Evidence for the Onset of Deconfinement from Longitudinal Momentum Distributions? Observation of the Softest Point of the Equation of State

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We analyze longitudinal pion spectra from $E_{\rm lab} = 2A$ GeV to $\sqrt{s_{\rm NN}} = 200$ GeV within Landau's hydrodynamical model. From the measured data on the widths of the pion rapidity spectra, we extract the sound velocity c_s^2 in the early stage of the reactions. It is found that the sound velocity has a local minimum (indicating a softest point in the equation of state, EoS) at $E_{\rm beam} = 30A$ GeV. This softening of the EoS is compatible with the assumption of the formation of a mixed phase at the onset of deconfinement.

Over the last years, a wealth of detailed data in the $20A - 160A$ GeV energy regime has become available. The systematic study of these data revealed surprising (non-monotonous) structures in various observables around $30A$ GeV beam energy. Most notable irregular structures in that energy regime include,

- the sharp maximum in the K^+/π^+ ratio [1, 2],
- a step in the transverse momentum excitation function (as seen through $\langle m_\perp \rangle - m_0$) [2, 3],
- an apparent change in the pion per participant ratio [2] and
- increased ratio fluctuations (due to missing data at low energies it is unknown if this is a local maximum or an ongoing increase of the fluctuations) [4].

It has been speculated, that these observation hint towards the onset of deconfinement already at $30A$ GeV beam energy. Indeed, increased strangeness production [5] and enhanced fluctuations have long been predicted as a sign of QGP formation [6, 7, 8, 9, 10, 11] within different frameworks and observables. The suggestion of an enhanced strangeness to entropy ratio ($\sim K/\pi$) as indicator for the onset of QGP formation was especially advocated in [12]. Also the high and approximately constant $K^\pm$ inverse slopes of the m_T spectra above $\sim 30A$ GeV - the 'step' - was also found to be consistent with the assumption of a parton $\leftrightarrow$ hadron phase transition at low SPS energies [13, 14]. Surprisingly, transport simulations (supplemented by recent lattice QCD (lQCD) calculations) have also suggested that partonic degrees of freedom might already lead to visible effects at $\sim 30A$ GeV [15, 16, 17]. Finally, the comparison of the thermodynamic parameters T and μ_B extracted from the transport models in the central overlap region [18] with the experimental systematics on chemical freeze-out configurations [19, 20, 21] in the $T - \mu_B$ plane do also suggest that a first glimpse on a deconfined state might be possible around $10A - 30A$ GeV.

In this letter, we explore whether similar irregularities are also present in the excitation function of longitudinal observables, namely rapidity distributions. Here we will employ Landau's hydrodynamical model [22, 23, 24, 25, 26, 27, 28]. This model entered the focus again after the most remarkable observation that the rapidity distributions at all investigated energies can be well described by a single Gaussian at each energy. The energy dependence of the width can also be reasonably described by the same model. For recent applications of Landau's model to relativistic hadron-hadron and nucleus-nucleus interactions the reader is referred to [29, 30, 31, 32, 33] (and Refs. therein).

The main physics assumptions of Landau's picture are as follows: The collision of two Lorentz-contracted nuclei leads to full thermalization in a volume of size $V/\sqrt{s_{\rm NN}}$. This justifies the use of thermodynamics and establishes the system size and energy dependence. Usually, a simple equation of state $p = c_s^2\epsilon$ with $c_s^2 = 1/3$ (c_s denotes the speed of sound) is assumed. For simplicity, chemical potentials are not taken into account. From these assumptions follows a universal formula for the distribution of the produced entropy, determined mainly by the initial Lorentz contraction and Gaussian rapidity spectrum for newly produced particles. Under the condition that c_s is independent of temperature, the rapidity density is given by [25, 26]:

$$\frac{dN}{dy} = \frac{K s_{\rm NN}^{1/4}}{\sqrt{2\pi\sigma_y^2}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \qquad (1)$$

with

$$\sigma_y^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln(\sqrt{s_{\rm NN}}/2m_p) \quad , \qquad (2)$$

where K is a normalisation factor and m_p is the proton mass. The model relates the observed particle multiplicity and distribution in a simple and direct way to the parameters of the QCD matter under consideration.

Let us now analyze the available experimental data on rapidity distributions of negatively charged pions in terms of the Landau model. Fig. 1 shows the measured root mean square σ_y of the rapidity distribution of negatively charged pions in central Pb+Pb (Au+Au) reactions as a function of the beam rapidity. The dotted line indicates the Landau model predictions with the commonly used constant sound velocity $c_s^2 = 1/3$. The full

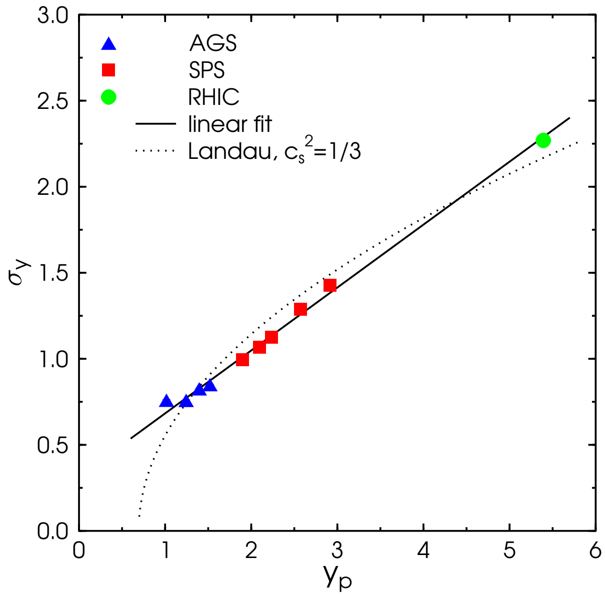

FIG. 1: The root mean square σ_y of the rapidity distributions of negatively charged pions in central Pb+Pb (Au+Au) reactions as a function of the beam rapidity y_p. The dotted line indicates the Landau model prediction with $c_s^2 = 1/3$, while the full line shows a linear fit through the data points. Data (full symbols) are taken from [3, 33, 34, 35]. The statistical errors given by the experiments are smaller than the symbol sizes. Systematic errors are not available.

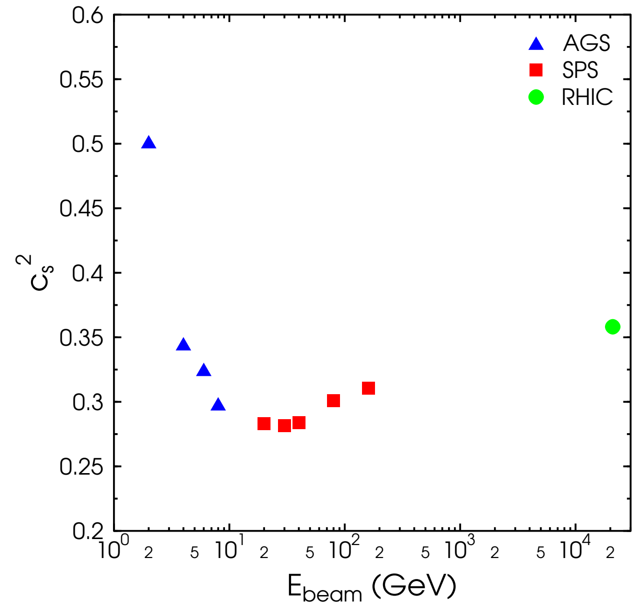

FIG. 2: Speed of sound as a function of beam energy for central Pb+Pb (Au+Au) reactions as extracted from the data using Eq. (3). The statistical errors (not shown) are smaller than 3%.

line shows a linear fit through the data points, while the data points [3, 33, 34, 35] are depicted by full symbols.

At a first glance the energy dependence looks structureless. The data seem to follow a linear dependence on the beam rapidity y_p without any irregularities. However, the general trend of the rapidity widths is also well reproduced by Landau's model with an equation of state with a fixed speed of sound. Nevertheless, there seem to be systematic deviations. At low AGS energies and at RHIC, the experimental points are generally underpredicted by Eq. (2), while in the SPS energy regime Landau's model overpredicts the widths of the rapidity distributions. Exactly these deviations from the simple Landau picture do allow to gain information on the equation of state of the matter produced in the early stage of the reaction. By inverting Eq. (2) we can express the speed of sound c_s^2 in the medium as a function of the measured width of the rapidity distribution:

$$c_s^2 = -\frac{4}{3}\frac{\ln(\sqrt{s_{\rm NN}}/2m_p)}{\sigma_y^2} + \sqrt{\left[\frac{4}{3}\frac{\ln(\sqrt{s_{\rm NN}}/2m_p)}{\sigma_y^2}\right]^2 + 1} \quad . \tag{3}$$

Let us now investigate the energy dependence of the sound velocities extracted from the data. Figure 2 shows the speed of sound as a function of beam energy for central Pb+Pb (Au+Au) reactions as obtained from the data using Eq. (3). The sound velocities exhibit a clear minimum (usually called the softest point) around a beam energy of 30A GeV. A localized softening of the equation of state is a long predicted signal for the mixed phase at the transition energy from hadronic to partonic matter [36, 37, 38]. Therefore, we conclude that the measured data on the rapidity widths of negatively charged pions are indeed compatible with the assumption of the onset of deconfinement at the lower SPS energy range. However, presently we can not rule out that also an increased resonance contribution may be the cause of the softening [39].

In conclusion, we have explored the excitation functions of the rapidity widths of negatively charged pions in Pb+Pb (Au+Au) collisions.

- The rapidity spectra of pions produced in central nucleus-nucleus reactions at all investigated energies can be well described by single Gaussians.
- The energy dependence of the width of the pion rapidity distribution follows the prediction of Landau's hydrodynamical model if a variation of the sound velocity is taken into account.
- The speed of sound excitation function extracted from the data has a pronounced minimum (softest point) at $E_{\rm beam} = 30A$ GeV.
- This softest point might be due to the formation of a mixed phase indicating the onset of deconfinement at this energy.

Further explorations of this energy domain is needed and can be done at the future FAIR facility and by CERN-SPS and BNL-RHIC experiments.

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References

[1] S. V. Afanasiev *et al.* [The NA49 Collaboration], Phys. Rev. C **66** (2002) 054902 [arXiv:nucl-ex/0205002].
[2] M. Gazdzicki *et al.* [NA49 Collaboration], J. Phys. G **30** (2004) S701 [arXiv:nucl-ex/0403023].
[3] C. Blume, J. Phys. G: Nucl. Part. Phys. 31, S57 (2005)
[4] C. Roland [NA49 Collaboration], J. Phys. G **31** (2005) S1075.
[5] P. Koch, B. Muller and J. Rafelski, Phys. Rept. **142** (1986) 167.
[6] M. Bleicher, S. Jeon and V. Koch, Phys. Rev. C **62** (2000) 061902 [arXiv:hep-ph/0006201].
[7] E. V. Shuryak and M. A. Stephanov, Phys. Rev. C **63** (2001) 064903 [arXiv:hep-ph/0010100].
[8] H. Heiselberg and A. D. Jackson, Phys. Rev. C **63** (2001) 064904 [arXiv:nucl-th/0006021].
[9] B. Muller, Nucl. Phys. A **702** (2002) 281 [arXiv:nucl-th/0111008].
[10] M. Gazdzicki, M. I. Gorenstein and S. Mrowczynski, Phys. Lett. B **585**, 115 (2004) [arXiv:hep-ph/0304052].
[11] M. I. Gorenstein, M. Gazdzicki and O. S. Zozulya, Phys. Lett. B **585**, 237 (2004) [arXiv:hep-ph/0309142].
[12] M. Gazdzicki and M. I. Gorenstein, Acta Phys. Polon. B **30**, 2705 (1999).
[13] M. I. Gorenstein, M. Gazdzicki and K. A. Bugaev, Phys. Lett. B **567**, 175 (2003) [arXiv:hep-ph/0303041].
[14] Y. Hama, F. Grassi, O. Socolowski, T. Kodama, M. Gazdzicki and M. Gorenstein, Acta Phys. Polon. B **35** (2004) 179.
[15] H. Weber, C. Ernst, M. Bleicher *et al.*, Phys. Lett. B **442**, 443 (1998).
[16] E. L. Bratkovskaya *et al.*, Phys. Rev. Lett. **92**, 032302 (2004)
[17] E. L. Bratkovskaya *et al.*, Phys. Rev. C **69**, 054907 (2004)
[18] L. V. Bravina *et al.*, Phys. Rev. C **60**, 024904 (1999), Nucl. Phys. A **698**, 383 (2002).
[19] P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **606**, 320 (1996).
[20] P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **638**, 3 (1998).
[21] J. Cleymans and K. Redlich, Phys. Rev. C **60**, 054908 (1999).
[22] E. Fermi, Prog. Theor. Phys. **5**, 570 (1950).
[23] L. D. Landau, Izv. Akad. Nauk Ser. Fiz. **17**, 51 (1953).
[24] S. Z. Belenkij and L. D. Landau, Usp. Fiz. Nauk **56**, 309 (1955).
[25] E. V. Shuryak, Yad. Fiz. **16**, 395 (1972).
[26] P. Carruthers, Annals N.Y.Acad.Sci. 229, 91 (1974).
[27] P. Carruthers and M. Doung-van, Phys. Rev. D **8**, 859 (1973).
[28] P. Carruthers, LA-UR-81-2221
[29] E. L. Feinberg, Z. Phys. C **38** (1988) 229.
[30] J. Stachel and P. Braun-Munzinger, Phys. Lett. B **216**, 1 (1989).
[31] P. Steinberg, arXiv:nucl-ex/0405022.
[32] M. Murray, arXiv:nucl-ex/0404007.
[33] G. Roland, Talk presented at Quark Matter 2004, see proceedings.
[34] J.Klay *et al.* [E895 Collaboration], Phys. Rev. C **68**, 054905 (2003)
[35] I.G. Bearden *et al.* [Brahms Collaboration], Phys. Rev. Lett. **94**, 162301 (2005)
[36] C. M. Hung and E. V. Shuryak, Phys. Rev. Lett. **75**, 4003 (1995) [arXiv:hep-ph/9412360].
[37] D. H. Rischke, Y. Pursun, J. A. Maruhn, H. Stoecker and W. Greiner, Heavy Ion Phys. **1**, 309 (1995) [arXiv:nucl-th/9505014].
[38] J. Brachmann, A. Dumitru, H. Stoecker and W. Greiner, Eur. Phys. J. A **8**, 549 (2000) [arXiv:nucl-th/9912014].
[39] R. Hagedorn, Nuov. Cim. Suppl. 3, 147 (1965); J. Rafelski and R. Hagedorn, Bielefeld Symp., ed. H. Satz, pp. 253 (1980)