

# 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 pseudo-rapidity 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  $\sqrt{s_{NN}} = 62.4$  GeV 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

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

A value of  $R_{AA} = 1$  corresponds to scaling of particle

production with the average number of binary nucleon-nucleon collisions,  $\langle N_{coll} \rangle$ , 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.

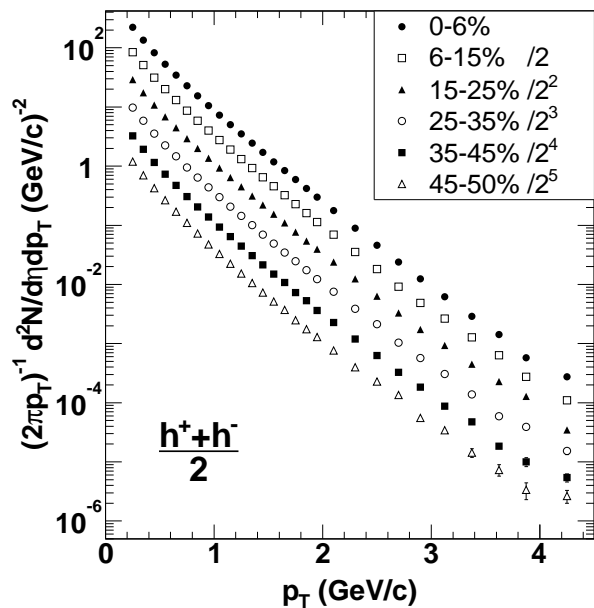


FIG. 1: Invariant yields for charged hadrons from Au+Au collisions at  $\sqrt{s_{NN}}=62.4$  GeV, in the pseudo-rapidity interval  $0.2 < \eta < 1.4$  as a function of  $p_T$  for 6 centrality bins. For clarity, consecutive bins are scaled by factors of 2. The systematic uncertainties are smaller than the symbol size.

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 10 Čerenkov counters, located at  $4.4 < |\eta| < 4.9$ , to select 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 pseudo-rapidities  $3.0 < |\eta| < 4.5$ . The use of this signal as a centrality measure requires that it increases monotonically with the number of participating nucleons,  $\langle N_{part} \rangle$ . This is not the case for collisions at a lower beam energy of 19.6 GeV ( $y_{beam} = 3.0$ ) [14]. We therefore tested the centrality determination at 62.4 GeV ( $y_{beam} = 4.2$ ) using an alternative centrality measure based around mid-rapidity, and found the results to be robust. A full detector simulation using HIJING events [15] was used to estimate  $\langle N_{part} \rangle$  for each centrality class and the corresponding  $\langle N_{coll} \rangle$  values were obtained from a Monte Carlo Glauber calculation [14]. For these calculation, as well as for the determination of  $R_{AA}$  at 62.4 GeV, we used  $\sigma_{pp}^{inel} = 36 \pm 1$  mb [16]. The results are listed in Table I.

The event selection and track reconstruction procedure for this analysis closely follows the previously published

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

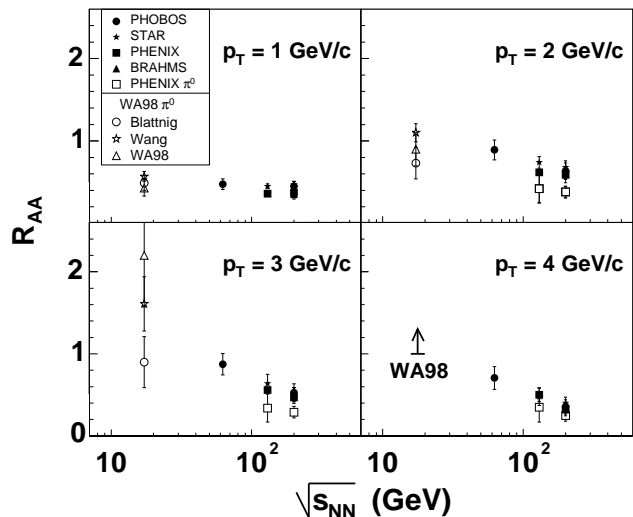


FIG. 2: Nuclear modification factor  $R_{AA}$  for central A+A events, as a function of collision energy for  $p_T = 1, 2, 3$  and  $4$  GeV/c. Filled symbols show data for charged hadrons, open symbols show  $\pi^0$  data. For the WA98  $\pi^0$  data,  $R_{AA}$  is shown using three different parameterizations 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  $R_{AA}$ .

analysis at  $\sqrt{s_{NN}} = 200$  GeV [4]. Events with a primary vertex position within  $\pm 10$  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

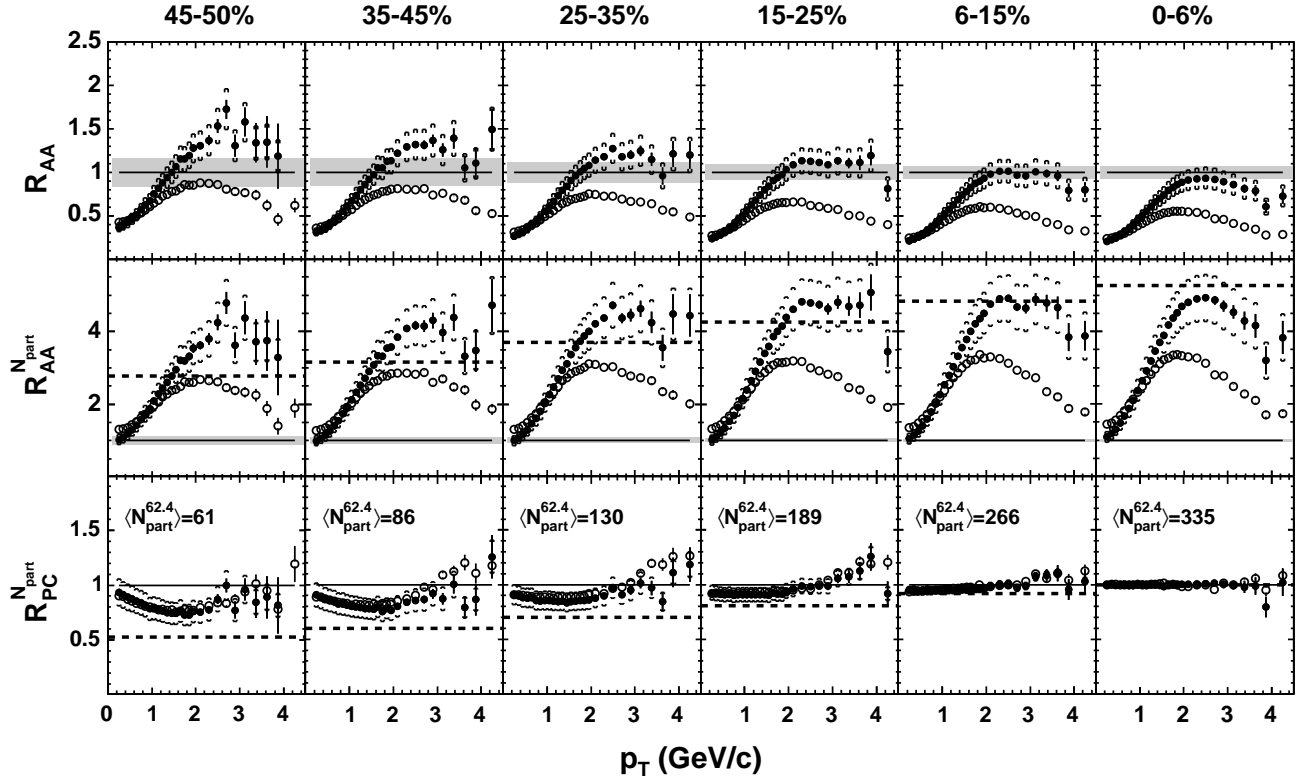


FIG. 3: Ratio of  $p_T$  distributions from Au+Au collisions to various reference distributions at  $\sqrt{s_{NN}} = 62.4$  GeV (filled symbols) and 200 GeV (open symbols). Data are shown in six bins of centrality, ranging from  $\langle N_{part} \rangle = 61$  to 335 for 62.4 GeV collisions. The top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

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 two.

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 pseudo-rapidity interval  $0.2 < \eta < 1.4$ .

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 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  $\pi^0$  production in Pb+Pb collisions at 17.2 GeV from WA98, obtained using three p+p reference parametrizations [10–12], as well as  $\pi^0$  data for 130 GeV and 200 GeV from PHENIX [1, 19]. The data indicate that  $R_{AA}$  for  $\pi^0$  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 pseudo-rapidity density over the same energy range changes by only a factor of two [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 datasets, a significant and systematic decrease in  $R_{AA}$  is observed going from peripheral to central events.

It has been previously 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

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

in analogy to Equation 1, where now we scale the reference spectrum by  $N_{part}/2$ , rather than  $N_{coll}$ . The centrality,  $p_T$  and energy dependence of  $R_{AA}^{N_{part}}$  is shown in the middle row of Fig. 3 for collisions at 62.4 GeV 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.

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

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

is shown as a function of  $p_T$  for the six centrality bins.  $R_{PC}^{N_{part}}$  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 GeV 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 multi-particle 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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