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# HIGH-$p_T$ SPECTRA OF CHARGED HADRONS IN Au + Au COLLISIONS AT $\sqrt{s_{NN}} = 9.2$ GeV IN STAR

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Спектры заряженных адронов при больших $p_T$
в Au + Au-столкновениях при энергии $\sqrt{s_{NN}} = 9{,}2$ ГэВ на установке STAR

Рождение адронов с большими поперечными импульсами в столкновениях тяжелых ионов дает важную информацию о механизме образования частиц и энергетических потерях конституентов в среде. Эта информация необходима для поиска критической точки и сигнатур фазового перехода ядерной материи. В работе сообщаются результаты коллаборации STAR по рождению заряженных адронов в широкой области поперечных импульсов $p_T = 0{,}2$–$4$ ГэВ/$c$ в Au + Au-столкновениях при энергии $\sqrt{s_{NN}} = 9{,}2$ ГэВ в центральной области быстрот. Представлены первые измерения спектров заряженных адронов при больших $p_T$ при этой энергии. Спектры проявляют зависимость от центральности, которая усиливается с ростом поперечного импульса. Получены оценки потерь энергии и ее зависимость от поперечного импульса частицы и центральности соударения в рамках теории $z$-скейлинга.

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Tokarev M. V. (on behalf of the STAR Collaboration) E1-2010-54
High-$p_T$ Spectra of Charged Hadrons
in Au + Au Collisions at $\sqrt{s_{NN}} = 9.2$ GeV in STAR

The production of hadrons in heavy-ion collisions at high $p_T$ provides an important information on mechanism of particle formation and constituent energy loss in medium. Such information is needed for search of a critical point and signatures of phase transition. Measurements by the STAR Collaboration of charged hadron production in Au + Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV over a wide transverse momentum $p_T = 0.2$–$4$ GeV/$c$ and at mid-rapidity range are reported. The first measurements of the spectra of charged hadrons at high $p_T$ at this energy are presented. The spectra demonstrate the dependence on centrality which enhances with $p_T$. The constituent energy loss and its dependence on transverse momentum of particle and centrality of collisions are estimated in the $z$-scaling approach.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energy Physics, JINR.

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## 1. INTRODUCTION

The heavy-ion collisions at RHIC have provided evidence that a new state of nuclear matter exists [1]. This new state is characterized by a suppression of particle production at high $p_T$ [2], a large amount of elliptic flow $(v_2)$, constituent quarks (NCQ) scaling of $v_2$ at intermediate $p_T$ [3] and enhanced correlated yields at large $\Delta\eta$ and $\Delta\phi \simeq 0$ (ridge) [4].

To understand the properties of the system in the framework of the Quantum Chromodynamics (QCD) is one of the main goals of the high-energy heavy-ion collision experiments at RHIC and SPS.

The calculations in lattice QCD (see [5,6] and references therein) indicate that the energy density (3–5 GeV/fm$^3$) and temperature ($T \simeq 170$ K) reached in central $\mathrm{Au}+\mathrm{Au}$ collisions at RHIC are enough to observe signatures (enhancement of multiplicity, transverse momentum and particle ratios fluctuations, long-range correlations, strange-hadron abundances, etc.) of a possible phase transition from hadronic to quark and gluon degrees of freedom. Nevertheless, a clear indication of such a transition has yet to be observed. This has been widely discussed in the literature [7–10]. The principal challenge remains the localization of a critical point on the QCD phase diagram. Near the QCD critical point, several thermodynamic properties of the system such as the heat capacity, compressibility, correlation length are expected to diverge with a power-law behavior in the variable $\epsilon = (T - T_\mathrm{c})/T_\mathrm{c}$, where $T_\mathrm{c}$ is the critical temperature. The rate of the divergence can be described by a set of critical exponents. The critical exponents are universal in the sense that they depend only on degrees of freedom in the theory and their symmetry, but not on other details of the interactions. This scaling postulate is the central concept of the theory of critical phenomena [11].

An important step towards understanding the structure of the QCD phase diagram is systematic analysis of particle production as a function of collision energy, centrality and collision species. Assuming the system is thermalized, temperature $T$ and baryon chemical potential $\mu_B$ can be determined. A search for the location of a possible critical point on the $\{T_c, \mu_c\}$ phase diagram, can be done by varying the beam energy. The proposed Beam Energy Scan (BES) has been tasked to carry out this search [12].

A first test run for Au + Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV made by the RHIC has allowed the STAR Collaboration to obtain the first results on identified particle ($\pi^{\pm}, K^{\pm}, p, \bar{p}$) production, azimuthal anisotropy, interferometry measurements [13], and on high-$p_T$ spectra data of charged hadron production, which are reported in this paper.

## 2. EXPERIMENT AND DATA ANALYSIS

The data presented here are from Au + Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV, recorded by the STAR experiment in a short run conducted at RHIC in 2008. The energy of collided Au ions is less than the injection energy. The data taking period covered about five hours. There are $\simeq 4000$ good events collected at about 0.6 Hz which are used for this analysis. The main detector used to obtain the results on particle spectra is the Time Projection Chamber (TPC) [14]. The TPC is the primary tracking device at STAR and can track up to 4000 charged particles per event. It is 4.2 m long and 4 m in diameter. Its acceptance covers $\pm 1.8$ units of pseudo-rapidity $\eta$ and the full azimuthal angle. The sensitive volume of the TPC contains P10 gas (10% methane, 90% argon) is regulated at 2 mb above atmospheric pressure. The TPC data are used to determine particle trajectories, momenta, and particle-type through ionization energy loss ($dE/dx$). The STAR's solenoidal magnetic field used for this low-energy Au + Au test run was 0.5 T. In the future, the time-of-flight (ToF) detector [15] (with $2\pi$ azimuthal coverage and $|\eta| < 1.0$) will further enhance the PID capability. All events were taken with a minimum bias trigger. The trigger detectors used in these data are the Beam–Beam Counter (BBC) and Vertex Position Detector (VPD) [16]. The BBCs are scintillator annuli mounted around the beam pipe beyond the east and west pole tips of the STAR magnet at about 375 cm from the center of the nominal interaction region (IR), and they cover a range of $3.8 < |\eta| < 5.2$ and a full azimuth ($2\pi$). The VPDs are based on the conventional technology of plastic scintillator read out by photomultiplier tubes. They consist of two identical detector setups very close to the beam pipe, one on each side at a distance of $|V_z| = 5.6$ m from the center of the IR. The details about the design and the other characteristics of the STAR detector can be found in [14].

Centrality selection for Au + Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV is defined using the uncorrected number of charged particle tracks reconstructed in the main TPC over the full azimuth, pseudo-rapidity $|\eta| < 0.5$ and $|V_z| < 75$ cm. Those primary tracks which originate within 3 cm of the primary vertex (distance of the closest approach or DCA) having transverse momentum $p_T > 0.2$ GeV/$c$ were selected for the analysis. The spectra of charged hadrons were corrected for total reconstruction efficiencies obtained by using efficiencies and yields of identified particles ($\pi, K, p, \bar{p}$) [13] from embedding Monte Carlo (MC) tracks into real

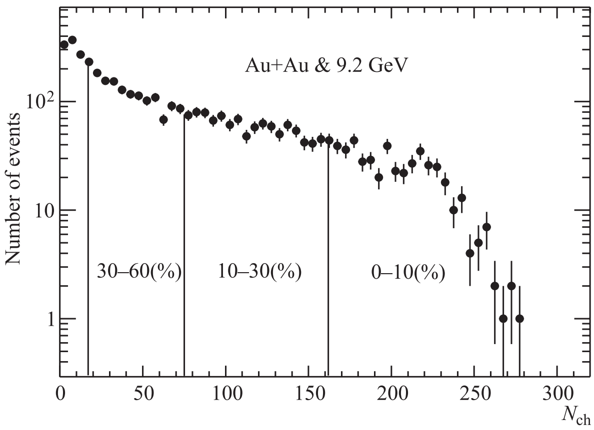


Fig. 1. Uncorrected charged particle multiplicity distribution measured in the TPC within $|\eta| < 0.5$ in Au + Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV. The vertical lines reflect the centrality selection criteria (centrality classes 0–10%, 10–30%, 30–60%) used in the paper [13]. Errors are statistical only

events at the raw data level and subsequently reconstructing these events. The background for identified particles was estimated in [13]. For charged hadrons it was estimated to be about $\sim 10\%$ at low $p_T$ and decreases up to $\sim 2\%$ at higher $p_T$.

Figure 1 shows the uncorrected multiplicity distribution for charged tracks from the real data. The centrality classes 0–10%, 10–30%, 30–60% include 483, 1049, 1391 events with the mean value $\langle N_{\rm ch}\rangle$ of charged tracks $199.7 \pm 1.2, 113.5 \pm 0.8, 41.5 \pm 0.4$, respectively. The results presented in this paper cover the collision centrality range of 0–60%. The results from more peripheral collisions are not presented due to large trigger inefficiencies in this test run, which bias the data in this region [13].

## 3. RESULTS AND DISCUSSION

**3.1. Spectra.** The transverse momentum spectrum of hadrons produced in high-energy collisions of heavy ions reflects features of constituent interactions in the nuclear medium. The medium modification is one of the effects (recombination, coalescence, energy loss, multiple scattering, etc.) that influences on the shape of the spectrum. The properties of the created medium are experimentally studied by variation of the event centrality and collision energy.

Figure 2 shows the charged hadron yields in Au + Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV and mid-rapidity $|\eta| < 0.5$ as a function of transverse momentum $p_T$.

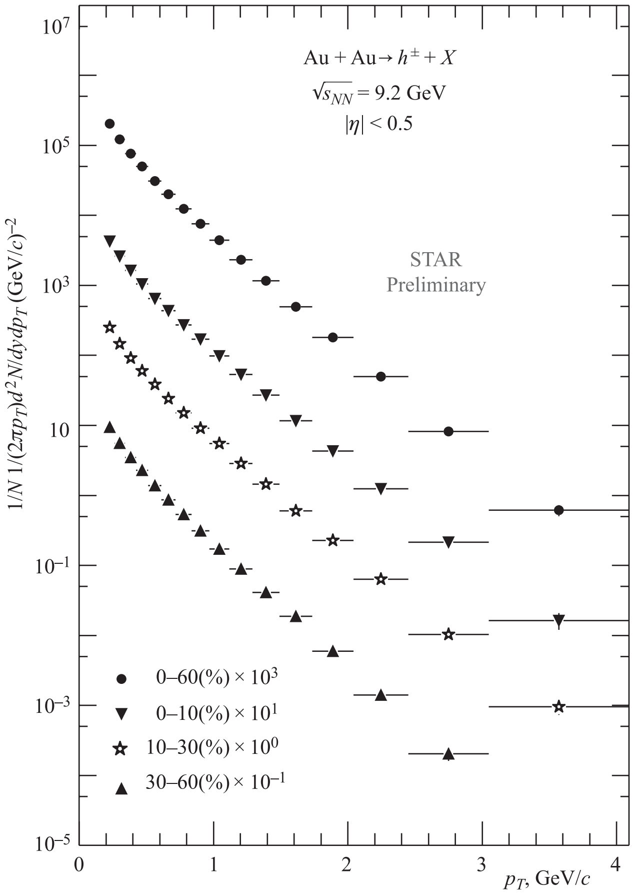


Fig. 2. Mid-rapidity ($|\eta| < 0.5$) transverse momentum spectra for charged hadrons produced in Au + Au collisions and energy $\sqrt{s_{NN}} = 9.2$ GeV for various (0–10%, 10–30%, 30–60%, and 0–60%) centralities. The errors shown are statistical only

The results are shown for the collision centrality classes of 0–10%, 10–30%, 30–60%, and 0–60%. The distributions are measured in the momentum range $0.2 < p_T < 4$. GeV/$c$. The multiplied factor of 10 is used for visibility. As seen from Fig. 2, the spectra fall more than four orders of magnitude. The shape of the spectra indicates the exponential and power-law behavior at $0.2 < p_T < 1$ GeV/$c$ and $p_T > 1$ GeV/$c$, respectively.

The centrality dependence of transverse momentum $\langle p_T \rangle$ is of interest, as for a thermodynamic system this quantity correlates with the temperature of the system, whereas $dN/d\eta \propto \ln(\sqrt{s_{NN}})$ has relevance to its entropy [17]. The mean

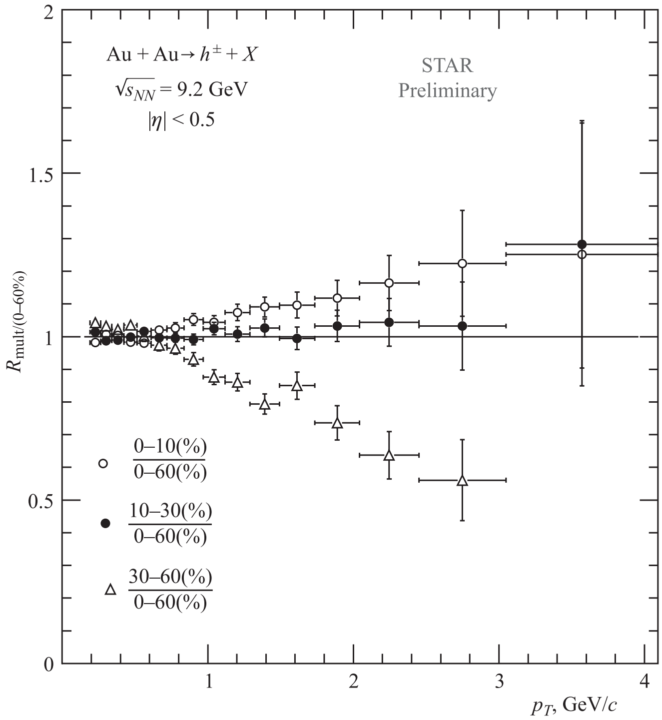


Fig. 3. The $R_{\rm mult/(0-60\%)}$ ratio of charged hadron yields in Au + Au collisions at midrapidity ($|\eta| < 0.5$) and energy $\sqrt{s_{NN}} = 9.2$ GeV for various (0–10%, 10–30%, 30–60%, 0–60%) centralities as a function of transverse momentum. The errors shown are statistical only

values of the transverse momentum $\langle p_T \rangle$ for the centrality classes 0–10%, 10–30%, 30–60%, and 0–60% are found to be $553.1 \pm 1.2$ MeV/$c$, $545.4 \pm 1.1$ MeV/$c$, $522.4 \pm 1.4$ MeV/$c$, and $543.9 \pm 0.7$ MeV/$c$, respectively. The value of $\langle p_T \rangle$ slowly increases with centrality. Similar behavior is observed for pions at $\sqrt{s_{NN}} = 9.2$ and 200 GeV [13]. Rapid growth of $\langle p_T \rangle$ vs. $dN_{\rm ch}/d\eta$ could be associated with enhancement of multiparticle interactions in the medium.

**3.2. The $R_{\rm mult/(0-60\%)}$ and $R_{\rm CP}$ Ratios.** The ratio of transverse momentum yields for different centralities allows us to study features of constituent interactions in the medium depending on the scale. Strong sensitivity of the ratio $R_{\rm mult/minbias}$ ($\simeq 0.1$ and 3 for $dN_{\rm ch}/d\eta = 1.97$ and $9.01$) at $p_T \simeq 4$ GeV/$c$ was observed even in $p + p$ collisions for strange particle ($K^0_S$, $\Lambda$) production [18].

Figure 3 shows the $R_{\rm mult/(0-60\%)}$ ratio of multiplicity binned $p_T$ spectra to multiplicity-integrated (0–60%) spectra scaled by the mean multiplicity in each bin for charged hadrons

$$R_{\mathrm{mult}/(0-60\%)} = F_{\mathrm{scale}} \frac{d^2 N^{\mathrm{mult}}/2\pi\, p_T\, dy\, dp_T}{d^2 N^{0-60\%}/2\pi\, p_T\, dy\, dp_T}, \tag{1}$$

where the factor $F_{\mathrm{scale}}$ is defined as follows:

$$F_{\mathrm{scale}} = \frac{N_{\mathrm{event}}^{0-60\%} \langle N_{\mathrm{ch}}^{0-60\%} \rangle}{N_{\mathrm{event}}^{\mathrm{mult}} \langle N_{\mathrm{ch}}^{\mathrm{mult}} \rangle}. \tag{2}$$

As seen from Fig. 3, the ratio is sensitive to centrality for high $p_T$. It increases from 0.6 to 1.2 at $p_T \simeq 3$ GeV/$c$ for low and high centralities, respectively.

Figure 4 shows the dependence of the $R_{\mathrm{CP}}$ ratio of yields for the central (C) 0–10% and the peripheral (P) 30–60% multiplicity classes on the transverse momentum

$$R_{\mathrm{CP}} = \frac{d^2 N^{\mathrm{C}}/2\pi\, p_T\, dy\, dp_T / \langle N_{\mathrm{bin}}^{\mathrm{C}} \rangle}{d^2 N^{\mathrm{P}}/2\pi\, p_T\, dy\, dp_T / \langle N_{\mathrm{bin}}^{\mathrm{P}} \rangle}. \tag{3}$$

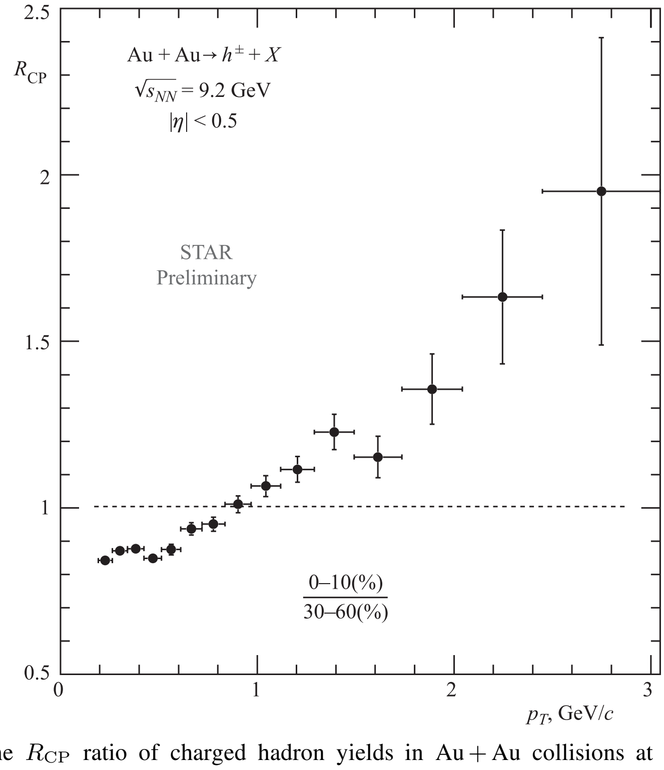


Fig. 4. The $R_{\mathrm{CP}}$ ratio of charged hadron yields in Au + Au collisions at mid-rapidity ($|\eta| < 0.5$) and energy $\sqrt{s_{NN}} = 9.2$ GeV as a function of transverse momentum. The errors shown are statistical only

The errors shown for data are the quadrature sum of statistical uncertainties. The ratio increases with transverse momentum. The similar trend is observed in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV for $p_T < 1.5$ GeV/$c$ even though the centrality classes used for definition of $R_{\mathrm{CP}}$ are different [20]. For $p_T > 1$ GeV/$c$ the ratio is higher than unity, while the $R_{\mathrm{CP}}$ at 200 GeV never goes above unity, it decreases for $p_T > 1.5$ GeV/$c$ and becomes approximately constant for $5 < p_T < 12$ GeV/$c$.

**3.3. Constituent Energy Loss.** The energy loss of particles created in heavy-ion collisions characterizes the properties of nuclear medium. The nuclear modification factor $R_{AA}$ measured at RHIC at $\sqrt{s_{NN}} = 62.4$, 130 and 200 GeV strongly shows a suppression of the charged hadron spectra at $p_T > 4$ GeV/$c$ [21–23]. These results are widely theoretically discussed (see [19, 20] and references therein).

The nuclear modification factor $R_{\mathrm{AuAu}}$ for peripheral collisions at $\sqrt{s_{NN}} = 200$ GeV is close to unity at $p_T > 4$ GeV/$c$, while for central collisions a suppression of up to a factor of 5 is observed. This suppression was one of the first indications of a strong final state modification of particle production in Au + Au collisions that is now generally ascribed to energy loss of the fragmenting parton in the hot and dense medium. The study of the evolution of the energy loss with collision energy has relevance to the evolution of created nuclear matter, and can be useful for searching for signature of phase transition and a critical point [24].

The measured spectra (see Fig. 2) allow us to estimate constituent energy loss in charged hadron production in Au + Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV and compare it to the values obtained from Au + Au collisions with $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. The estimations are based on a microscopic scenario of particle production proposed in [24]. The approach relies on a hypothesis about self-similarity of hadron interactions at a constituent level. The assumption of self-similarity transforms to the requirement of simultaneous description of transverse momentum spectra corresponding to different collision energies, rapidities, and centralities by the same scaling function $\psi(z)$ depending on a single variable $z$. The scaling function is expressed in terms of the experimentally measured inclusive invariant cross section, the multiplicity density, and the total inelastic cross section. It is interpreted as a probability density to produce an inclusive particle with the corresponding value of $z$. The scaling variable $z$ is expressed via momentum fractions $(x_1, x_2, y_a)$, multiplicity density, and three parameters $(\delta, \epsilon, c)$. The constituents of the incoming nuclei carry $x_1, x_2$ fractions of their momenta. The inclusive particle carries the momentum fraction $y_a$ of the scattered constituent. The parameters $\delta$ and $\epsilon$ describe structure of the colliding nuclei and fragmentation process, respectively. The parameter $c$ is interpreted as «specific heat» of the created medium. Simultaneous description of different spectra with the same $\psi(z)$ puts strong constraints on the values of these parameters, and thus allows for their determination. It was found that $\delta$ and $c$ are constant and $\epsilon$ depends on multiplicity. For the obtained values of $\delta, \epsilon$ and $c$, the momentum fractions are determined to minimize the resolution $\Omega^{-1}(x_1, x_2, y_a, y_b)$, which enters in the definition of the variable $z$. The system of the equations $\partial\Omega/\partial x_1 = \partial\Omega/\partial x_2 = \partial\Omega/\partial y_a = \partial\Omega/\partial y_b = 0$ was numerically resolved under the constraint $(x_1P_1 + x_2P_2 - p/y_a)^2 = (x_1M_1 + x_2M_2 + m/y_b)^2$, which has sense of the momentum conservation law of a constituent subprocess [24].

The scaling behavior of $\psi(z)$ for charged hadrons in Au + Au collisions at $\sqrt{s_{NN}} = 200$ and 9.2 GeV is consistent with $\delta = 0.5$ and 0.1, respectively. The parameter $c$ was found to be 0.11. This value is less than one (0.25) determined from $pp$ data [24]. In this approach the energy loss of the scattered constituent during its fragmentation in the inclusive particle is proportional to the value $(1 - y_a)$.

Figure 5 shows the dependence of the fraction $y_a$ on the centrality of Au + Au collision and transverse momentum at $\sqrt{s_{NN}} = 9.2$ and 200 GeV. The behavior of $y_a$ demonstrates a monotonic growth with $p_T$. It means that the energy loss associated with the production of a high-$p_T$ hadron is smaller than for hadron with lower transverse momenta. The decrease of $y_a$ with centrality collision represents larger energy loss in the central collisions as compared with peripheral

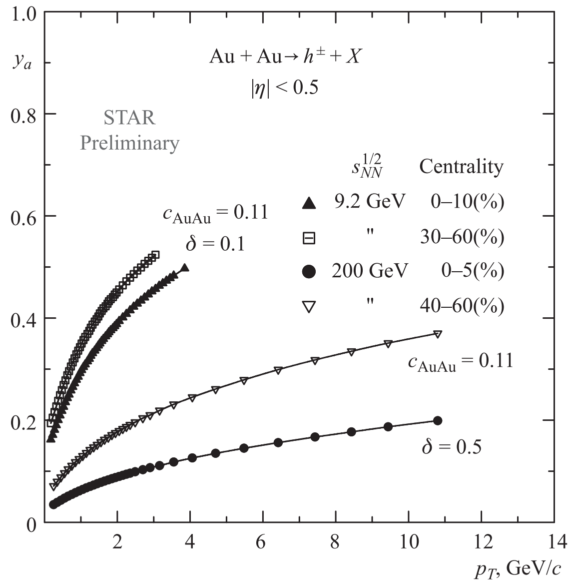


Fig. 5. The momentum fraction $y_a$ for charged hadron production in Au + Au collisions at mid-rapidity ($|\eta| < 0.5$) as a function of the energy, centrality collision and hadron transverse momentum

interactions. The energy dissipation grows as the collision energy increases. It is estimated to be about 50% at $\sqrt{s_{NN}} = 9.2$ GeV and 80–90% at $\sqrt{s_{NN}} = 200$ GeV for $p_T \simeq 3$ GeV/$c$, respectively.

The saturation of hadron production established in [24] at low $z$ (low $p_T$) is governed by the single parameter $c$. The value of $c$ was found to be constant in Au + Au collisions at $\sqrt{s_{NN}} = 9.2$, 62.4, 130, and 200 GeV. Discontinuity of this parameter was assumed to be a signature of phase transition and a critical point.

## 4. SUMMARY AND OUTLOOK

In summary, we have presented the first STAR results for charged hadron production in Au + Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV. The spectra and ratios of particle yields at mid-rapidity are measured over the range of $0.2 < p_T < 4$ GeV/$c$. The centrality dependence of the hadron yields and ratios are studied. We observed that the sensitivity of the ratios $R_{\mathrm{mult}/(0-60\%)}$ and $R_{\mathrm{CP}}$ to centrality is enhanced at high $p_T$. Hadron yields can be used to estimate a constituent energy loss. The energy loss of the secondary constituents passing through the medium created in the Au + Au collisions was estimated in the $z$-scaling approach. It depends on the collision energy, transverse momentum, and centrality. It is shown that the energy loss increases with the collision energy and centrality, and decreases with increasing $p_T$.

These results provide an additional motivation for the Beam Energy Scan (BES) program at the RHIC [12]. In the STAR experiment, the large and uniform acceptance and extended particle identification (TPC, ToF) is suitable for a critical point search at low energy $\sqrt{s_{NN}} = 5$–39 GeV. The study of the transition regime is of interest with respect to a possible modification of the number constituent quark $v_2$-scaling, high-$p_T$ hadron suppression, and the ridge formation, which take place in Au + Au collisions at higher energy at the RHIC.

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