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An effective model of the quark-gluon plasma with thermal parton masses

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Abstract: A model is presented which reproduces the pure SU(3) gauge theory on the lattice for thermodynamical quantities. It exploits only thermal quark and gluon masses $m(T) \propto g(T)\, T$ and no other interaction or bag constant. The latent heat at confinement temperature is much smaller compared with the bag model parametrization; this modifies drastically the cooling velocity of the quark-gluon plasma and the duration of the deconfinement phase. The effective thermal quark masses lead to a kinematical threshold and violate the M_T scaling of the transverse dilepton spectrum from the plasma.

1 Introduction: Recent "numerical experiments" provide thermodynamical quantities of pure SU(3) gauge theory in lattice approximation [1]. These data, corrected at least partially for finite lattice effects, are thermodynamically selfconsistent [2], i.e., energy density and pressure are related via $e = T\partial p/\partial T - p$, and exhibit a striking difference from the popular bag model parametrization $p = e/3 - 4B/3$ (which would imply for the energy density and the pressure $e, p \propto T^4$). In the available temperature range $T/T_c = 1 - 2.2$ the data [1] obey $e/e_{SB} < 1$ (the bag model would yield $e/e_{SB} > 1$; the subscript SB means Stefan-Boltzmann). Only for $T/T_c > 1.4$ one can fit the data [1] by a bag model-like parametrization $p = ae - 4B/3$ with $a = 0.297$ (not 1/3 as for the bag model!) and $B^{1/4} = 205$ MeV [3].

In Ref. [2] the data [1] were interpreted within an effective model with low momentum cut-off employing bag constant and first order perturbative corrections. Here we follow a conceptionally different interpretation [4] of the data [1] by a non-interacting quasi-particle description with only thermal masses $m(T) \propto g(T)T$ (g is the first-order strong coupling constant). Temperature dependent parton masses have been previously extracted from SU(2) lattice gauge data [5], while in Ref. [6] one describes the lattice data by a bag constant and finite but constant quark masses. We extrapolate our approach to the quark-gluon plasma and derive a model equation of state which has a smaller latent heat at confinement in comparison with the bag model. Our model describes available lattice data which incorporate also quarks, despite the fact that they do not seem to reflect the same reliability as the corresponding data for a pure gluon gas.

Finite effective quark and gluon masses have distinct observable consequences, such as the modification of the strangeness production rates [6, 7] or the violation of the M_T scaling of dilepton rates [8]. Here we study selfconsistently their impact on the cooling of a quark-gluon plasma and the transverse-mass dependence of the dilepton yield.

2 The gluon gas: Our first aim is to reproduce the gluon lattice data [1] by the ideal gas formula for the pressure (no bag constant is used!)

$$p(T) = \frac{d_g}{6\pi^2} \frac{T^4}{(\hbar c)^3} \int dx \, \frac{x^4}{A} \frac{1}{\exp(A) - 1}, \quad A = \sqrt{\frac{m_g^2(T)}{T^2} + x^2} \qquad (1)$$

with the temperature dependent effective mass

$$m_g^2(T) = \gamma_g \, g^2(T + T_{s,g}) \, T^2 \, , \qquad (2)$$

$$g^2(T) = \frac{16\pi^2}{11 - \frac{2}{3}N_f} \frac{1}{\ln\left(\frac{T}{T_c}\right)^2} \qquad (3)$$

and the gluon degeneracy $d_g = 16$ and the flavor number $N_f = 0$. Here we have introduced a shift parameter $T_{s,g}$ to avoid the divergence of the first-order running coupling constant $g(T)$ at confinement temperature T_c. γ_g accounts for the effective number of degrees of freedom. For thermal gluon masses in the perturbative high-temperature limit one obtains $\gamma_g^{-1} = 3$ [9]. Also hard thermal loops resummed would require this value [10].

Fig. 1 displays the quality of our fit for $\gamma_g^{-1} = 3.3$ and $T_{s,g}/T_c = 0.023$. We assume as in Ref. [2] $(e/e_{SB})|_{\text{lattice}} = (e/e_{SB})|_{\text{infinite continuum}}$. The energy density is, of course, calculated self-consistently. Note the rather perfect agreement of our simple model with the data [1], in particular at $T \to T_c$ where the more involved model [2] reproduces the lattice energy density not so well. It is surprizing that γ_g^{-1} is so close to the predictions of the high-temperature perturbative thermal gluon mass [9], which approaches also the lattice data [1], see Fig. 1. A recent next-to-leading order calculation of the gluon plasma frequency, within the Braaten Pisarski resumation technique, indicates in line with our finding $\gamma_g^{-1} > 3$ [11] at the same time. Near T_c the perturbative coupling constant obtained within the renormalization group analysis ($g^2 = 16\pi^2[4\pi + (11 - \frac{2}{3}N_f)\ln(T/T_0)^2]^{-1}$ [9]) differs obviously from our form (3). Note that the shift parameter $T_{s,g}$ affects the pressure and energy density only at temperatures near T_c. Therefore, when using $T_{s,g} = 0$ the model with $\gamma^{-1} = 3$ would underestimate the pressure and energy density in the full temperature range in a similar way as the model with $\gamma_g^{-1} = 3$, $T_{s,g} = 0.023\,T_c$ does at $T > 1.5\,T_c$.

Remarkably, the temperature dependence of $m_g(T)$, found in Ref. [5] for the pure SU(2) gauge theory, is very similar to the present SU(3) case: In approaching T_c the mass increases steeply, and displays a minimum near $\sim 1.6 T_c$, and rises at larger temperatures to achieve at very large T the perturbative regime.

3 The quark-gluon plasma: While the model (1 - 3) might be directly applied to Shuryak's hot glue scenario (i.e., a gluon gas with only a few quarks admixed) we would generalize it to the standard reference model of a quark-gluon plasma in chemical equilibrium. In doing so we employ eqs. (1 - 3) also for quarks (suitably modified for Fermi statistics of fermions, and $d_q = 24$) and use $m_q = \gamma_q g^2(T + T_{s,q})T^2$, and write $p_{qg} = p_g + p_q$. In expression (3) the number of accessible quark flavors N_f is now assumed to be 2. Since the gluon self-energies are modified by quark loops the parameters γ_g and $T_{s,g}$ of the pure gluon gas need not necessarily apply for the quark-gluon plasma. Lacking of high-precision lattice data which include quarks reliably we consider two possibilities of the parametrization of thermal masses. As first guess (set I) we employ the well-known finite-temperature QCD value $\gamma_q^{-1} = 6$ [12] and take $\gamma_g^{-1} = 3$ [9], while our set II uses $\gamma_q^{-1} = 7$ and $\gamma_g^{-1} = 3.3$. In both cases we adjust $T_{s,g} = T_{s,q}$ to get $T_c = 170$ MeV. According to Ref. [13] we assume that the confined strongly interacting matter (i.e., the hadron gas) is well approximated by a free pion gas up to temperatures $T \sim m_\pi$ and slightly above. Then T_c is determined as usual by $p_\pi(T_c) = p_{qg}(T_c)$.

Fig. 2 displays the energy density for the two parameter sets compared with the bag model equation of state. The latent heat is less than in the bag model; the jump in the entropy density is reduced in a similar way, too. Larger values of $\gamma_{q,g}$ reduce the energy density and pressure, and also the weak local maximum above T_c disappears. Giving up the constraint $T_{s,q} = T_{s,g}$ one can also reduce further the latent heat, but there is a very steep increase of energy density slightly above T_c. The common outcome of such different parameter choices is that at $T \sim 400$ MeV the scaled energy density $e/(T^4 \frac{\pi^2}{30})$ is about 27, while the bag model is near to 37.

The available lattice results with quarks [14] give $e/e_{SB} \sim 0.8$ for $T/T_c = 1.2$ - 2.3, while our parameter sets I and II give $e/e_{SB} \sim 0.75$ at $T \sim 300$ MeV with e/e_{SB} slightly increasing with increasing temperature. A similar agreement with the entropy lattice data [14] is found, where e/e_{SB} slightly above 0.8 can be deduced.

One of the most important application of the equation of state of strongly interacting matter is connected with the thermo-hydrodynamical description of the evolution of the quark-gluon plasma in high-energy heavy-ion collisions. We have studied the cooling behaviors of the quark-gluon plasma in the idealized Bjorken scenario [15] where $\dot{e} = -(e + p)/\tau$ with $\tau = \sqrt{x^2 - t^2}$ as proper time of a plasma piece at longitudinal coordinate x and time t in c.m.s. For a fixed initial entropy density the cooling of pure deconfined matter in our model is slower compared with the bag model, especially near to the transition temperature, while the duration of the mixed phase is shorter due to the reduced latent heat. One can even expect a stronger effect of the delayed phase transition due to the higher viscosity of massive partons as shown in Ref. [16].

4 Dileptons from a plasma with thermal particle masses: Now we apply our model of thermal masses to the dilepton emission from a quark-gluon plasma. The analysis shows the presence of a kinematical threshold in the emission rate caused by the finite thermal masses. E.g., at a given transverse dilepton mass $M_T = (M^2 + q_T^2)^{1/2}$ the minimum invariant mass M is given by twice the quark mass in case of the dominating

quark fusion processes $q\bar{q} \to l\bar{l}$ (higher order QCD corrections to this main electromagnetic process with thermal parton masses need separate consideration, e.g. within the Braaten Pisarski approach [10]); therefore at large transverse dilepton momentum q_T the rate has to approach zero due to kinematics. (An analog threshold which is caused by the cut-off parameter in the quark momenta distribution is considered in Ref. [17].) If the thermal quark mass is large enough it might lead to the violation of the M_T scaling [18] of the thermal dilepton spectra as pointed out in Ref. [8]. To quantify these effects we calculate the transverse dilepton spectrum

$$\begin{aligned} \frac{dN_{q\bar{q}\to l\bar{l}}}{dM_T^2\, dq_T^2\, dY} &= \frac{5\alpha^2 R^2}{36\pi^2} \int d\tau \tau K_0 \left(\frac{M_T}{T(\tau)}\right) \left[1 - \frac{4m_q^2(T(\tau))}{M^2}\right]^{1/2} \times \\ & \left[1 - \frac{4m_\mu^2}{M^2}\right]^{1/2} \left(1 + \frac{2(m_q^2(T(\tau)) + m_\mu^2)}{M^2} + \frac{4m_q^2(T(\tau))m_\mu^2}{M^4}\right). \end{aligned} \quad (4)$$

at fixed transverse mass ($R = 5$ fm is the transverse radius of the radiating matter; K_0 stands for the modified Bessel function; the evolution starts at initial time $\tau_0 = 1$ fm/c and terminates at temperature $T_c = 170$ MeV, m_μ is the lepton mass). Eq. (4) is derived for our temperature dependent quark masses, scale-invariant longitudinal expansion, Boltzmann approximation of the distribution functions and the temperature $T(\tau)$ determined by the above Bjorken equation. It takes into account correctly the masses in the elementary cross section.

A calculated dimuon spectrum is displayed in Fig. 3. To demonstrate how the violation of the M_T scaling depends on the thermal quark mass and initial state of the plasma we change the parameters γ and T_0. The dilepton spectra are known to depend sensitively on the initial temperature. One observes in Fig. 3 at fixed initial temperatures that the thermal masses are not operative in the small q_T region. The main conclusion is that the value of the threshold at larger q_T is mainly related to the effective quark masses at temperature being near T_c and appears to be almost independent of the initial state of the plasma and its hydrodynamical evolution. Such universal threshold behavior of the dilepton q_T spectra can be useful for the experimental verification of high effective parton masses in the quark-gluon plasma. In this case the appropriate value of M_T should be moderately high (say about 3 GeV) to provide the dominant contribution to the dilepton spectra from parton matter (problems of the experimental observation of M_T scaling have been also discussed in Refs. [19]).

5 Outlook: At the same time the dilepton emission reflects another important consequence of our quark-gluon plasma model. It is related to the change of the latent heat of the deconfinement transition and slower cooling of the plasma during the hydrodynamical expansion in comparison with the standard bag model. Actually it leads to a higher initial temperature of the matter at fixed entropy density (or rapidity density of final pions), and consequently to an additional dilepton yield compared to bag model estimates in the invariant mass region $M \sim 2$ - 3 GeV. This is in accordance with the recently observed dilepton continuum in central S - W collisions at CERN - SPS energies [20]. Although the invariant dilepton mass region and the rapidity density of secondary pions achieved in these collisions seem to correspond to the formation of quark - hadron mixed phase [21], the observed yield cannot be explained in the framework of a mixed phase picture which is based on the bag model [22]. Our model in principle opens a natural way for an explanation. A detailed analysis will be published separately.

6 Summary: In summary we reproduce the SU(3) gluon data of pressure and energy density by a quasi-particle model with thermal masses and extrapolate to a new thermodynamical description of the quark-gluon plasma. As possible manifestations of the finite effective parton masses we consider the scaling violation of the transverse dilepton spectra at large transverse pair momenta.

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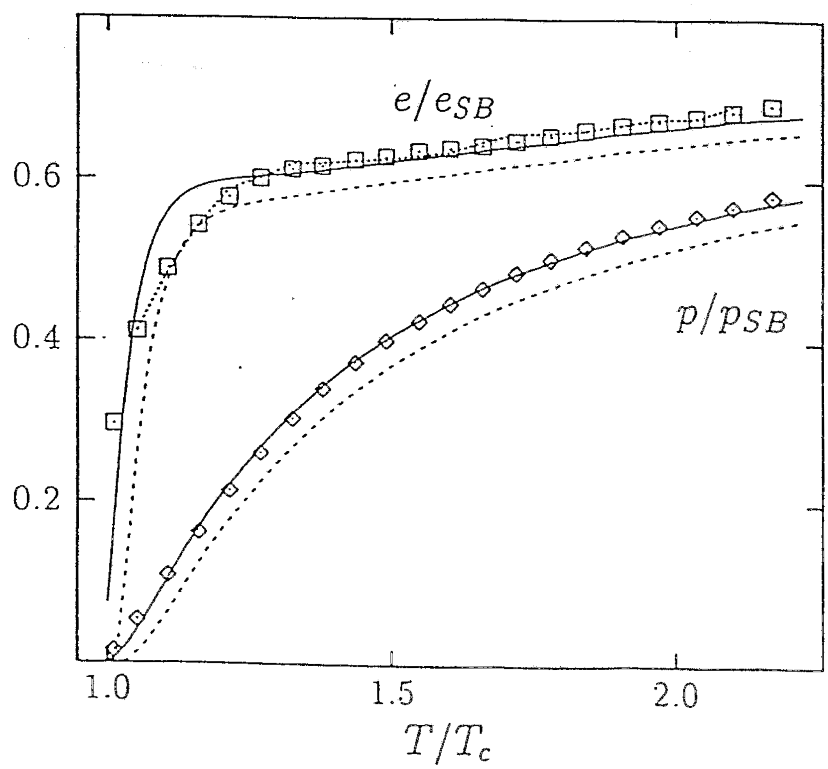

Fig. 1: Lattice data [1, 2] (symbols) and our model eqs. (1,2) (full lines [fitted to the pressure]: $\gamma_g^{-1} = 3.3$, $T_{s,g} = 0.023\,T_c$, dashed lines employ the finite-temperature gluon mass with $\gamma_g^{-1} = 3$ and the shift parameter $T_{s,g} = 0$). The dotted line displays the energy density calculated from the pressure data when using a mid-point derivative.

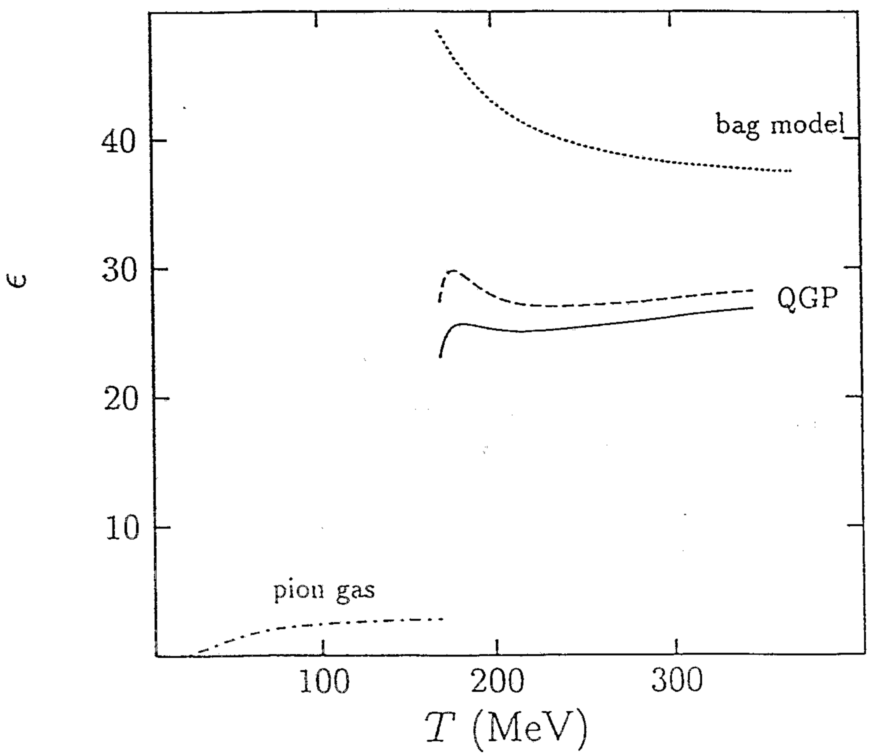

Fig. 2: The energy density $\epsilon \equiv e/(T^4 \frac{\pi^2}{30})$ as function of the temperature for the parameter sets I, II (full, dashed lines) described in text. Also displayed are the pion gas (dot-dashed line) and the bag model equation of state (dotted line).

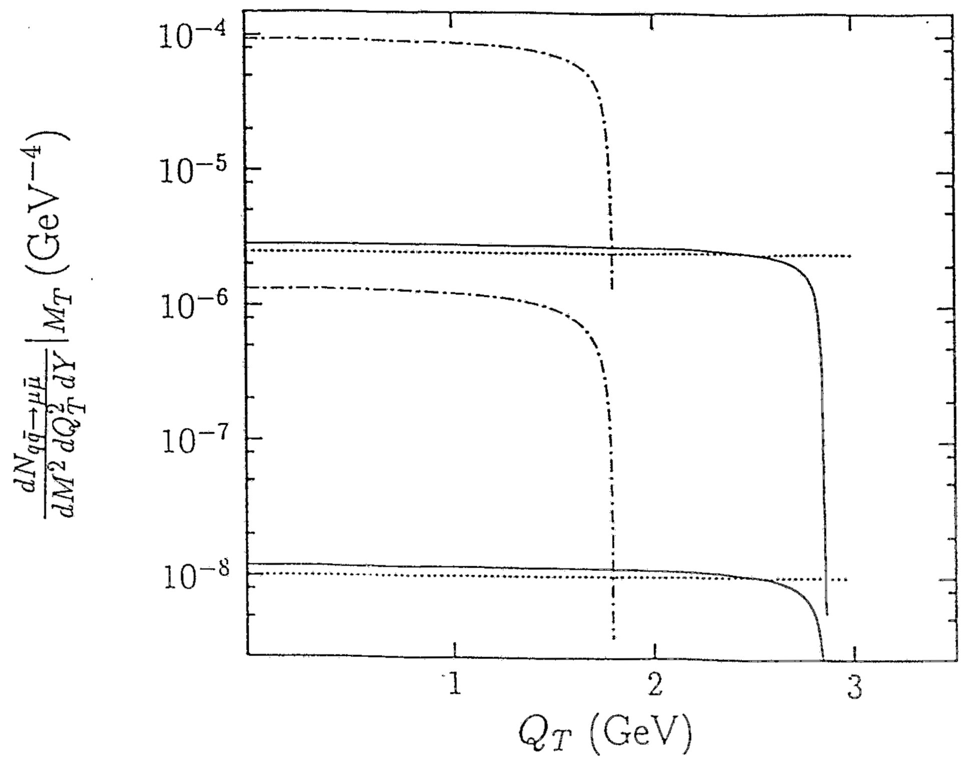

Fig. 3: The dilepton yield at fixed transverse pair mass $M_T = 2, 3$ GeV (dot-dashed, full lines) as function of the transverse momentum q_T. The upper (lower) curve uses the initial temperature $T_0 = 400$ (250) MeV. There is no apparent variation when using the parameter sets I or II (only for drastically smaller values of $\gamma_{q,g}$ the suppression near threshold is enhanced; at small q_T there is no change). The dotted lines are for $m_q = 0$ GeV and bag model cooling in case of $M_T = 3$ GeV.