$J/\psi$ Production vs Centrality, Transverse Momentum, and Rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

A. Adare,8 S. Afanasiev,22 C. Aidala,9 N.N. Ajitanand,49 Y. Akiba,43,44 H. Al-Bataineh,38 J. Alexander,49 A. Al-Jamel,38 K. Aoki,28,43 L. Aphecetche,51 R. Armendariz,28 S.H. Aronson,3 J. Asai,44 E.T. Atoussa,29 R. Averbeke,50 T.C. Awes,29 B. Azmoun,3 V. Babintsev,18 G. Baksay,14 L. Baksay,14 A. Baldissierii,11 K.N. Barish,4 P.D. Barnes,31 B. Bassalleck,37 S. Bathe,9,39 S. Batsouli,9,39 V. Baublis,42 F. Bauer,4 A. Bazilevsky,3 S. Belikov,3,21 R. Bennett,50 Y. Berdnikov,46 A.A. Bickler,8 M.T. Bjorndal,9 J.G. Boissevain,31 H. Borel,11 K. Boyle,50 M.L. Brooks,33 D.S. Brown,38 D. Bucher,34 H. Buesching,3 V. Bumazhnov,18 G. Bunce,3,44 J.M. Burward-Hoy,31 S. Butsyk,31,50 S. Campbell,50 J.-S. Chai,25 B.S. Chang,58 J.-L. Charvet,31 S. Chernichenko,18 J. Chiba,24 C.Y. Chi,9 M. Chiuz,9,19 I.L. Choi,58 T. Chuo,55 P. Chung,49 A. Churyu,18 V. Ciocci,39 C.R. Cleven,16 Y. Cobigo,11 B.A. Cole,9 M.P. Comets,40 P. Constantin,21,31 M. Csanád,13 T. Csörgő,25 T. Dahms,50 K. Das,15 G. David,3 M.B. Deaton,1 K. Dehmelt,14 H. Delagrange,51 A. Denisov,18 D. d’Enterria,9 A. Deshpande,44,50 E.J. Desmond,3 O. Dietzsch,57 A. Dion,50 M. Donadelli,47 J.L. Drachenberg,1 O. Drapier,29 A. Drees,50 A.K. Dubey,57 A. Durum,18 V. Dzhordzhadze,4,52 Y.V. Efremenko,39 J. Egedism,50 F. Ellingshaus,8 W.S. Emam,4 A. Enokizono,17,30 H. En’yo,43,44 B. Espagnon,40 S. Esuni,54 K.O. Eyser,4 D.E. Fields,37,44 M. Finger,5,22 F. Fleuret,29 S.L. Fokin,27 B. Forestier,32 Z. Fraenkel,57 J.E. Franz,9,50 A. Franz,3 A.D. Frawley,15 K. Fujiwara,43 Y. Fukao,28,43 S.-Y. Fung,4 F. Fusayasu,36 S. Gadat,32 I. Garishvili,52 F. Gastineau,51 M. Germain,51 A. Glenn,8,52 H. Gong,50 M. Gonin,29 J. Gosset,11 Y. Goto,43,44 R. Granier de Cassagnac,29 N. Grau,21 S.V. Greene,55 M. Grosse Perdekamp,19,44 T. Gunji,3 H.-A. Gustafsson,33 T. Hachiya,17,43 A. Hadji Henni,51 C. Haegemann,57 J.S. Hagerty,3 M.N. Haghighi,3 R. Han,41 H. Harada,17 E.P. Hartouni,30 K. Haruna,17 M. Harvey,3 E. Haslum,33 K. Hasuoka,43 R. Hayano,7 M. Heffner,30 T.K. Hemmick,50 T. Hester,4 J.M. Heuser,43 X. He,16 H. Hiejima,19 J.C. Hill,21 R. Hobbs,14 M. Hohlmann,14 M. Holmes,55 W. Holzmoli,49 K. Homma,17 B. Hong,26 T. Horaguchi,43,53 D. Hornback,52 M.G. Hur,23 T. Ichihara,43,44 K. Imai,28,43 M. Inaba,54 Y. Ine,45,43 D. Isehnower,1 L. Isehnower,1 M. Ishihara,43 T. Isobe,7 M. Issah,49 A. Isupov,22 B.V. Jacak,50 J. Ji,9 J. Jin,9 O. Jinnouchi,44 B.M. Johnson,3 K.S. Joo,35 D. Jouan,40 F. Kajihara,7,43 S. Kametani,7,56 N. Kamihira,43,53 J. Kamin,50 M. Kaneta,44 J.H. Kang,58 H. Kanou,43,53 T. Kawagishi,54 D. Kawall,44 A.V. Kazantsev,27 S. Kelly,8 A. Khanzadeev,42 J. Kikuchi,56 D.H. Kim,35 D.J. Kim,58 E. Kim,48 Y.-S. Kim,23 E. Kinney,8 A. Kiss,13 E. Kistenev,3 A. Kiymovich,43 J. Klay,30 C. Klein-Boesing,34 L. Kochenda,42 V. Kochetkov,18 B. Komkov,42 M. Konno,54 D. Kotchetkov,4 A. Kozlov,57 A. Král,10 A. Kravitz,9 P.J. Kroon,3 J. Kubart,5,20 G.J. Kunde,31 N. Kurihara,7 K. Kurita,45,43 M.J. Kweon,26 Y. Kwon,52,58 G.S. Kyle,38 R. Lacey,49 Y.-S. Lai,9 J.G. Lajoie,21 A. Lebedev,21 Y. Le Borne,40 S. Leckey,50 D.M. Lee,31 M.K. Lee,58 T. Lee,48 M.J. Leitch,31 M.A.L. Leite,47 B. Lenzi,47 H. Lim,48 T. Liska,9 A. Litvinenko,22 M.X. Liu,31 X. Li,9 X.H. Li,3 B. Love,55 D. Lynch,3 C.F. Maguire,55 Y.I. Makdisi,3 A. Malakhov,52 M.D. Malik,37 V.I. Manko,27 Y. Mao,31,43 L. Mašek,5,20 H. Masui,54 F. Matathias,9,50 M.C. McCain,19 M. McCumber,50 P.L. McGaughey,31 Y. Miate,54 P. Mikes,5,20 K. Miki,54 T.E. Miller,55 A. Milov,50 S. Mioduszewski,3 G.C. Mishra,16 M. Misra,7 J.T. Mitchell,3 M. Mitrovski,18 A. Morreale,4 D.P. Morrison,3 J.M. Moss,31 T.V. Moukhanova,27 D. Mukhopadhyay,55 J. Murata,45,43 S. Nagamiya,24 Y. Nagata,54 J.L. Nagle,5 M. Naglis,57 I. Nakagawa,43,44 Y. Nakamuk,17 T. Nanakura,17 K. Nakano,43,53 J. Newby,30 M. Nguyen,50 B.E. Norman,31 A.S. Nyanin,27 J. Nystrand,33 E. O’Brien,3 S.X. Oda,7 C.A. Ogilvie,21 H. Ohnishi,43 I.D. Ojha,55 H. Okada,28,43 K. Okada,44 M. Oka,54 O.O. Omwade,1 A. Oskarsson,33 I. Otterlund,33 M. Ouchida,17 K. Ozawa,7 R. Pak,3 D. Pal,55 A.P.T. Palounek,31 V. Pantuev,50 V. Papavassiliou,38 J. Park,48 W.J. Park,26 S.F. Pate,38 H. Pei,21 J.C. Peng,19 H. Pereira,11 V. Peresedov,22 D.Yu. Peressounko,27 C. Pinkenburg,53 R.P. Pisani,3 M.L. Putschke,3 A.K. Purwar,31,50 H. Qu,16 J. Rak,21,37 A. Rakotozafindraibe,29 I. Ravinovich,57 K.F. Read,39 S. Rembецki,14 M. Reuter,50 K. Reygers,34 V. Riabov,32 Y. Riabov,42 G. Roche,32 A. Roman,29 M. Rosati,23 S.S. Rose,33 P. Rosset,32 P. Ruokotkin,22 V.L. Rykov,43 S.S. Ryu,58 B. Sahlmuller,54 N. Saito,28,43,44 T. Sakaguchi,3,7,56 S. Sakai,54 H. Sakata,17 V. Samsonov,42 H.D. Sato,28,43 S. Sato,3,24,54 S. Sawada,24 J. Seidel,8 R. Seidl,19 V. Semenov,18 R. Seto,4 D. Sharma,27 T.K. Shea,3 I. Shein,18 A. Shelev,42 T.-A. Shibata,43,53 K. Shigaki,17 M. Shimomura,54 T. Shohjoh,54 K. Shoji,38,43 A. Sickles,50 C.L. Silva,47 D. Silvermyhr,39 C. Silvestre,11 K.S. Sim,29 C.P. Singh,2 V. Singh,2 S. Skutnik,21 M. Slunečka,5,22 W.C. Smith,1 A. Soldatov,18 R.A. Soltz,30 W.E. Sondheim,31 S.P. Sorensen,52 I.V. Sourikova,3 F. Staley,51 P.W. Stankus,39 E. Stenlund,33 M. Stepanov,48 A. Ster,25 S.P. Stoll,3 T. Sugitate,17 C. Suire,40
The PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) has measured \( J/\psi \) production for rapidities \( -2.2 < y < 2.2 \) in Au + Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV. The \( J/\psi \) invariant yield and nuclear modification factor \( R_{AA} \) as a function of centrality, transverse momentum and rapidity are reported. A suppression of \( J/\psi \) relative to binary collision scaling of proton-proton reaction yields is observed. Models which describe the lower energy \( J/\psi \) data at the Super Proton Synchrotron (SPS) invoking only \( J/\psi \) destruction based on the local medium density would predict a significantly larger suppression at RHIC and more suppression at mid rapidity than at forward rapidity. Both trends are contradicted by our data.

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The Quark-Gluon-Plasma (QGP) is a state of deconfined quarks and gluons which is predicted by lattice Quantum Chromodynamics (QCD) calculations to be formed above a temperature of order \( T_\mathrm{c} = 170 \) MeV for a baryon chemical potential \( \mu_B = 0 \) [1]. Heavy quarkonia (\( J/\psi \), \( \psi' \), \( \chi_c \) and \( \Upsilon \)) have long been considered one of the most promising probes to study formation and properties of QGP. In the deconfined state, the attraction between heavy quarks and anti-quarks is predicted to be reduced due to dynamic screening effects, leading to the suppression of heavy quarkonia yield. The strength of the suppression depends on the binding energies of the quarkonia and the temperature of the surrounding system [2]. Recent lattice QCD calculations suggest that the \( J/\psi \) may not dissociate until well above \( T_\mathrm{c} \) [3, 4]. On the other hand, several models predict that the \( J/\psi \) yield will decay are expected to dissolve at lower temperatures due to smaller binding energies.

A \( J/\psi \) suppression observed at lower energies by the NA50 experiment at the SPS [5, 6] could be reproduced by various theoretical calculations, some invoking QGP formation and others not. A larger suppression is expected at RHIC compared to SPS due to the larger energy density of the medium created [7, 8].

We report results on \( J/\psi \) production measured by the PHENIX collaboration at mid-rapidity \( (|y| < 0.35) \) via \( e^+e^- \) decay and at forward rapidity \( (|y| \in [1.2, 2.2]) \) via \( \mu^+\mu^- \) decay in Au + Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV. These results do not separate primordial \( J/\psi \) and \( J/\psi \) from \( \chi_c \), \( \psi' \) or \( B \) decay. The \( J/\psi \) invariant yields as a function of centrality, rapidity \( (y) \) and transverse momentum \( (p_T) \) are shown. They are combined with the \( J/\psi \) yield measured in \( p + p \) collisions [14] to form the \( J/\psi \) nuclear modification factor \( R_{AA} \).

The PHENIX apparatus is described in [15]. At mid-rapidity electrons are measured with two spectrometers consisting of Drift Chambers (DC), Pad Chambers (PC), Ring Imaging Cerenkov Counters (RICH), and Electromagnetic Calorimeters (EMCal). They are identified by matching charged tracks reconstructed with the DC and the first layer of the PC to clusters in the EMCal and to hits in the RICH. The energy-momentum matching requirement is \( (E/p - 1) \geq -2.5 \) standard deviations \( (\sigma) \). The position matching between the track and the cluster in the EMCal is \( \leq 2.5\sigma \) \((4\sigma)\) in azimuth and along the beam axis, for central (peripheral) collisions. For the RICH, at least 4 \((2)\) matching hits are required. Muons are measured with two forward spectrometers consisting of a front absorber to stop most hadrons produced in the collision, cathode strip chambers (MuTr) which provide momentum information and a Muon Identifier (MuID) which uses alternating layers of steel absorber and Iarocci tubes. Charged particle trajectories are first reconstructed in the MuID then in the MuTr. They must reach the last plane of the MuID and have a good geometrical match between the MuID and the MuTr to be identified as muons. The matching is \( < 9^\circ \) for the slope and \( < 15 \) \((20)\) cm for the position in the first layer of the MuID at positive (negative) rapidity. The collision centrality is determined using two Beam-Beam Counters (BBC) and Zero Degree Calorimeters (ZDC) [16].

The data used for this analysis were collected during the 2004 run at RHIC using a minimum bias trigger (a coincidence of the two BBC) which covers 92 ± 3% of the
Au + Au inelastic cross-section. After quality assurance and vertex cut ($|z| \leq 30$ cm), $9.9 \times 10^{5}$ (1.1 × 10$^{5}$) events were analyzed for mid (forward) rapidity, corresponding to an integrated luminosity of 157 $\mu$b$^{-1}$ (174 $\mu$b$^{-1}$). The forward rapidity data were filtered using an offline level-2 trigger which provides a fast reconstruction of the particle trajectory in the MuID. Events are accepted by this filter when at least two good quality tracks reaching the last plane of the MuID are found within the acceptance.

The $J/\psi$ yield is obtained from the unlike sign dilepton invariant mass distribution after subtracting the combinatorial background using an event-mixing technique. The background is normalized to the real data using the like-sign dilepton invariant mass distribution, $2\sqrt{N^{++}N^{--}}$, with $N^{++}$ ($N^{--}$) being the number of positive (negative) dilepton pairs. The accuracy of the normalization is estimated to be 2 % and accounted for in the systematic errors. At midrapidity the $J/\psi$ mass resolution is $\sim 35$ MeV/$c^2$. The number of $J/\psi$ is determined by counting the remaining unlike sign pairs in the mass range $2.9 \leq M_{e^+e^-} \leq 3.3$ GeV/$c^2$. This number is corrected by the estimated contribution of the dielectron continuum and the loss due to the radiative tail. A total of $\sim 1000$ $J/\psi$ are obtained and the signal to background (S/B) varies from 0.5 for central collisions to 15 for peripheral collisions. At forward rapidity, the $J/\psi$ mass resolution varies from 150 to 200 MeV/$c^2$ and is larger than at midrapidity primarily because of the multiple scattering and energy loss straggling in the front absorber. The residual background (notably from the open charm pairs and Drell-Yan) in the unlike-sign invariant mass distribution is evaluated using an exponential form. The $J/\psi$ signal is estimated with direct counting of the remaining pairs in the mass range $2.6 \leq M_{\pi^+\pi^-} \leq 3.6$ GeV/$c^2$ and using a fit with different line shapes. The average of the resulting values is used as the number of $J/\psi$ and their dispersion is included in the systematic error. A total of $\sim 4500$ $J/\psi$ are obtained and S/B varies from 0.2 for central collisions to 3 for peripheral collisions.

The $J/\psi$ invariant yield in a given centrality, $p_T$ and $y$ bin is:

$$\frac{B_{ll} d^2N_{J/\psi}}{2\pi p_T dy} = \frac{1}{N_{evt}\Delta y\Delta p_T A_e} \frac{N_{J/\psi}}{N_{coll}d^{2}N_{J/\psi}/dp_T dy}$$  \hspace{1cm} (1)

with $B_{ll}$ being the branching ratio for $J/\psi \rightarrow l^+l^-; N_{J/\psi}$ the number of $J/\psi$ measured in the centrality bin; $N_{evt}$ the corresponding number of events; $\Delta y$ the rapidity range; $\Delta p_T$ the transverse momentum range and $A_e$ the acceptance and efficiency correction for $J/\psi$. $A_e$ is determined by full GEANT simulation. It decreases with the collision centrality due to overlapping hits in the RICH, EMCal and MuTr, leading to an increasing amount of mis-reconstructed tracks which are then rejected by the analysis cuts. This effect is evaluated by embedding simulated $J/\psi$ in real events. For the most central collisions the efficiency loss is 20 % at mid rapidity and 75 % (50 %) at positive (negative) rapidity.

The nuclear modification factor in a given centrality, $p_T$ and $y$ bin is:

$$R_{AA} = \frac{d^2N_{J/\psi}^{AA}/dp_T dy}{N_{coll}d^{2}N_{J/\psi}/dp_T dy}$$  \hspace{1cm} (2)

with $d^2N_{J/\psi}^{AA}/dp_T dy$ being the $J/\psi$ yield in Au + Au collisions in the centrality bin, $N_{coll}$ the corresponding mean number of binary collisions and $d^{2}N_{J/\psi}/dp_T dy$ the $J/\psi$ yield in $p + p$ inelastic collisions.

The systematic errors on the $J/\psi$ invariant yield (Table I) are grouped into three categories: point to point uncorrelated (type A) for which the points can move independently one from the other; point to point correlated (type B) for which the points can move coherently though not necessarily by the same amount; and global errors for which all points move by the same relative amount. Statistical and uncorrelated systematic errors are summed in quadrature and represented with vertical bars; correlated systematic errors are represented with boxes and different colors/symbols are used for forward and mid rapidity because they are independent; global systematic errors are quoted directly on the figures. For $R_{AA}$, additional systematic errors are associated with uncertainties in the calculation of $N_{coll}$ (10 to 28 %) and the $J/\psi$ yield in $p + p$ (12 % and 7 % at mid and forward rapidity, respectively). On the other hand the systematic errors that are common to Au + Au and $p + p$ cancel.

Figure I shows the $J/\psi$ yield vs. $p_T$ for different centrality bins (see Table II) for the corresponding number of participants, $N_{part}$). Data from the two muon spectrometers are combined to obtain the forward rapidity points. In each centrality bin, the $J/\psi$ mean square transverse momentum, $\langle p_{T}^2 \rangle$, is numerically calculated from the data for $p_T \leq 5$ GeV/$c$ and is shown in Table II. The first error corresponds to the statistical and uncorrelated systematic error on the $J/\psi$ yield. The second corresponds to the correlated systematic error. At midrapidity the $\langle p_{T}^2 \rangle$ shows no variation versus centrality within

| source | $|y| < 0.35$ | $|y| \in [1.2, 2.2]$ | type |
|--------|-------------|----------------|------|
| signal extraction | 6.5 to 9 % | 4 to 24 % | A |
| acceptance | 6 % | 10 % | B |
| efficiency | 4.5 to 8 % | 4 to 16 % | B |
| run by run variation | 4 % | 5 % | B |
| input, $p_T$ distributions | 2 % | 4 % | B |
The error bars. It increases slightly with the RMS of each distribution is shown in Table II. For the most central collisions (0-20 % and 20-40 %), the RMS is compatible with that measured in Au + Au collisions and in p + p collisions. The errors are described in the text. Column 5: Calculated RMS of the corresponding J/ψ y distributions.

| centrality (%) | N_{part} | 〈p_T^2〉 (GeV/c)^2 | 〈p_T^2〉 (GeV/c)^2 | y RMS |
|----------------|----------|----------------------|----------------------|-------|
| 0-20           | 280      | 3.6 ± 0.6 ± 0.1      | 4.4 ± 0.4 ± 0.4      | 1.32 ± 0.06 |
| 20-40          | 140      | 4.6 ± 0.5 ± 0.1      | 4.6 ± 0.3 ± 0.4      | 1.30 ± 0.05 |
| 40-60          | 60       | 4.5 ± 0.7 ± 0.2      | 3.7 ± 0.2 ± 0.3      | 1.40 ± 0.04 |
| 60-92          | 14       | 3.6 ± 0.9 ± 0.2      | 3.3 ± 0.3 ± 0.3      | 1.43 ± 0.04 |
| p + p          | 2        | 4.1 ± 0.2 ± 0.1      | 3.4 ± 0.1 ± 0.1      | 1.41 ± 0.03 |

The ratio of forward/mid rapidity R_{AA} vs. N_{part}. The ratio first decreases then reaches a plateau of about 0.6 for N_{part} > 100.

We observed a significant J/ψ suppression relative to binary scaling of proton-proton is observed for central Au + Au collisions at RHIC. The magnitude of the suppression is similar to that observed at the SPS and greater than the suppression expected by extrapolating the cold nuclear matter effects measured in d + Au collisions [12, 13]. Models that describe the SPS data using a J/ψ and/or χ_c and ψ' suppression based on the local density predict a significantly larger suppression at RHIC than SPS and more suppression at mid rapidity than at forward rapidity [7, 8]. Both trends are contradicted by our data. Additionally, the J/ψ mean square transverse momentum, restricted to p_T ≤ 5 GeV/c, shows little dependence on centrality. Various models of J/ψ production and suppression, which predict very different transverse momentum and rapidity dependencies, can be significantly constrained by the data presented here and recent results on open charm [11].

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FIG. 3: $J/\psi R_{AA}$ vs. $p_T$ for several centrality bins in Au + Au collisions. Mid (forward) rapidity data are shown with open (filled) circles. See text for description of the errors.

FIG. 4: $J/\psi R_{AA}$ vs. $y$ for different centrality bins. Open (filled) circles are for mid (forward) rapidity. See text for description of the errors.