Inverse Slope Systematics in High-Energy p+p and Au+Au Reactions

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We employ the Monte-Carlo PYTHIA to calculate the transverse mass spectra of various hadrons and their inverse slopes $T^*$ at $m_T - m = 1.5 - 2$ GeV in p+p reactions at $\sqrt{s} = 200$ GeV. Due to (multiple) minijet production $T^*$ in general increases as a function of the hadron mass. Moreover, the $T^*(m)$ systematics has a “discontinuity” at the charm threshold, i.e. the inverse slope of $D$-mesons is much higher than that of non-charmed hadrons and even of the heavier $\Lambda_C$ baryon. The experimental observation of this characteristic behaviour in Au+Au collisions would indicate the absence of c-quark rescattering. In contrast, the assumption of thermalized partons and hydrodynamical evolution would lead to a smoothly increasing $T^*(m)$, without discontinuity at the charm threshold. The degree of collective transverse flow, indicated by the slope of the $T^*(m)$ systematics, depends strongly on whether kinetic equilibrium is maintained for some time after hadronization or not.

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Experimental data on single-inclusive hadron production in p+p reactions at $\sqrt{s} = 23 - 63$ GeV show nearly exponential transverse mass spectra at low transverse momentum $[1]$. Moreover, the inverse slopes (“apparent temperatures”) are practically the same for pions, kaons, protons and their antiparticles, i.e. they do not depend on the hadron mass. The observed deviation from this behaviour in nucleus-nucleus collisions has been interpreted as a signature for collective transverse flow $[2]$.

In this letter, we discuss how the inverse slope systematics extends to higher energies, i.e. p+p reactions at $\sqrt{s} = 200$ GeV, and transverse momenta on the order of a few GeV. In this kinematic domain, minijet production and fragmentation gives an important contribution.

We shall also discuss Au+Au collisions, where minijets might rescatter substantially. This, in turn, should reflect in a characteristic mass dependence of the inverse slopes. We will confront the predictions of two extreme scenarios: superposition of minijet production (and fragmentation) without final-state interactions (as in p+p reactions) versus local thermalization of parton matter undergoing hydrodynamical expansion.

In p+p reactions at $\sqrt{s} = 200$ GeV, we expect that the hadrons with transverse masses on the order of a few GeV are dominantly produced via fragmentation of minijets. As a first step, we estimate the transverse momentum distribution of $c$-quarks at midrapidity employing the well-known expression for inclusive single-jet production within perturbative QCD (pQCD) in leading-logarithm approximation (LLA) $[3]$,

$$E \frac{d^3 \sigma}{d^3 p} (pp \to c\bar{c} + X) = \int dx_a dx_b G \left( x_a, \mu^2 \right) G \left( x_b, \mu^2 \right) \frac{\hat{s}}{\hat{t} \hat{u}} \frac{d\sigma^{gg \to c\bar{c}}}{dt} \delta \left( \hat{s} + \hat{t} + \hat{u} - 2m_c^2 \right). \quad (1)$$

$\hat{s}$, $\hat{t}$, $\hat{u}$ are the usual Mandelstam variables of the parton-parton scattering subprocess, and $d\sigma^{ab \to cd}/dt$ denotes its differential cross section in lowest order of perturbative QCD. For simplicity, we take into account only the contribution from the $gg \to q\bar{q}$ process. This is
sufficient to illustrate our point.

The expression for $d\sigma/dt$ that accounts for the finite quark-mass is rather lengthy and can be found in the literature, cf. e.g. [4]. We therefore omit it here. We assume $m_c = 1.5$ GeV, $\Lambda_{\text{QCD}} = 300$ MeV, and evaluate the strong coupling constant at the momentum transfer scale given by the transverse mass of the produced quark, $Q^2 = m_T^2 = m_c^2 + p_T^2$.

$G(x, \mu^2)$ denotes the LO gluon distribution function in the proton, which we take from ref. [6]. Since we work only in LLA, we employ the same momentum scale in the parton distribution functions as in the strong coupling constant, i.e. $\mu^2 \equiv Q^2$.

In principle, the hadron spectra could be calculated by convoluting the expression for jet production with fragmentation functions [3]. However, for transverse masses of a few GeV such an analysis would at best be qualitative since, e.g., multi jet production and initial state radiation are not included. Also, in this domain the fragmentation functions suffer from logarithmic infrared divergences which have to be regulated by a model for soft particle production.

Therefore, to calculate the hadron transverse mass spectra we rather employ the PYTHIA event generator [7], using the default parameter settings (version 6.115). PYTHIA simulates high energy hadronic and leptonic interactions by implementing a large number of hard and soft (sub-)processes, and in particular, a scheme for the nonperturbative hadronization mechanism. The model goes significantly beyond pQCD in LLA. It describes not only single-inclusive minijet production but also includes multi-jet production and initial state radiation. PYTHIA is designed to model the complete event structure (like jet profiles, multiplicity fluctuations, various types of correlations etc.) and it has been shown to agree reasonably well with experimental observations at collider energies [8].

The Lund string scheme [9] is an integral part of the model used to describe the fragmen-
tation of (mini-)jets. They are modeled as one dimensional color flux tubes which decay into hadrons: quark-antiquark pairs tunnel in the color field and the field energy is transformed into the sum of the transverse masses $m_{T}$. 

The tunnel probability is proportional to $\exp(-\pi m_{T}^{2}/\kappa)$, where $\kappa$ is the string tension. Thus, the creation of quarks with high transverse momentum is heavily suppressed. As a consequence, also the produced hadrons cannot acquire large values of $m_{T}$. The above formula also leads to a strong suppression of heavy quarks. The probability for producing a light quark as compared to a charm quark is about $1 : 10^{-11}$. The energy $E$ and the longitudinal momentum $p_z$ of the produced hadrons are determined by an iterative scheme: for each hadron the fragmentation function $f(z)$ determines the probability that the hadron picks a fraction $z$ out of the available $E + p_z$. The default fragmentation function used in PYTHIA reads $f(z) \sim z^{-1}(1 - z)^{0.3} \exp(-0.58 \text{GeV}^{-2} m_{T}^{2}/z)$.

The Lund string model has been shown to successfully describe the nonperturbative hadronization in $e^+e^-$ annihilation events. Moreover, the concept of a color flux tube, fragmenting according to a universal fragmentation scheme, has been carried over to hadron-hadron interactions. The microscopic models FRITIOF, RQMD, and UrQMD utilize string fragmentation routines for the simulation of soft particle production in $p+p$, $p+A$ and $A+A$ reactions. The only difference to strings from $e^+e^-$ annihilation are the leading valence (di-)quarks — the remnants of the incident hadrons — as string end-points. The excitation of the strings is due to single or double diffractive interactions which can be understood and parametrized in the framework of Regge theory (see e.g. [11]). These nonperturbative

\footnote{Note that 'transverse' is defined with respect to the string axis. Nothing is said here about the orientation of the string with respect to the beam axis.}
processes account for the major part of the total cross sections at CERN-SPS energies or higher, $\sqrt{s} > 20$ GeV. Strings which are excited in these processes are preferentially oriented along the beam axis of the incident hadrons, leading to much higher typical longitudinal than transverse momenta of produced hadrons.

![Transverse mass spectra](image)

**FIG. 1.** Transverse mass spectra (at midrapidity, $y = 0$) of various hadrons in p+p reactions at $\sqrt{s} = 200$ GeV, as calculated with PYTHIA 6.115. The spectra of the individual hadron species include all isospin projections and charge conjugated states. The c-quark spectrum (without $\bar{c}$-quarks) is calculated within pQCD in LLA.

In the kinematic region where perturbative minijet production becomes important, the color flux tubes may no longer be oriented longitudinally, but according to the pQCD subprocess that produces the minijets acquire significant transverse momentum. In the frame where the $z$-axis is parallel to the flux tube, the hadrons are still produced according to the above fragmentation function. However, the string axis and the particles’ momenta are now
rotated with respect to the lab frame.

Figure \[\text{Figure 1}\] depicts the resulting transverse mass spectra. One observes that the PYTHIA-spectra follow nonexponential distributions, remnant of the perturbative QCD processes that describe the minijet production. Also, the “stiffness” of the spectra increases with the mass of the hadron. This will be discussed in more detail below. In particular, the slope of the $D$-meson spectrum equals that of the $c$-quarks, which are produced purely by perturbative parton-parton scattering\[\text{2}\]. The reason is that $D$-mesons can only be produced as the leading hadron from a $c/\bar{c}$ quark jet since the tunneling probability of a $c-\bar{c}$ pair in a color flux tube is practically zero (as discussed above). The $m_T$-distribution of $\Lambda_C$-baryons, on the other hand, is slightly “softer” since it involves tunneling of a diquark-antidiquark pair out of the vacuum (besides the perturbative production of a $c$-quark).

In Fig. \[\text{Figure 2}\], we show the inverse slopes as a function of hadron mass. We compute the inverse slope by a fit of the transverse mass spectrum to a Boltzmann distribution,

$$\frac{1}{m_T^2} \frac{d^2N}{dm_Tdy} \propto \exp\left(-\frac{m_T}{T^*}\right),$$

We restrict the fit to the range $m_T - m \in [1.5, 2]$ GeV.

As already mentioned in the introduction, in $p+p$ reactions at lower energies, the apparent temperatures at small $p_T$ were found to be about the same for pions, kaons, protons and their antiparticles \[\text{1,2}\]. This changes at higher $p_T$ and $\sqrt{s}$ due to the contribution from minijets.

\[\text{2}\] To obtain the number distribution of $c$-quarks we have simply divided the differential cross section, eq. \[\text{(1)}\], by 40 mb. If we multiplied by two (to include also $\bar{c}$-quarks) the quark and $D$-meson spectra would coincide.
FIG. 2. Inverse slopes (at midrapidity, $y = 0$) as a function of hadron mass; PYTHIA 6.115 predictions for p+p at $\sqrt{s} = 200$ GeV, and results from hydrodynamics of p+p and Au+Au (calculated on the boundary between mixed and hadronic phase and on the $T = 130$ MeV isotherm, respectively).

The single inclusive cross section at midrapidity and $m_T - m \geq 1$ GeV is dominated by color flux tubes that are no longer oriented longitudinally, but have significant transverse momentum (due to the pQCD subprocess). This leads to much higher $m_T$ than in case of longitudinally oriented strings. Moreover, the inverse slopes of the $m_T - m$ distributions in the lab frame are strongly $m$-dependent. Such an increase of the inverse slope with particle mass can also be extracted from p + p collider experiments [12] at $\sqrt{s} = 540$ GeV, and from the parametrization of the $p_T$-distributions given in ref. [13]. Although that parametrization was restricted to the energy region $\sqrt{s} < 63$ GeV, it yields slopes for the pi-, phi-, and D-mesons that agree with those obtained from PYTHIA to within 20%, if one simply extrapolates it.
to $\sqrt{s} = 200$ GeV.

The qualitative reason for this behaviour can be traced back to $e^+e^-$ annihilation processes which can be modeled as the fragmentation of a string with fixed energy. The observed kinetic energy distribution of produced hadrons show a considerably harder spectrum for kaons and protons than for pions [14].

Thinking of the initial state in A+A collisions as a superposition of p+p reactions one could attribute any change of the particle slopes to final state interactions. The multiple soft $p_T$-kicks that a projectile nucleon can experience while propagating through the target, i.e. the Cronin effect, has been shown to be small for pions produced in Au+Au at $\sqrt{s} = 200A$ GeV [15]. However, this does not automatically hold true for heavier hadrons. Since we have not made any attempt to include such multiple scattering effects, nor modifications of the parton distribution functions in nuclei, we restrict the application of the minijet/string fragmentation model to p+p reactions.

In ultrarelativistic head-on collisions of heavy nuclei ($A \sim 200$), the situation might, however, be very different as compared to the p+p case. Transport calculations [16] suggest that the initially directed momenta of the partons could be quickly redistributed through rescattering. This would then lead to the formation of a very hot ($T \approx 300$ GeV) vacuum of “macroscopic” size (volume $\sim 100$ fm$^3$), offering the opportunity to study hot QCD.

Indeed, if minijets with transverse masses of a few GeV thermalize quickly, energy densities in excess of 10 GeV/fm$^3$ can be reached [16] (for Au+Au at $\sqrt{s} = 200A$ GeV). This energy density is much higher than in p+p since the contribution due to minijets increases as $A^{2/3}$ [17].

For definiteness we consider Au+Au collisions at $\sqrt{s} = 200A$ GeV that will be studied at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven in the near future. As the extreme
case we assume that the produced minijets rescatter so frequently that they thermalize locally. The subsequent evolution is then described within hydrodynamics.

The pQCD processes that produce the minijets in the central region occur on a time scale of \(1/m_T \simeq 0.1 \text{ fm}\). We assume that one to two rescatterings per particle are necessary for local thermalization, and take \(\tau_0 = 0.6 \text{ fm}\). This seems also reasonable in view of the fact that with \(\tau_0 = 1 \text{ fm}\) one is able to reproduce the measured single particle spectra for central Pb+Pb reactions at \(\sqrt{s} = 18A\ \text{GeV}\), cf. e.g. [18]. At the higher center of mass energy of RHIC, the parton density in the central region increases, and therefore a smaller thermalization time is expected, cf. also [16,19].

As initial conditions we assume a net baryon rapidity density of \(dN_B/dy = 25\), and an energy density of \(\epsilon_0 = 17 \text{ GeV/fm}^3\). Employing the formula of Bjorken [20], \(\epsilon_0 \tau_0 \pi R_T^2 = dE_T(\tau_0)/dy\), with a nuclear radius of \(R_T = 6 \text{ fm}\), we obtain an initial transverse energy at midrapidity of \(dE_T/dy = 1.2 \text{ TeV}\). We have extracted this value for \(dE_T/dy\) for central \((b < 2 \text{ fm})\) Au+Au collisions at \(\sqrt{s} = 200A\ \text{GeV}\) from the minijet/string fragmentation model FRITIOF 7.02 [21]. It is also compatible with the prediction of HIJING [22]. Note that for an isentropic hydrodynamical expansion \(dE_T/dy\) decreases with time. On the hadronization hypersurface, we obtain \(dE_T/dy = 640 \text{ GeV}\) [18].

The initial (net) baryon density at midrapidity, \(\rho_0\), is given by a similar expression as \(\epsilon_0\) above, except that \(dE_T/dy\) is replaced by \(dN_B/dy\). These densities are (initially) assumed to be distributed in the transverse plane according to a so-called “wounded nucleon” distribution, \(\epsilon(\tau_i) = \epsilon_0 f(r_T), \rho(\tau_i) = \rho_0 f(r_T)\), with \(f(r_T) = \frac{3}{2} \sqrt{1 - r_T^2/R_T^2}\).

In order to respect boost-invariance, we require the longitudinal flow to have a “scaling flow” profile, \(v_z = z/t\) [20,23]. Cylindrically symmetric transverse expansion [18,24,25] is superimposed. For \(T > T_C = 160 \text{ MeV}\) we employ the well-known MIT bagmodel equation
of state, \( p = (\epsilon - 4B)/3 \), where \( p \) denotes the pressure and \( B \) the energy density of the QGP at \( T = 0 \) and vanishing net baryon charge. For simplicity we assume an ideal gas of quarks, antiquarks (with masses \( m_u = m_d = 0, m_s = 150 \text{ MeV} \)), and gluons.

For \( T < T_C \) we assume an ideal hadron gas that includes the complete hadronic spectrum up to a mass of 2 GeV. At \( T = T_C \) we require that both pressures are equal, which fixes the bag constant to \( B = 380 \text{ MeV/fm}^3 \). The normalization is such that for \( T \to 0 \) the pressure of the nonperturbative vacuum (i.e. that of the hadronic phase) vanishes. By construction the EoS exhibits a first-order phase transition. This “softening” of the EoS in the transition region strongly reduces the tendency of matter to expand on account of its pressure [25,26].

For a more detailed discussion of the initial conditions and expansion dynamics in Au+Au at RHIC energy please refer to ref. [18].

For comparison, we have also extracted the inverse slopes from hydrodynamics in p+p at \( \sqrt{s} = 200 \text{ GeV} \). In this case, we employ \( R_T = 1.18 \text{ fm}, f(r_T) = \Theta(R_T - r_T), dN_B/dy = 0, dE_T/dy = 2.8 \text{ GeV} \) (as obtained from PYTHIA), and (for simplicity) the same \( \tau_0 \) as for Au+Au.

In Fig. 2 we compare the PYTHIA predictions for p+p with those of hydrodynamics of p+p and Au+Au. Within the hydrodynamical solution for Au+Au, strong collective flow of quark-gluon matter\(^3\) Doppler-shifts \( T^* \) far above the real emission temperature \( T_C \). If kinetic equilibrium in the hot hadron gas is maintained for some time after hadronization (say, until the temperature drops to 130 MeV), the collective transverse flow can increase even further, and \( T^* \sim 400 \text{ MeV} \) can be reached for the charmed hadrons (cf. open squares in fig. 2).

\(^3\)The average flow velocity on the phase boundary to purely hadronic matter is approximately one third of the velocity of light [18].
Hadrons produced in the expanding QGP can thus reach comparably “stiff” $m_T$-spectra as those produced in p+p via minijets.

One also observes that in hydrodynamics $T^*$ is nearly proportional to $m$. In particular, there is no jump in $T^*$ at the charm threshold and the inverse slope of the $\Lambda_C$ is larger than that of the $D$, unlike in the minijet/string fragmentation model. In a thermal environment (without interactions), the mass is the only hadron-specific quantity that enters its momentum distribution. Thus, if the perturbatively produced $c-\bar{c}$ pairs equilibrate with the QGP, the inverse slope of the $D$-mesons is significantly smaller than in p+p reactions at the same energy per nucleon (cf. also the discussion of $\langle p_T \rangle_D$ in refs. [18,27], and [28] for the effect of $c$-quark energy loss on lepton radiation in ultrarelativistic heavy-ion collisions).

In p+p reactions, on the other hand, the initial energy density $\epsilon_0 = 1.1$ GeV/fm$^3$ is much smaller than in Au+Au. In fact, for our choice of initial conditions the initial state is not in the pure QGP phase but in the phase coexistence region. Consequently, on the hadronization hypersurface there is practically no collective transverse flow, and the inverse slopes of the various hadrons are similar, and equal to the real emission temperature $T = T_C$. If freeze-out occurs deeper in the hadronic phase, e.g. on the $T = 130$ MeV isotherm, a small flow is created due to rescattering in the purely hadronic phase. The pressure in p+p reactions at $\sqrt{s}$ of a few hundred GeV can not exceed that of the nonperturbative vacuum by far, and we thus find no significant transverse expansion [29]. Therefore, in contrast to the minijet/string fragmentation model hydrodynamics can not reproduce the experimentally observed [12] bending of the $m_T$ distributions and the increase of $T^*$ with $m$.

In summary, we have shown that in p+p reactions at high energy the inverse slopes $T^*$ of the transverse mass spectra (at midrapidity and $m_T - m$ of a few GeV) of various hadrons are correlated to their mass. This is due to the underlying pQCD subprocess (i.e. minijet
production) that produces fragmenting color strings that are not parallel to the beam axis. $T^*(m)$ shows a very strong increase at the charm threshold, i.e. the inverse slope of the $D$-mesons is much higher than that of the $\Omega$-baryons.

If a dense QGP is created in central Au+Au collisions, in which $u$, $d$, $s$, and $c$-quarks, and the gluons (up to a few GeV of $p_T$) equilibrate kinetically, the inverse slope of the $D$-mesons decreases substantially as compared to the p+p case, and that of the $\Omega$-baryons increases. Collective transverse flow of such a hypothetical quark-gluon fluid would establish a nearly linear relationship between the inverse slopes and the hadron masses. Thus, the $T^*(m)$ systematics at $m_T - m \simeq 1 - 3$ GeV provides an opportunity to experimentally determine the degree of heavy quark rescattering and equilibration in relativistic heavy ion collisions.

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