Pions and Strangeness in Pb+Pb Collisions at SPS

Recent Results from NA49

Marek Gaździcki* for the NA49 Collaboration

Results on the energy dependence of pion, kaon and Λ hyperon production in central Pb+Pb collisions at 40, 80 and 158 A·GeV are presented and compared with results at lower and higher energies. The mean pion multiplicity increases approximately linearly with $s^{1/4}$ with a change of the slope around 40 A·GeV. The change from a pattern of pion suppression observed at low collision energies to pion enhancement seen at high energies is located at about 40 A·GeV. A non–monotonic energy dependence of the $\langle K^+\rangle/\langle\pi^+\rangle$ ratio is observed. A maximum is found close to 40 A·GeV followed by a nearly constant value at higher energies. The measured behaviour is consistent with the hypothesis, derived within a statistical model of the early stage of nucleus–nucleus reactions, that a transient state of deconfined matter is created in Pb+Pb collisions for energies larger than about 40 A·GeV.

1. The primary purpose of the heavy ion programme at the CERN SPS is the search for evidence of a transient deconfined state of strongly interacting matter during the early stage of nucleus–nucleus collisions [1]. When sufficiently high initial energy density is reached a formation of a state of quasi free quarks and gluons, the quark gluon plasma (QGP) is expected. A key problem is the identification of experimental signatures of the QGP creation [2]. Numerous proposals were discussed in the past [3]. A possible, promising strategy is a study of the energy dependence of pion and strangeness yields. It was suggested [4,5] that the transition may lead to anomalies in this dependence: a steepening of the increase of the pion yield and a non monotonic behaviour of the strangeness to pion ratio. First experimental results from Pb+Pb (Au+Au) collisions at top SPS (158 A·GeV) and AGS (11 A·GeV) energies have suggested [4] that anomalies in pion and strangeness production should take place between these energies.

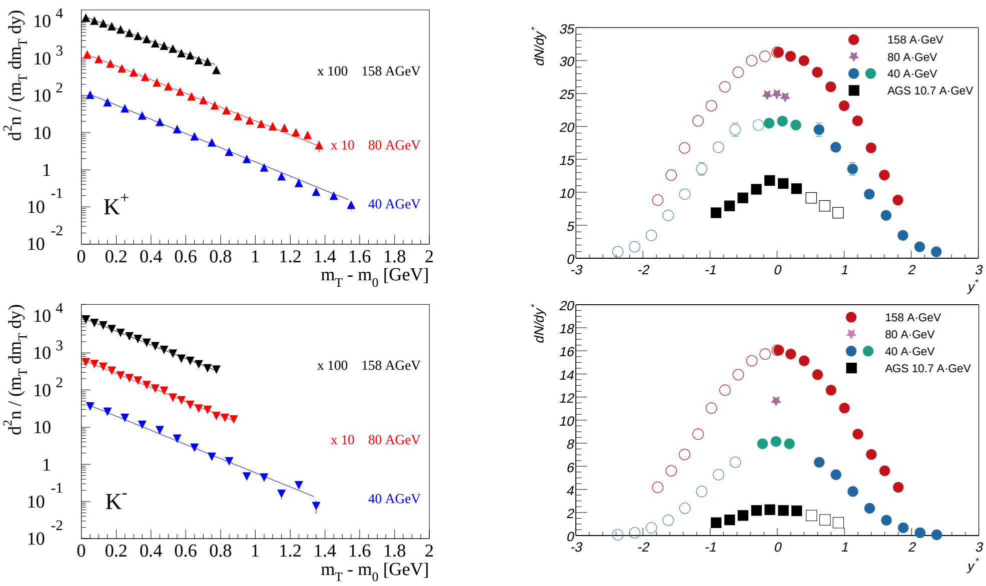

FIG. 1. The transverse mass (at midrapidity) and rapidity spectra of K^+ and K^- mesons produced in central Pb+Pb collisions at 40, 80 and 160 A·GeV. The AGS measurements are also shown for comparison [11]. The measured y^* spectra (full symbols) are reflected with respect to midrapidity, $y^* = 0$, (open symbols).

*e–mail: Marek.Gazdzicki@cern.ch

The need for further study of this hypothesis triggered an energy scan at the CERN SPS [8]. Within this ongoing project NA49 has recorded central Pb+Pb collisions at 40 and 80 A·GeV during the heavy ion runs in 1999 and 2000, respectively. The data at the top SPS energy (158 A·GeV) were taken in the previous SPS runs. In this paper we report results on the energy dependence of pion, kaon and Λ hyperon production.

2. The NA49 experimental set–up [9] consists of four large volume Time Projection Chambers (TPCs). Two of them, Vertex TPCs (VTPC1 and VTPC2), are placed in the magnetic field of two super-conducting dipole magnets and allow a precise measurement of particle momenta p ($\sigma(p)/p^2 \approx (0.3-7)\cdot 10^{-4}$ (GeV/c)$^{-1}$) and electric charge. The other two TPCs (MTPCL and MTPCR), positioned downstream of the magnets were optimised for high precision detection of ionization energy loss dE/dx (relative resolution of about 4%) and consequently provide a means of measuring the particle mass. The TPC data yield spectra of identified hadrons above midrapidity.

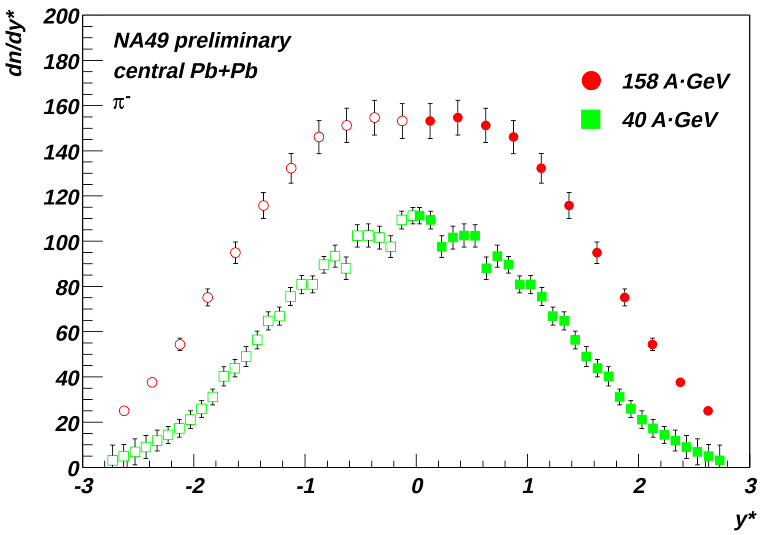

FIG. 2. The rapidity spectra of π^- mesons produced in central Pb+Pb collisions at 40 and 160 A·GeV. The measured y^* spectra (full symbols) are reflected with respect to midrapidity, $y^* = 0$, (open symbols).

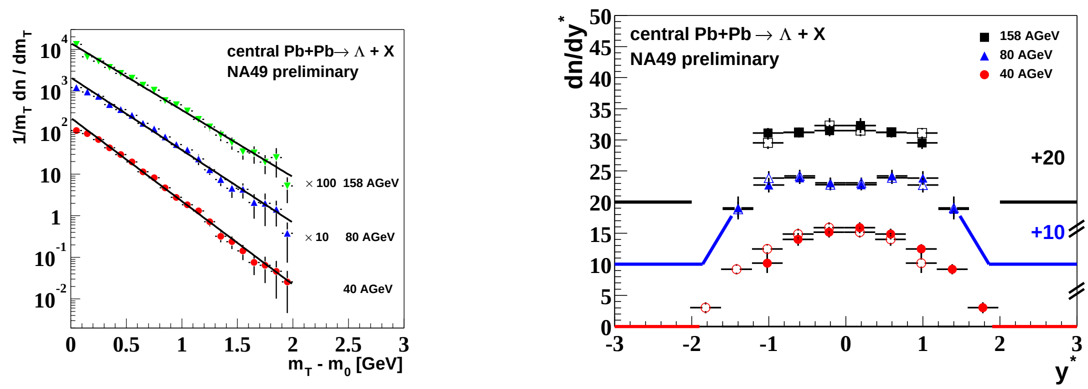

FIG. 3. The transverse mass and rapidity spectra of Λ hyperons produced in central Pb+Pb collisions at 40, 80 and 160 A·GeV. The y^* spectra at 80 and 160 A·GeV are shifted by 10 and 20 respectively. The measured y^* spectra (full symbols) are reflected with respect to midrapidity, $y^* = 0$, (open symbols).

The particle identification capability of the MTPCs is augmented by two Time of Flight (TOF) detector arrays (resolution $\sigma_{tof} \approx 60$ ps). The combined TPC and TOF information allow for the measurement of charged kaon spectra at midrapidity. Central collisions (7%, 7% and 5% of all inelastic interactions at 40, 80 and 160 A·GeV, respectively) were selected by a trigger using information from a downstream calorimeter, which measured the energy of the projectile spectator nucleons. The geometrical acceptance of the Veto Calorimeter was adjusted for each energy by the proper setting of a collimator.

3. The transverse mass ($m_T = \sqrt{p_T^2 + m_0^2}$, m_0 is the rest mass of the particle) and rapidity in c.m. system (y^*) spectra of K^+ and K^- mesons produced in central Pb+Pb collisions at 40, 80 and 158 A·GeV are shown in Fig. 1. The solid lines indicate the result of a fit of the function $dn/(m_T dm_T dy) = C \cdot exp(-m_T/T)$. The obtained values of the inverse slope parameter T range between 220 and 240 MeV.

The rapidity distributions dn/dy were obtained by integration of the m_T spectra. The rapidity distributions for π^- mesons at 40 and 158 A·GeV are shown in Fig. 2. The mean multiplicities of pions and kaons in full phase space were derived by integration of the measured rapidity spectra. A necessary correction for the part of the spectrum not covered by the NA49 acceptance was applied based on a fit of two Gauss functions to the rapidity distributions. The m_T and y^* spectra for Λ hyperons analysed by the reconstruction of their decays are plotted in Fig. 3. The preliminary results are not corrected for feeddown from Ξ decays, the correction was estimated to be below several %. The inverse slope parameter increases with energy from ≈250 MeV at 40 A·GeV to ≈280 MeV at 160 A·GeV. The midrapidity density seems to decrease with increasing energy in the SPS range. This may be interpreted as due to a strong decrease of baryon density at hadronization [10] with increasing energy, which at high energies overcompensates the increase of strangeness production.

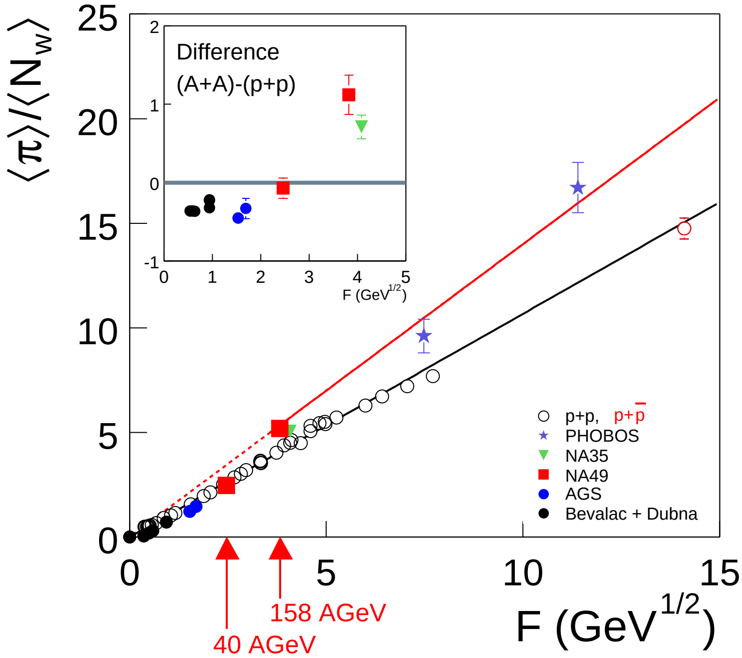

FIG. 4. The dependence of the total pion multiplicity per wounded nucleon on Fermi's energy measure F (see text for definition) for central A+A collisions (closed symbols) and inelastic p+p($\overline{\text{p}}$ interactions (open symbols). The results of NA49 are indicated by squares. The inset shows the difference between the results for A+A collisions and p+p interactions.

4. The energy dependence of the pion multiplicity calculated here as $\langle\pi\rangle = 3/2(\langle\pi^+\rangle + \langle\pi^-\rangle)$ is shown in Fig. 4, where the ratio $\langle\pi\rangle/\langle N_W\rangle$ ($\langle N_W\rangle$ is the mean number of wounded nucleons), is plotted as a function of the collision energy expressed by Fermi's measure [12]: $F \equiv (\sqrt{s} - 2m_N)^{3/4}/\sqrt{s}^{1/4}$, where $\sqrt{s}$ is the c.m.s. energy per nucleon–nucleon pair and m_N the rest mass of the nucleon. Measurements by NA49 are compared to results from other experiments on central nucleus–nucleus collisions [11,13,4] and to a compilation of data from nucleon–nucleon interactions (see references in [4]).

One observes that the mean pion multiplicity in p+p interactions increases approximately in proportion to F ($\approx s^{1/4}$). In the case of central A+A collisions the dependence is more complicated. Below 40 A·GeV the ratio $\langle\pi\rangle/\langle N_W\rangle$ in A+A collisions is lower than in p+p interactions (pion suppression), however the slopes of the dependence on F are similar. An increase of the slope is observed for A+A data at about 40 A·GeV and at higher energies the $\langle\pi\rangle/\langle N_W\rangle$ ratio is higher in A+A collisions than in p+p interactions (pion enhancement). The dependence established at the top CERN SPS energies continues up to RHIC energies [13]. The transition from pion suppression to pion enhancement is demonstrated more clearly in the insert of Fig. 4, where the difference between the $\langle\pi\rangle/\langle N_W\rangle$ ratio for A+A and p+p interactions is plotted as a function of F up to top CERN SPS energies.

The observed energy dependence of pion production is consistent with the prediction of a Statistical Model of the Early Stage [5] assuming that a transition from a reaction with purely confined matter to a reaction with a QGP at the early stage occurs close to 40 A·GeV. Within this model the steepening of the pion energy dependence is due to an activation of a large number of partonic degrees of freedom at the onset of deconfinemt.

5. The full phase space K^+/π^+ ratio is shown as a function of $\sqrt{s}$ in Fig. 5 (left). A steep increase of the ratio in the low (AGS) energy region [11] is followed by a rapid turnover (around 40 A·GeV) into a decrease and a successive saturation suggested by preliminary RHIC data [14].

This behaviour is again consistent with the hypothesis of a transition to a QGP occuring close to 40 A·GeV. Within a Statistical Model of the Early Stage [5] the decrease of the ratio $\langle K^+\rangle/\langle\pi^+\rangle$ in the transition region is related to the lower value of the strangeness to entropy ratio in a QGP compared to confined matter. Preliminary results on the K^+ to π^+ ratio in central Au+Au collisions at RHIC [15] indicate that it is similar to the ratio measured at top SPS energy. This is again in agreement with the hypothesis of a transition to QGP in the low SPS energy region. Within the model the strangeness to entropy ratio is independent of the collision energy provided that the threshold for deconfiment has been crossed.

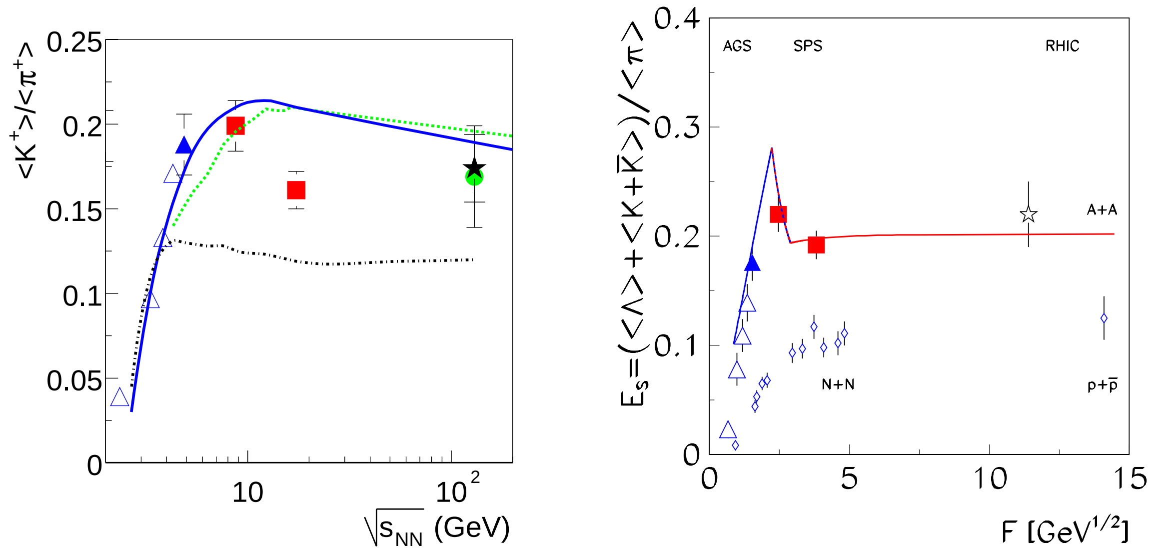

FIG. 5. The energy dependence of K^+/π^+ and E_S ratios for central Pb+Pb (Au+Au) collisions and nucleon–nucleon interactions. The experimental results for A+A collisions are compared with models which do not assume a transition to QGP (left) (RQMD [20,21] dotted line, UrQMD [22] dashed–dotted line, and Extended Hadron Gas Model [10] solid line) and with a Statistical Model of the Early Stage (right) [5] solid line) in which a transition to a QGP at about 30 A·GeV is incorporated.

In Fig. 5 (right) an alternative measure of the strangeness to entropy ratio, $E_S = (\langle\Lambda\rangle + \langle K + \overline{K}\rangle)/\langle\pi\rangle$, is plotted as a function of F for A+A collisions and p+p($\overline{\mathrm{p}}$) interactions. For A+A collisions the Λ multiplicity was estimated as $\langle\Lambda\rangle = 2/1.6 \cdot (\langle K^+\rangle - \langle K^-\rangle$, based on strangeness conservation and approximate isospin symmetry of the colliding nuclei. This estimate agrees with the preliminary Λ measurements presented in this contribution. Rich data on Λ and K^0_S production in p+p interaction allow to establish precisely the energy dependence in elementary interactions, much better than it is possible for the K^+/π^+ ratio. Consequently it is possible to conclude that a sharp non-monotonic energy dependence might occur as a unique property of heavy ion collisions not observed in elementary interactions. The results on A+A collisons are compared in Fig. 5 (right) with the predictions of a Statistical Model of the Early Stage [5]. As discussed above, within this model, a rapid change of the energy dependence of strangeness to entropy ratio is due to the transition from confined to deconfined matter.

6. Numerous models have been developed to explain reactions of heavy nuclei without explicitely invoking a transient deconfined or QGP phase. The simplest one is a Statistical Hadron Gas Model [16,18]. It assumes that independently of the collision energy the hadrochemical freeze–out creates a hadron gas in full equilibrium [17]. The temperature, baryo–chemical potential and hadronization volume are basic free parameters of the model. By itself, the model makes no prediction concerning the energy dependence of hadron production; the parameters are fitted independently to each data set. However the standard formulation was recently extended by adding additional input i.e. the measured energy dependence of pion production and an interpolation between values of thermal parameters (temperature and baryo–chemical potential) fitted at several energies [10]. The energy dependence calculated within this Extended Hadron Gas Model for the K^+/π^+ ratio is compared with the experimental results in Fig. 5 (left, solid line). The main trend of the ratio is, by construction of the model, captured but the decrease of the K^+/π^+ ratio between 40 and 160 A·GeV is not reproduced by the model. The measured strangeness to pion yield in central Pb+Pb collisions at 158 A·GeV is 25% lower than that expected in the fully equilibrated hadron gas [19,10].

Several dynamical hadron–string models are used to study hadron production in A+A collisions. In this class of models the resulting energy dependence in heavy ion collisions is governed by the parametrised energy dependence of elementary interactions and the details of the approach used to model A+A collisions. In Fig. 5 (left) our data are compared with the RQMD (dotted line) and the UrQMD (dashed–dotted line) model. The RQMD model [20] predicts a monotonic increase of the $\langle K^+\rangle/\langle\pi^+\rangle$ ratio between top AGS and top SPS energies. It over-predicts the measurement at 158 A·GeV by about 25 % [21]. The UrQMD model overestimates pion production by more than 30 % [22] at SPS energies. The calculated $\langle K^+\rangle/\langle\pi^+\rangle$ ratio is significantly lower (e.g. by about 40 % at 40 A·GeV) than the measured one and does not show any significant energy dependence above top AGS energies.

7. In summary, first results on pion, kaon and Λ hyperon production in central Pb+Pb collisions at 40, 80 and 158 A·GeV are presented. The change from a pattern of pion suppression observed at low collision energies to pion enhancement seen at high energies is located at about 40 A·GeV. A non–monotonic energy dependence of the $\langle K^+\rangle/\langle\pi^+\rangle$ ratio is observed. A maximum is found close to 40 A·GeV followed by a nearly constant value at higher energies. The observed behaviour can be understood, within a Statistical Model of the Early Stage of nucleus–nucleus collisions if the assumption is made that a transient state of deconfined matter is created in Pb+Pb collisions for energies larger than about 40 A·GeV.

Acknowledgements

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the US Department of Energy (DE-ACO3-76SFOOO98 and DE-FG02-91ER40609), the US National Science Foundation, the Bundesministerium fur Bildung und Forschung, Germany, the Alexander von Humboldt Foundation, the UK Engineering and Physical Sciences Research Council, the Polish State Committee for Scientific Research (5 P03B 13820 and 2 P03B 02418), the Hungarian Scientific Research Foundation (T14920 and T23790), the EC Marie Curie Foundation, and the Polish-German Foundation.

---

[1] for review see Proceedings of the 14th International Conference on Ultra–Relativistic Nucleus–Nucleus Collisions, Quark Matter 99, eds.: L. Riccati, M. Masera and E. Vercellin, Nucl. Phys. **A661**, 1c (1999).

[2] J. C. Collins and M. J. Perry, Phys. Rev. Lett. **34** (1975) 151,
E. V. Shuryak, Phys. Rep. **C61** (1980) 71 and **C115** (1984) 151.

[3] J. Rafelski and B. Müller, Phys. Rev. Lett. 48, 1066 (1982),
T. Matsui and H. Satz, Phys. Lett. **B178** (1986) 416.

[4] M. Gaździcki and D. Röhrich, Z. Phys. **C65**, 215 (1995) and Z. Phys. **C71**, 55 (1996).

[5] M. Gaździcki and M. I. Gorenstein, Acta Phys. Polon. **B30**, 2705 (1999).

[6] C.M. Hung and E. Shuryak, Phys. Rev. Lett. **75**, 4003 (1995).

[7] M. Stephanov, K. Rajagopal and E. Shuryak, Phys. Rev. **D60**, 114028 (1999).

[8] J. Bächler et al. (NA49 Collab.), *Searching for QCD Phase Transition*, Addendum–1 to Proposal SP-SLC/P264, CERN/SPSC 97 (1997).

[9] S. Afanasiev et al., Nucl. Instrum. Meth. **A430**, 210 (1999).

[10] J. Cleymans and K. Redlich, Phys. Rev. **C60**, 054908 (1999),
P. Braun-Munzinger et al., e-Print Archive: hep-ph/0106066.

[11] L. Ahle et al. (E802 Collab.), Phys. Rev. **C57**, 466 (1998),
L. Ahle et al. (E802 Collab.), Phys. Rev. **C58**, 3523 (1998),
L. Ahle et al. (E802 Collab), Phys. Rev. **C60**, 044904 (1999),
L. Ahle et al. (E866 Collab. and E917 Collab.), Phys. Lett. **B476**, 1 (2000),
L. Ahle et al. (E866 Collab. and E917 Collab.), Phys. Lett. **B490**, 53 (2000),
J. Barrette et al. (E877 Collab.), Phys. Rev. **C62**, 024901 (2000)
D. Pelte et al. (FOPI Collab.), Z. Phys. **A357**, 215 (1997).

[12] E. Fermi, Prog. Theor. Phys. **5**, 570 (1950).

[13] B. B. Back et al. (PHOBOS Collab.), Phys. Rev. Lett. **85**, 3100 (2000).

[14] C. Adler et al. (Star Collab.), Phys. Rev. Lett. **86** (2001) 4778,
B. B. Back et al. (Phobos Collab.), Phys. Rev. Lett. **87** (2001) 102301.

[15] J. Harris et al. (STAR Collab.), Proceedings of 15th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (QM2001), Stony Brook, New York, 15-20 Jan 2001, to be published in Nucl. Phys. **B**,
B. Jacak et al. (PHENIX Collab.), Proceedings of "International Workshop of the Physics of the Quark-Gluon Plasma", Ecole Polytechnique, Palaiseau, France, September 4–7, 2001.

[16] R. Hagedorn, CERN report CERN-TH-7190-94 and Proccedings of NATO Advanced Study Workshop on Hot Hadronic Matter: Theory and Experiment, Divonne-les-Bains, Switzerland, 27 Jun - 1 Jul 1994, Hot Hadronic Matter, 13 (1994).

[17] R. Stock, Phys. Lett. **B456** (1999) 277.

[18] J. Cleymans and H. Satz, Z. Phys. **C57** (1993) 135.
J. Sollfrank, M. Gaździcki, U. Heinz and J. Rafelski, Z. Phys. **C61** (1994) 659;
P. Braun–Munzinger, J. Stachel, J. Wessels and N. Xu, Phys. Lett. **365B** (1995) 1;
G. D. Yen, M. I. Gorenstein, W. Greiner, S.N. Yang, Phys. Rev. **C56** (1997) 2210;
G. D. Yen and M. I. Gorenstein, Phys. Rev. **C59** (1999) 2788.

[19] F. Becattini, M. Gaździcki and J. Sollfrank, Eur. Phys. J. **C5**, 143 (1998).

[20] H. Sorge, H. Stöcker and W. Greiner, Nucl. Phys. **A489**, 567c (1989) and
H. Sorge, Phys. Rev. **C52**, 3291 (1995).

[21] F. Wang, H. Liu, H. Sorge, N. Xu and J. Yang, Phys. Rev. **C61**, 064904 (2000).

[22] S. A. Bass et al., Prog. Part. Nucl. Phys. **41**, 225 (1998).