

Centrality Dependence of Charged Hadron Transverse Momentum Spectra in Au + Au Collisions from $\sqrt{s_{NN}} = 62.4$ to 200 GeV

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We have measured transverse momentum distributions of charged hadrons produced in Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV. The spectra are presented for transverse momenta $0.25 < p_T < 4.5$ GeV/c, in a pseudorapidity range of $0.2 < \eta < 1.4$. The nuclear modification factor R_{AA} is calculated relative to $p + p$ data at the same collision energy as a function of collision centrality. For $2 < p_T < 4.5$ GeV/c, R_{AA} is found to be significantly larger than in Au + Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV. In contrast to the large change in R_{AA} , we observe a very similar centrality evolution of the p_T spectra at $\sqrt{s_{NN}} = 62.4$ and 200 GeV. The dynamical origin of this surprising factorization of energy and centrality dependence of particle production in heavy-ion collisions remains to be understood.

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The yield of charged hadrons produced in collisions of gold nuclei at an energy of $\sqrt{s_{NN}} = 62.4$ GeV has been measured with the PHOBOS detector at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory. The data are presented as a function of transverse momentum (p_T) and collision centrality. The goal of these measurements is to study the modification of particle production in the presence of the produced medium by comparing to nucleon-nucleon collisions at the same energy.

This measurement was motivated by results from Au + Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV. Hadron production at these energies was found to be strongly suppressed relative to expectations based on an independent superposition of nucleon-nucleon collisions at p_T of 2–10 GeV/c [1–4]. The modification of high- p_T hadron yields has commonly been investigated using the nuclear modification factor R_{AA} , defined as

$$R_{AA} = \frac{\sigma_{pp}^{\text{inel}}}{\langle N_{\text{coll}} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}. \quad (1)$$

A value of $R_{AA} = 1$ corresponds to scaling of particle production with the average number of binary nucleon-nucleon collisions, $\langle N_{\text{coll}} \rangle$, within a heavy-ion collision.

For the production of charged hadrons in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, values of $R_{AA} \approx 0.2$ are observed at $p_T = 4$ GeV/c [2–4]. Such a suppression had been predicted to occur as a consequence of the energy loss of high- p_T partons in the dense medium formed in Au + Au collisions [5]. This hypothesis is consistent with results obtained from deuteron-gold collisions at $\sqrt{s_{NN}} = 200$ GeV [6–9], where no such suppression was seen.

While studies of the system-size dependence of the high- p_T suppression exist, the dependence on the collision energy is poorly known. Data on the production of neutral pions in Pb + Pb collisions at $\sqrt{s_{NN}} = 17.2$ GeV suffer from large uncertainties in the parametrizations of the $p + p$ reference data [10–12]. The results presented here for Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV, in combination with the results from 130 and 200 GeV collisions, allow the first detailed examination of the connection between high p_T suppression and collision energy, charged-particle density, and collision geometry.

The data were collected using the PHOBOS two-arm magnetic spectrometer. Details of the experimental setup can be found in [13]. The primary event trigger used the time difference between signals in two sets of ten Čerenkov counters, located at $4.4 < |\eta| < 4.9$, to select

TABLE I. Details of the centrality classes used in this analysis. Bins are expressed in terms of percentage of the total inelastic Au + Au cross section.

| Centrality | $\langle N_{\text{part}}^{62.4} \rangle$ | $\langle N_{\text{coll}}^{62.4} \rangle$ | $\langle N_{\text{part}}^{200} \rangle$ | $\langle N_{\text{coll}}^{200} \rangle$ |
|------------|--|--|---|---|
| 45%–50% | 61 ± 7 | 85 ± 14 | 65 ± 4 | 99 ± 11 |
| 35%–45% | 86 ± 9 | 136 ± 22 | 93 ± 5 | 164 ± 15 |
| 25%–35% | 130 ± 10 | 240 ± 30 | 138 ± 6 | 286 ± 25 |
| 15%–25% | 189 ± 9 | 402 ± 36 | 200 ± 8 | 483 ± 40 |
| 6%–15% | 266 ± 9 | 643 ± 48 | 276 ± 9 | 762 ± 57 |
| 0%–6% | 335 ± 11 | 883 ± 65 | 344 ± 11 | 1040 ± 77 |

collisions along the beam axis that were close to the nominal vertex position.

The selected events were divided into six centrality classes, based on the signal in two sets of 16 scintillator counters covering pseudorapidities $3.0 < |\eta| < 4.5$. The use of this signal as a centrality measure requires that it increases monotonically with the number of participating nucleons, $\langle N_{\text{part}} \rangle$. This is not the case for collisions at a lower beam energy of 19.6 GeV ($y_{\text{beam}} = 3.0$) [14]. We therefore tested the centrality determination at 62.4 GeV ($y_{\text{beam}} = 4.2$) using an alternative centrality measure based around midrapidity, and found the results to be robust. A full detector simulation using HIJING events [15] was used to estimate $\langle N_{\text{part}} \rangle$ for each centrality class, and the corresponding $\langle N_{\text{coll}} \rangle$ values were obtained from a Monte Carlo Glauber calculation [14]. For these calculations, as well as for the determination of R_{AA} at 62.4 GeV, we used $\sigma_{pp}^{\text{inel}} = 36 \pm 1$ mb [16]. The results are listed in Table I.

The event selection and track reconstruction procedure for this analysis closely follows the previously published analysis at $\sqrt{s_{NN}} = 200$ GeV [4]. Events with a primary vertex position within ± 10 cm of the nominal vertex position were selected. Only particles traversing a full spectrometer arm were included in the analysis, resulting in a low transverse momentum cutoff at $p_T \approx 0.2$ GeV/c.

The transverse momentum distribution for each centrality bin was corrected separately for the geometrical acceptance of the detector, the inefficiency of the tracking algorithm, secondary and incorrectly reconstructed particles, and the distortion due to binning and momentum resolution. The relative importance of most of the corrections and the associated estimated systematic uncertainties are similar to those reported in the previous analysis [4]. The exception is the correction for momentum resolution and binning effects at high p_T , where changes to the track fitting procedure improved the resolution and reduced the corresponding uncertainty by a factor of 2.

In Fig. 1, we present the invariant yield of charged hadrons as a function of transverse momentum, obtained by averaging the yields of positive and negative hadrons. Data are shown for six centrality bins and are averaged over a pseudorapidity interval $0.2 < \eta < 1.4$.

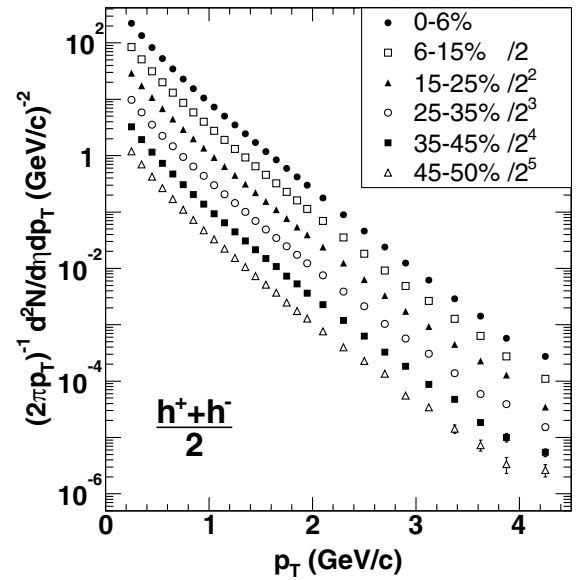


FIG. 1. Invariant yields for charged hadrons from Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV, in the pseudorapidity interval $0.2 < \eta < 1.4$ as a function of p_T for six centrality bins. For clarity, consecutive bins are scaled by factors of 2. The systematic uncertainties are smaller than the symbol size.

Focusing first on central events, Fig. 2 shows the nuclear modification factor R_{AA} for the 6% most central Au + Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV for four different values of p_T ranging from 1 to 4 GeV/c. Results from $p + p$ collisions at the same energy [17] were used in the calculation of R_{AA} . The small differences in geometrical acceptance

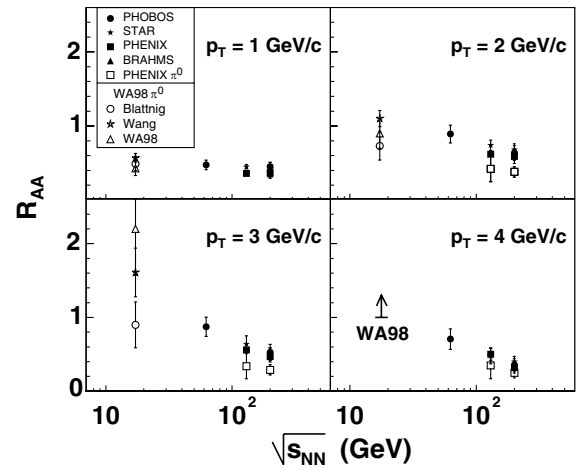


FIG. 2. Nuclear modification factor R_{AA} for central A + A events, as a function of collision energy for $p_T = 1, 2, 3,$ and 4 GeV/c. Filled symbols show data for charged hadrons, and open symbols show π^0 data. For the WA98 π^0 data, R_{AA} is shown using three different parametrizations for the $p + p$ reference spectrum [10–12]; for $p_T = 4$ GeV/c, the arrow indicates the lower limit on R_{AA} . The error bars show the combined systematic and statistical uncertainty obtained by interpolating the p_T dependence of R_{AA} .

between the $p + p$ data and our data were corrected for using PYTHIA [18]. Uncertainties in the $p + p$ reference introduce a scale error in R_{AA} of $(7.5 + p_T)\%$, which is included in the systematic error. The new results are compared with results for charged hadrons at $\sqrt{s_{NN}} = 130$ and 200 GeV. For $p_T = 2$ GeV/ c and above, we observe a smooth decrease of R_{AA} from 62.4 to 200 GeV in central Au + Au collisions.

Also shown in Fig. 2 is R_{AA} for π^0 production in Pb + Pb collisions at 17.2 GeV from the WA98 Collaboration, obtained using three $p + p$ reference parametrizations [10–12], as well as π^0 data for 130 and 200 GeV from PHENIX [1,19]. The data indicate that R_{AA} for π^0 production at $p_T > 3$ GeV/ c drops from $R_{AA} > 1$ at $\sqrt{s_{NN}} = 17.2$ GeV to $R_{AA} < 0.2$ at $\sqrt{s_{NN}} = 200$ GeV, whereas the charged hadron pseudorapidity density over the same energy range changes by only a factor of 2 [14]. The data also show that, for the p_T range studied here, R_{AA} for neutral pions is consistently lower than for charged hadrons at the same collision energy.

The centrality evolution of R_{AA} for the 62.4 GeV data can be studied in detail in the top row of Fig. 3. For comparison, we include the results from Au + Au collisions at 200 GeV [4], using the same centrality binning. We

observe that R_{AA} reaches a maximum of approximately 1.6 for peripheral collisions at 62.4 GeV, whereas the maximum value observed at 200 GeV is close to 1. For both data sets, a significant and systematic decrease in R_{AA} is observed going from peripheral to central events.

It has previously been noted that the observed strong centrality dependence of R_{AA} at $\sqrt{s_{NN}} = 200$ GeV corresponds to a relatively small change in the yield per participating nucleon [4] and that over the same centrality range, the total yield of charged particles per participating nucleon is constant within the experimental uncertainties [20]. These observations lead us to define

$$R_{AA}^{N_{\text{part}}} = \frac{\sigma_{pp}^{\text{inel}}}{\langle N_{\text{part}}/2 \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}, \quad (2)$$

in analogy to Eq. (1), where now we scale the reference spectrum by $N_{\text{part}}/2$, rather than N_{coll} . The centrality, p_T , and energy dependence of $R_{AA}^{N_{\text{part}}}$ is shown in the middle row of Fig. 3 for collisions at 62.4 and 200 GeV. Over the full range of p_T studied here, the yield per participant pair shows a variation of only $\approx 25\%$ from peripheral to central collisions for both collision energies.

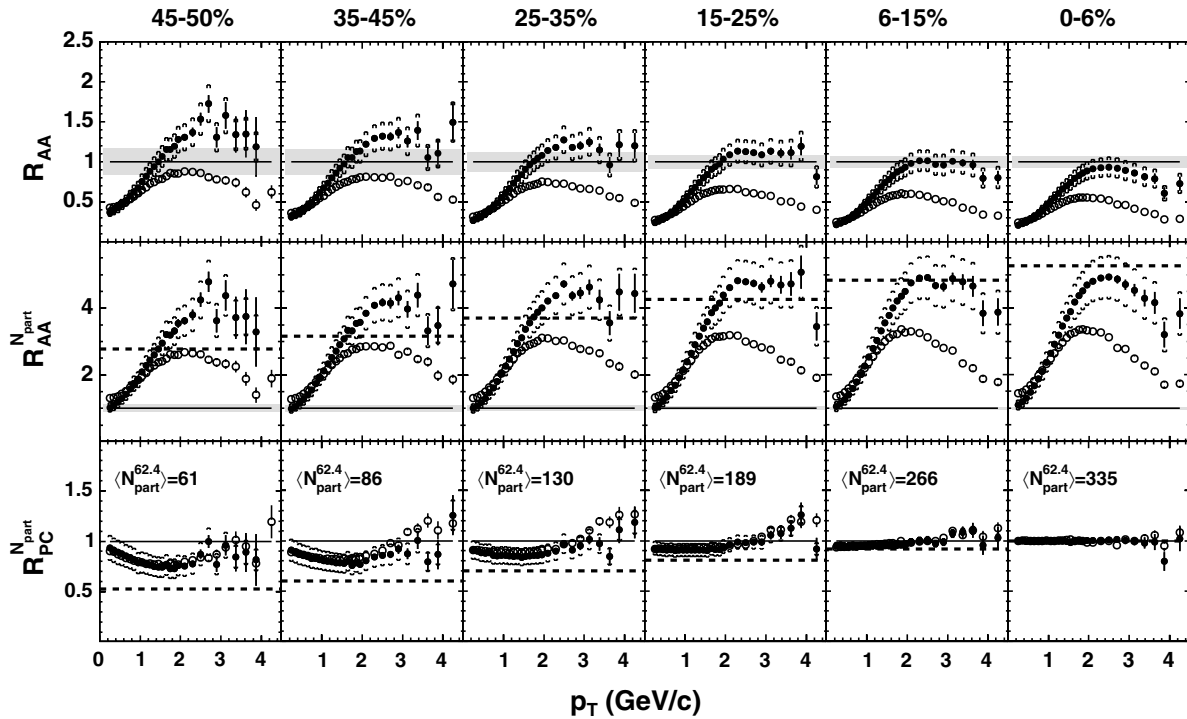


FIG. 3. Ratio of p_T distributions from Au + Au collisions to various reference distributions at $\sqrt{s_{NN}} = 62.4$ GeV (filled symbols) and 200 GeV (open symbols). Data are shown in six bins of centrality, ranging from $\langle N_{\text{part}} \rangle = 61$ to 335 for 62.4 GeV collisions. The top row shows the nuclear modification factor R_{AA} , i.e., the ratio relative to proton-(anti)proton collisions scaled by $\langle N_{\text{coll}} \rangle$. The gray band shows the uncertainty in N_{coll} . The middle row shows $R_{AA}^{N_{\text{part}}}$, which uses proton-(anti)proton spectra scaled by $\langle N_{\text{part}}/2 \rangle$. The bottom row shows $R_{PC}^{N_{\text{part}}}$, using a fit to central data scaled by $\langle N_{\text{part}}/2 \rangle$ as a reference. The dashed line in the middle and bottom rows indicates the expectation for $\langle N_{\text{coll}} \rangle$ scaling at $\sqrt{s_{NN}} = 62.4$ GeV relative to the reference distribution. Systematic uncertainties for all plots are shown by brackets (90% C.L.)

This centrality independence is further illustrated in the bottom row of Fig. 3. The quantity $R_{PC}^{N_{\text{part}}}$, defined as

$$R_{PC}^{N_{\text{part}}} = \frac{\langle N_{\text{part}}^{0\%-6\%} \rangle}{\langle N_{\text{part}} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 N_{AA}^{0\%-6\%}/dp_T d\eta}, \quad (3)$$

is shown as a function of p_T for the six centrality bins. $R_{PC}^{N_{\text{part}}}$ measures the change in yield per participant pair, relative to a fit to the central data. Normalizing to the central, rather than the peripheral, data has the advantage that the results are more easily compared among different experiments with different ranges in centrality, while providing the same information in comparisons with theoretical calculations. Data are shown for collisions at 62.4 and 200 GeV. This plot again shows the small variation of the yield per participant pair from peripheral to central collisions. Furthermore, it demonstrates that the modification of the yield from peripheral to central collisions is the same for both energies, over the full p_T range, within experimental uncertainties of less than 10%. This striking agreement can be compared with the much larger variation of R_{AA} as a function of energy, centrality, and p_T .

Particle production at $p_T > 1$ GeV/c in heavy-ion collisions is expected to be influenced by the interplay of many effects. This includes p_T broadening due to initial and final state multiple scattering (the ‘‘Cronin effect’’), the medium-induced energy loss of fast partons, and the effects of collective transverse velocity fields and of parton recombination [21]. The relative magnitude of these effects at 62.4 GeV is not yet known and will require further investigation. However, all these processes are expected to exhibit distinctly different dependences on collision energy and centrality, yet the results presented here demonstrate, within the experimental uncertainty, a surprisingly clean factorization of the energy and centrality dependence of charged hadron yields at all measured values of p_T . This factorization of energy and centrality dependence is also a characteristic feature of total and differential particle yields [14,20] and of multiparticle correlation measurements such as Bose-Einstein correlations [22]. These observations, which indicate the presence of as-yet-unexplained global constraints on particle production, present a challenge to theoretical models of heavy-ion collisions and appear to be a key feature of these interactions that remains to be understood.

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