dependence. This is either due to a cancellation effect in Eq. (6), since the parameters are anti-correlated, or indicates that the hydrodynamics description is no longer valid at these large transverse momenta. We conclude that although the $\phi$ data themselves cannot constrain the kinematic freeze-out conditions, they are consistent with the hydrodynamical results obtained from the simultaneous fit to the $\pi^\pm, K^\pm, p$ and $\bar{p}$ spectra.

### Table VI: Blast wave model parameters [59] as a function of centrality from fitting $\pi^\pm, K^\pm, p$ and $\bar{p}$ spectra.

| Centrality | $T_{f_0}$ [MeV] | $\beta_T$ | $<\beta_T>$ | $\chi^2/NDF$ |
|------------|-----------------|----------|-------------|--------------|
| 0–10%      | 108.9^{+2.6}_{-2.4} | 0.771^{+0.003}_{-0.004} | 0.572^{+0.004}_{-0.003} | 148.0/46 |
| 10–40%     | 119.0^{+1.5}_{-1.5}  | 0.748^{+0.003}_{-0.003} | 0.550^{+0.004}_{-0.002} | 212.1/46 |
| 40–92%     | 150^{+2}_{-2}     | 0.630^{+0.005}_{-0.005} | 0.447^{+0.004}_{-0.004} | 150.9/46 |

### E. Nuclear modification factor $R_{CP}$ for $\phi$ mesons

One of the most important result demonstrated so far in the study of relativistic heavy ions at RHIC is the
obvious suppression of high \( p_T \) pions in central collisions as compared to either \( pp \) collisions or peripheral \( Au + Au \) collisions. A second, quite surprising observation is the unusually large (anti)proton-to-pion ratio at high \( p_T \). In particular PHENIX has observed that in central \( Au + Au \) collisions the \( p/\pi \) and \( \bar{p}/\pi \) ratios are enhanced by a factor of 3 at intermediate \( p_T \) (1.5 < \( p_T \) < 4.5 GeV/c) as compared to the ratios in \( pp \) collisions and the ratios obtained in quark and gluon jets measured in \( e^+e^- \) collisions. It was also observed that proton and anti-proton production scales with \( N_{coll} \) in this \( p_T \) region, in sharp contrast to the strong suppression of pion production. In \( pp \) collisions high \( p_T \) particles are the result of the fragmentation of partons. Because of the power law nature of the hard scattering spectrum, most of the particles at high \( p_T \) are expected to be leading hadrons. The fragmentation functions, at least in the vacuum, are expected to be universal and independent of the colliding system under consideration. However, at intermediate \( p_T \) (1.5–4.5 GeV/c) the PHENIX results from central \( Au + Au \) collisions are inconsistent with the known fragmentation functions.

There are several conjectures which may explain the unexpected PHENIX result:

1) hydrodynamic flow generated from the hadronic stage, or
2) hydrodynamic flow generated at a partonic stage together with particle production from the recombination,
3) baryon junctions as a mechanism for an unusually large build-up of baryons and anti-baryons at mid-rapidity,
4) in-medium modified fragmentation functions.

The first three possibilities invoke soft processes to populate a region of \( p_T \) that is dominated by hard-scattering in \( pp \) collisions. The soft production at intermediate \( p_T \) is enhanced for protons and anti-protons, while pions remain dominated by hard-scattering. In
conjecture (4), the production for both pions and $p, \bar{p}$ is by hard-scattering, but the fragmentation functions are modified in the medium, thus resulting in an enhanced $p/\pi$ and $\bar{p}/\pi$ ratios.

The second of these conjectures is particularly important since this hypothesis presupposes a partonic state with collective behavior. A critical factor which may differentiate among these scenarios is whether the large abundance of protons is due to its mass, or to the number of constituent valence quarks $[32, 33, 34, 35]$. Hydrodynamic flow generated at the hadronic stage imparts a single velocity to the moving matter, hence similar mass particles should exhibit the same momentum increase from this effect. In contrast, hypotheses 2 and 3 are dependent on whether the particles are baryons or mesons. The $\phi$ meson which has a mass similar to that of a proton yet, like the pion, has two valence quarks, should distinguish between (1) and (2) or (3). We examine the scaling properties of the intermediate $p_T$ yields of the $\phi$ and compare those to the yields of $(p + \bar{p})/2$. Fig. 22 shows the transverse momentum spectra measured in three different centralities, each scaled down by the number of binary nucleon-nucleon collisions. The (anti)proton spectra show two pronounced features. Below $p_T < 1.5$ GeV/c, the spectral shapes are strongly influenced by the radial flow and thus the more central data have harder slope. Above $p_T = 1.5$ GeV/c, the effect of radial flow is negligible. The spectra converge to the same line. Moreover, they scale with $N_{coll}$ for all centrality classes, as expected for hard-scattering unaffected by the nuclear medium. The $\phi$ spectra have a quite different behavior. There is no visible curvature at lower $p_T$ since this curvature is not expected to be prominent in the measured region. At higher $p_T$ the $\phi$ spectra run parallel to the (anti)proton spectra, but do not obey $N_{coll}$ scaling. To examine this feature on a linear scale, we plot the ratio between the central and peripheral data, i.e. the ratio $R_{CP}$ (Fig. 23). The systematic error arising from the determination of $N_{coll}$ is represented by the dotted bar and is about 19%. This systematic error is common for all three particle species shown in the figure. The solid bar around $R_{CP} = 1$ represents the $N_{coll}$ error.
for the protons (the same 19%). Since these errors are correlated, if the curves in the figure were to change due to a change in the value of $N_{\text{coll}}$, they will move together within the extent of the error bars shown. We would like to emphasize the comparison between the $R_{CP}$ values for the protons and the φ. In this comparison, the systematic errors to consider are those that can move the φ points with respect to the proton points. When determining a ratio of spectra measured at different centralities, most systematic errors cancel. After removing the $N_{\text{coll}}$ error, the sources of error that remain for the φ come from the multiplicity dependent corrections and the effect of the mass window as described above. For the protons and pions, the error that remains is independent from the error determined for the φ, comes from the multiplicity dependent corrections. The relative error between the φ and the proton measurements is evaluated at 7% and is represented by the extended solid bar just below $R_{CP} = 1$. Clearly the φ’s behavior is more like that of the pions and not like that of the protons. Thus we conclude that the φ meson exhibits a suppression effect at intermediate $p_T$ similar to that of the pions. Although we cannot conclude whether φ production at this intermediate $p_T$ is dominated by soft or hard processes, this observation provides support for models which depend on the number of valence quarks in the particle as opposed to models which depend upon just the mass of the particle in order to explain the anomalous proton yields.

V. CONCLUSIONS

A systematic measurement has been made of φ production at mid-rapidity in Au+Au collisions with $\sqrt{s_{NN}} = 200$ GeV at RHIC. The general features of the data include the yield which rises from $0.318\pm0.028$ (stat)$\pm0.051$ (syst) in peripheral collisions to $3.94\pm0.60$ (stat)$\pm0.62$ (syst) in central collisions. There is seen to be little centrality dependence to the inverse slope which is about 360 MeV. The centroid mass and res-
onance width are extracted with high enough precision to rule out any large (MeV/c^2 scale) deviations from the accepted PDG values. At p_T below 1.5 GeV/c, a blast wave analysis of the most central pion, kaon and proton spectra with a freeze-out temperature T_fo of 109 MeV, and a transverse velocity β_T of 0.77 describes the most central φ data as well. A similar conclusion, with monotonically changing results for T_fo and β_T, holds for the less central events. At higher transverse momenta, all particles lie above the blast wave fits, which suggests that the dominant particle production mechanism is no longer soft physics but is giving way to the expected jet fragmentation. A study of the ratio R_CP of the φ provides a critical new piece of information in understanding the anomalous proton-to-pion ratio seen in central heavy ion collisions at RHIC, since the φ is a meson with a mass similar to that of a proton. The R_CP value for the φ above a transverse momentum of 1.5 GeV/c is about 0.6, similar to that of the pions but inconsistent with the proton value of 1. This indicates that the φ meson is being suppressed in this p_T range for the more central collisions. The lower p_T blast wave fits imply hydrodynamic behavior at the hadronic stage, while the inconsistency with simple hydrodynamics at higher p_T, is something one would expect in the jet fragmentation region. This transition is an important factor to consider as one begins to understand the mechanism of particle production in central collisions at RHIC.
FIG. 23: $N_{\text{coll}}$ scaled central to peripheral ratio $R_{CP}$ for $(p + \pi)/2$, $\pi^0$, and $\phi$. The proton and pion results are published [30]. The vertical dotted bar on the right represents the error on $N_{\text{coll}}^{0-10\%}/N_{\text{coll}}^{40-92\%}$. The shaded solid bar around $R_{CP} = 1$ represents 12% systematic error which can move the proton and/or $\phi$ points with respect to one another. The dotted horizontal line at $R_{CP} = 0.62$ is a straight line fit to the $\phi$ data.
Acknowledgments

We thank the staff of the Collider-Accelerator and Physics Departments at Brookhaven National Laboratory and the staff of the other PHENIX participating institutions for their vital contributions. We acknowledge support from the Department of Energy, Office of Science, Nuclear Physics Division, the National Science Foundation, Abilene Christian University Research Council, Research Foundation of SUNY, and Dean of the College of Arts and Sciences, Vanderbilt University (U.S.A), Ministry of Education, Culture, Sports, Science, and Technology and the Japan Society for the Promotion of Science (Japan), Conselho Nacional de Desenvolvimento Científico e Tecnológico and Fundação de Amparo à Pesquisa do Estado de São Paulo (Brazil), Natu

ral Science Foundation of China (People’s Republic of China), Centre National de la Recherche Scientifique, Commissariat à l’Énergie Atomique, Institut National de Physique Nucléaire et de Physique des Particules, and Institut National de Physique Nucléaire et de Physique des Particules, (France), Bundesministerium für Bildung und Forschung, Deutscher Akademischer Austausch Dienst, and Alexander von Humboldt Stiftung (Germany), Hungarian National Science Fund, OTKA (Hungary), Department of Atomic Energy and Department of Science and Technology (India), Israel Science Foundation (Israel), Korea Research Foundation and Center for High Energy Physics (Korea), Russian Ministry of Industry, Science and Tekhnologies, Russian Academy of Science, Russian Ministry of Atomic Energy (Russia), VR and the Wallenberg Foundation (Sweden), the U.S. Civilian Research and Development Foundation for the Independent States of the Former Soviet Union, the US-Hungarian NSF-OTKA-MTA, the US-Israel Binational Science Foundation, and the 5th European Union TMR Marie-Curie Programme.

APPENDIX A: COMBINATORIAL BACKGROUND

Assume there are N tracks per event of which n are positive and N-n are negative, the probability of the partition being \( P(n) \) such that \( \sum_{n=0}^{N} P(n) = 1 \).

All expressions below refer to the average number of pairs per event

1. General relation between the number of like and unlike pairs

The total number of pairs is:

\[
N_{\text{pairs}} = \frac{N(N-1)}{2} \quad (A1)
\]

The number of + - pairs is:

\[
n_{+-} = \sum_{n=0}^{N} n(N-n)P(n) = N\langle n \rangle - \langle n^2 \rangle \quad (A2)
\]

The number of + + pairs is:

\[
n_{++} = \sum_{n=0}^{N} \frac{n(n-1)}{2}P(n) = \frac{\langle n^2 \rangle - \langle n \rangle}{2} \quad (A3)
\]

The number of - - pairs is:

\[
n_{--} = \sum_{n=0}^{N} \frac{(N-n)(N-n-1)}{2}P(n) = \frac{N(N-1)}{2} - (N-\frac{1}{2})\langle n \rangle + \langle n^2 \rangle \quad (A4)
\]

We therefore get:

\[
n_{++} + n_{--} = N\langle N-1 \rangle \quad (A6)
\]

The last expression is trivial: the number of like-sign pairs is equal to the total number pairs minus the number of of unlike-sign pairs.

The ratio R of unlike to like pairs is therefore:

\[
R = \frac{n_{+-}}{n_{++} + n_{--}} = \frac{N\langle n \rangle - \langle n^2 \rangle}{N(N-1)/2 - (N\langle n \rangle - \langle n^2 \rangle)} \quad (A7)
\]

This is a general result, free of any assumption and should always be fulfilled, in pure combinatorial background as well as in a mixture of signal + combinatorial background.

2. Combinatorial background

Consider a pure combinatorial background sample. By its essence there are no correlations between tracks in such a sample i.e. within an event the probability \( p \) to have a positive (or a negative) track is constant and independent of the number of tracks. Therefore the probability \( P(n) \) of having \( n \) positive tracks out of the total of \( N \) tracks is given by a binomial distribution:

\[
P(n) = \frac{N!}{n!(N-n)!} p^n (1-p)^{N-n} \quad (A8)
\]

\[
\langle n \rangle = np \quad (A9)
\]

\[
\langle n^2 \rangle = \sigma^2 + \langle n \rangle^2 = Np(1-p) + p^2 N^2 \quad (A10)
\]
Replacing these values in expression (6) gives:
\[ R = \frac{(p - p^2)}{(1/2 - p + p^2)} \]  
(A11)

If there is charge symmetry, i.e. \( p = 0.5 \) one gets \( R = 1 \) and consequently the combinatorial background is given by:

\[ n_{++}^{CB} = n_{++} + n_{--} \]  
(A12)

This is an exact relation. It holds with quite good accuracy even if there is some charge asymmetry. For example for an asymmetry of 10% (i.e. \( p = 0.525 \)) \( R = 0.995 \).

3. The formula \( N_{++}^{CB} = 2\sqrt{N_{++}N_{--}} \)

The combinatorial background is rigorously given by this formula provided that the number \( N \) of tracks per event has a Poisson distribution:

\[ \mathcal{P}(N) = \frac{(N)^Ne^{-N}}{N!} \]  
(A13)

Again we assume that the \( N \) tracks are divided into \( n \) positive and \( (N-n) \) negative tracks, the partition is given by the binomial distribution (A7) and all expressions below refer to average number of pairs per event.

Number of \( ++ \) pairs:

\[ N_{++} = \sum_{N=2}^{\infty} \mathcal{P}(N) \sum_{n=0}^{N} P(n) \frac{n(n-1)}{2} \]  
(A14)

Using relations (A7) and (A11) and some algebra leads to:

\[ N_{++} = \frac{1}{2}p^2(N)^2 \]  
(A15)

Similarly the number of \( -- \) pairs is given by:

\[ N_{--} = \sum_{N=2}^{\infty} \mathcal{P}(N) \sum_{n=0}^{N} P(n) \frac{(N-n)(N-n-1)}{2} \]  
(A16)

\[ = \frac{1}{2}(1-p)^2(N)^2 \]  
(A17)

The number of combinatorial background \( ++ \) - pairs is:

\[ N_{++}^{CB} = \sum_{N=2}^{\infty} \mathcal{P}(N) \sum_{n=0}^{N} P(n)n(N-n) \]  
(A18)

\[ = p(1-p)(N^2) \]  
(A19)

Inspecting (A15), (A16) and (A17) shows that:

\[ N_{++}^{CB} = 2\sqrt{N_{++}N_{--}} \]  
(A20)

APPENDIX B: DATA TABLES OF CENTRALITY SELECTED \( \phi \) SPECTRA

The invariant yields, \( \frac{1}{2\pi m_T} \cdot \frac{d^2N}{dm_T dy} \), of the \( \phi \) mesons in different centrality bins are shown in Table VII.

APPENDIX C: SYSTEMATIC ERRORS ON \( dN/dy \) AND \( T \)

The sources of the systematic errors on yield \((dN/dy\) and \(T\) measurements are as follows:

a) Systematic error on the combinatorial background normalization, \( \delta_{norm} \): This originates from the systematics of the event mixing. Since both same event and mixed event like sign distributions represent pure combinatorials, we estimated unlike sign combinatorial background by normalizing the mixed event unlike sign distributions to \( 2\sqrt{N_{++}^{same \ event} \cdot N_{--}^{same \ event}} \) and \( 2\sqrt{N_{++}^{mixed \ event} \cdot N_{--}^{mixed \ event}} \) and the difference in the extracted \( \phi \) signal from the real data between these two normalizations are attributed as the systematic uncertainty.

We use the same normalization factor for all \( m_T \) bins. So, the above systematics are applicable to the measured \( dN/dy \) only, not on the inverse slope, \( T \).

b) Systematics of \( \phi \) mass window, \( \delta_{mass} \): We count the number of reconstructed \( \phi \) mesons by integrating the \( \phi \) meson invariant mass spectra within \( \pm \) 5 MeV mass window with respect to the measured centroids in both data and Monte Carlo. The systematic associated with this mass window is estimated by measuring the extent of the changes in \( dN/dy \) and \( T \) after constructing \( \phi \) meson \( m_T \) spectra within five different mass windows \( \pm 3, \pm 5, \pm 8, \pm 10 \) and \( \pm 15 \) MeV, with respect to the measured \( \phi \) centroids.

c) Uncertainties in extrapolation of \( \phi \) meson \( m_T \) spectra to \( m_T = m_\phi \cdot \delta_{extrap} \): This is studied by

(i) fitting the \( m_T \) distributions using exponential and Boltzmann functions. Two different fitting functions, exponential and Boltzmann, and

(ii) fitting the transverse mass spectra within different \( m_T \) ranges. These are applied to both \( dN/dy \) and \( T \).

d) Acceptance correction systematics, \( \delta_{MC} \): The systematics associated with acceptance correction factors derived from Monte Carlo analysis are investigated by considering two sources:

(i) Tuning of detector alignments in Monte Carlo with reference to the real data (~3%), and

(ii) Systematics in the fiducial geometries in data and Monte Carlo (~12%).

The systematic error from this source is independent of the momenta of reconstructed \( \phi \) mesons. So, this is attributed to \( dN/dy \) only.
TABLE VII: $m_T$ spectra of $\phi$ mesons in different centrality bins. The systematic errors on invariant yields are from combinatorial background normalization, $\phi$ counting mass window, acceptance correction efficiencies from Monte Carlo and occupancy dependent corrections.

| Centrality (%) | $m_T$ (GeV/$c^2$) | $m_T$ bin size (GeV/$c^2$) | $\frac{1}{2\pi m_T^2} \frac{d^2N}{dm_T dy}$ | Stat. error | Syst. error |
|----------------|------------------|-----------------------------|-------------------------------------------|-------------|-------------|
| 0 - 10         | 1.365            | 0.4                         | 0.51111                                   | 0.15120     | 0.077847    |
|                | 1.691            | 0.2                         | 0.19114                                   | 0.04656     | 0.029121    |
|                | 1.891            | 0.2                         | 0.12065                                   | 0.02702     | 0.018382    |
|                | 2.091            | 0.2                         | 0.07313                                   | 0.01758     | 0.011142    |
|                | 2.291            | 0.2                         | 0.03335                                   | 0.01372     | 0.005081    |
|                | 2.565            | 0.4                         | 0.01683                                   | 0.00541     | 0.002564    |
|                | 2.891            | 0.2                         | 0.01353                                   | 0.00406     | 0.002061    |
|                | 3.300            | 1.0                         | 0.00268                                   | 0.00074     | 0.000408    |
| 10 - 40        | 1.364            | 0.4                         | 0.37232                                   | 0.04145     | 0.05667     |
|                | 1.691            | 0.2                         | 0.09224                                   | 0.01255     | 0.01404     |
|                | 1.891            | 0.2                         | 0.04872                                   | 0.00719     | 0.00742     |
|                | 2.091            | 0.2                         | 0.03867                                   | 0.00483     | 0.00589     |
|                | 2.291            | 0.2                         | 0.02320                                   | 0.00389     | 0.00353     |
|                | 2.564            | 0.4                         | 0.01246                                   | 0.00160     | 0.00189     |
|                | 2.891            | 0.2                         | 0.00415                                   | 0.00110     | 0.00063     |
|                | 3.294            | 1.0                         | 0.00120                                   | 0.00021     | 0.00018     |
| 40 - 92        | 1.364            | 0.4                         | 0.04432                                   | 0.00622     | 0.00645     |
|                | 1.691            | 0.2                         | 0.01295                                   | 0.00185     | 0.00189     |
|                | 1.891            | 0.2                         | 0.01009                                   | 0.00110     | 0.00147     |
|                | 2.091            | 0.2                         | 0.00531                                   | 0.00074     | 0.00077     |
|                | 2.291            | 0.2                         | 0.00287                                   | 0.00060     | 0.00042     |
|                | 2.563            | 0.4                         | 0.00126                                   | 0.00024     | 0.00018     |
|                | 2.891            | 0.2                         | 0.00062                                   | 0.00019     | 0.00009     |
|                | 3.293            | 1.0                         | 0.00019                                   | 0.00004     | 0.00003     |

TABLE VIII: Systematic error in $dN/dy$.

| Centrality (%) | $\delta_{\text{norm}}$ (%) | $\delta_{\text{mass}}$ (%) | $\delta_{\text{extrap}}$ (%) | $\delta_{\text{MC}}$ (%) | $\delta_{\text{occu}}$ (%) | $\delta_{\text{tot}}$ (%) |
|----------------|-----------------------------|-----------------------------|-------------------------------|--------------------------|---------------------------|--------------------------|
| Minimum Bias   | 0.7                         | 2.6                         | 4.0                           | 12.4                     | 7.8                       | 15                       |
| 0 - 10         | 0.8                         | 4.2                         | 5.2                           | 12.4                     | 10                        | 17                       |
| 10 - 40        | 1.1                         | 2.3                         | 5.9                           | 12.4                     | 8.5                       | 16                       |
| 40 - 92        | 0.7                         | 3.1                         | 6.0                           | 12.4                     | 7                         | 16                       |

TABLE IX: Systematic error in $T$.

| Centrality (%) | $\delta_{\text{mass}}$ (%) | $\delta_{\text{fit}}$ (%) | $\delta_{\text{tot}}$ (%) |
|----------------|-----------------------------|---------------------------|--------------------------|
| Minimum Bias   | 0.6                         | 4.9                       | 5                        |
| 0 - 10         | 1.1                         | 5.2                       | 5                        |
| 10 - 40        | 1.1                         | 6.2                       | 6                        |
| 40 - 92        | 1.1                         | 4.2                       | 4                        |

e) Systematic error in the occupancy dependent efficiency corrections, $\delta_{\text{occu}}$: The systematic error associated with this efficiency is estimated by calculating the occupancy dependent correction with different track confirmation criteria and is independent of the pair momenta. This is a systematic effect on $dN/dy$ only.

The above systematic errors are quoted in Tables VIII and IX for $dN/dy$ and $T$, respectively.
