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Pion and Strangeness Puzzles

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Abstract

Dependence of pion and strangeness production on number of participant nucleons and collision energy is discussed for central A+A collisions. A possible interpretation of the experimental results assuming transition to QGP is sketched within a simple statistical approach.

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1. Introduction

Massive hadrons are effective degrees of freedom in strongly interacting matter at low energy density. We expect that in the matter at high enough energy density the degrees of freedom are almost massless quarks and gluons. This new form of matter conjectured long ago [1] is called Quark Gluon Plasma (QGP) [2]. By studies of the transition to QGP and the QGP properties itself we can better understand the structure of the QCD vaccum, the origin of the hadron masses and confinement of quarks inside hadrons.

Relativistic nucleus–nucleus collisions (A+A) are used as a tool to study strongly interacting matter under extreme conditions. In the laboratory we can control two basic parameters determining the property of the matter: the size of the colliding nuclei and the collision energy. With the increasing size of the colliding nuclei we increase the volume of the created matter and its life time. Increasing collision energy we increase the initial energy density of the created matter. Thus the transition from hadronic matter (HM) to QGP should be observed as a change of the collision properties studied as a function of the size of colliding nuclei and/or collision energy.

The characteristic feature of the transition from hadronic matter to QGP is an increase of the effective number of degrees of freedom and the reduction of their masses [3]. The increase of the effective number of degrees of freedom should cause an increase of entropy production. Thus the produced entropy, at high energies mainly determined by the multiplicity of pions, can be considered as one of the important observables in search for a transition to QGP [4]. The reduction of the effective masses of the degrees of freedom should result in the weaker dependence of the ratio *particle number/entropy* on the temperature of matter (collision energy). The corresponding observable is the ratio *strangeness/entropy* [5, 6], at high energy mainly determined by the ratio *strangeness/pion*; by strangeness we mean here total number of s and $\overline{s}$ quarks in the system. Note that entropy, strangeness and baryon number are defined in any form of strongly interacting matter like QGP or HM. Therefore their values (or ratios) can be followed through hadronization and freeze–out stages of the collision when the distribution of entropy, strangeness and baryon number among final states hadrons takes place.

We argue below that the existing data on pion and strangeness production in central collisions of heavy nuclei indicate rapid changes occuring between BNL AGS (≈ 15 A·GeV/c) and CERN SPS (≈ 200 A·GeV/c) collision energies. Can these changes be interpreted as due to transition from HM to QGP?

This presentation reviews several recent works of Dieter Röhrich and myself [7, 8, 9] where the details of the analysis and the references to the original experimental papers used in the compilations [7, 9] are given.

The paper is organized as follows. In the Section 2 the main properties of the analysis of the experimental data are described. In Sections 3 and 4 the experimental results are presented. The dependence of pion and strangeness production

on the number of participant nucleons and collision energy is shown. The results are discussed in Section 5. The paper is closed by summary and conclusions given in Section 6.

2. Analysis

The aim of this paper is to study basic features of pion and strangeness production in nuclear collisions as a function of the size of the colliding nuclei and the collision energy. This goal suggests a specific way of data selection and presentation.

Matter created in A+A collisions expands in a complicated way. This expansion depends on the size of the colliding nuclei and collision energy. In order to reduce the influence of the expansion on the results and allow comparison of the data for various systems and energies we limit analysis to the data integrated over the full momentum space.

Comparison and interpretation of the data can be further simplified by concentrating on the data for head–on collisions of identical nuclei. Thus in the present paper the analysis is limited to the central collisions of similar nuclei.

Even in head–on collisions of identical nuclei not all nucleons participate in the interaction. Therefore to study the volume dependence an average number of participant nucleons, $\langle N_P \rangle$, measured experimentaly for each reaction is used instead of the total number of nucleons in the colliding nuclei. The A+A results are compared with the corresponding results for all inelastic nucleon–nucleon (N+N) interactions. In the case of N+N interactions the number of participant nucleons is taken to be 2.

The collision energy dependence is studied using the Fermi energy variable [10, 11]:

$$F = \frac{(\sqrt{s}_{NN} - 2m_N)^{3/4}}{\sqrt{s}_{NN}^{1/4}},\tag{1}$$

where $\sqrt{s}_{NN}$ is the c.m. energy for a nucleon–nucleon pair and m_N is the mass of the nucleon. There are several advantages in using F as an energy variable. The measured mean pion multiplicity in N+N interactions, $\langle \pi \rangle_{NN}$, in the studied collision energy range is approximately proportional to F [7, 8, 12]. In the Landau model [11] both the entropy and the initial temperature of the matter (for $\sqrt{s}_{NN} >> 2m_N$) are also proportional to F.

3. Pion Puzzle

The dependence of the average pion multiplicity per participant nucleon, $\langle \pi \rangle / \langle N_P \rangle$, on the number of participant nucleons is shown in Fig. 1 for three different collision energies.

Results for central collisions of identical nuclei (A > 30) are plotted together with the results for N+N interactions. The $\langle \pi \rangle / \langle N_P \rangle$ ratio for central A+A col-

lisions at all energies is independent of $\langle N_P \rangle$ [13]. At low energies ($p_{LAB} < 15$ A·GeV/c) the value of the saturation level of the $\langle \pi \rangle / \langle N_P \rangle$ ratio for central A+A collisions is significantly lower than the corresponding value for N+N interactions. This effect is called **pion suppression** in low energy A+A collisions. At high energies **pion enhancement** is observed; the saturation level for central A+A collisions is higher than the corresponding ratio for N+N interactions.

The independence of the $\langle \pi \rangle / \langle N_P \rangle$ ratio of $\langle N_P \rangle$ simplifies a study of the energy dependence for which data for various nuclei can be put together. The difference between the ratio $\langle \pi \rangle / \langle N_P \rangle$ for central A+A collisions and N+N interactions:

$$\Delta \frac{\langle \pi \rangle}{\langle N_P \rangle} = \frac{\langle \pi \rangle_{AA}}{\langle N_P \rangle_{AA}} - \frac{\langle \pi \rangle_{NN}}{\langle N_P \rangle_{NN}} \tag{2}$$

is plotted in Fig. 2 as a function of F.

The difference is energy independent and equal to about –0.35 for low energy collisions ($p_{LAB} < 15$ A·GeV/c). The low energy scaling is violated by high energy results (Pb+Pb at 158 A·GeV/c and S+S at 200 A·GeV/c), where the enhancement of pion production is observed. A possible origin of this unusual energy behaviour, called **pion puzzle**, is discussed in Section 5.

4. Strangeness Puzzle

Total production of strangeness relative to pion production is studied using the ratio [14]:

$$E_S = \frac{\langle \Lambda \rangle + \langle K + \overline{K} \rangle}{\langle \pi \rangle}, \tag{3}$$

where $\langle \Lambda \rangle$ is the mean multiplicity of produced Λ / Σ^0 hyperons and $\langle K + \overline{K} \rangle$ is the mean multiplicity of kaons and antikaons. The dependence of the E_S ratio on $\langle N_P \rangle$ is shown in Fig. 3 for three different collision energies. The results for central A+A collisions [16] are shown together with the results for N+N interactions. Due to the fact that the data on strangeness production are sparse the data for collisions between non–equal mass nuclei are also included (C+Cu/Zr at 4.5 A·GeV/c, Si+Au/Pb at 14.6 A·GeV/c [15] and S+Ag at 200 A·GeV/c).

There is a significant increase of the relative strangeness production (measured by the E_S ratio) when going from N+N interactions to central A+A collisions at all studied collision energies. This increase is called **strangeness enhancement**. It appears to be strongest at BNL AGS energy. The relative strangeness production saturates for large enough values of $\langle N_P \rangle$ at AGS BNL and CERN SPS energies. The saturation effect can not be established at 4.5 A·GeV/c as the results for collisions of heavy nuclei do not exist at this energy.

The collision energy dependence of the E_S ratio is shown in Fig. 4. The results for N+N interactions are shown in Fig. 4a. A monotonic increase of E_S between Dubna energy ($p_{LAB} = 4.5$ A·GeV/c) and CERN SPS energy ($p_{LAB} = $

200 A·GeV/c) is observed. In the range from 15 A·GeV/c to 200 A·GeV/c the E_S ratio for N+N interactions increases by a factor of about 2. A qualitatively different energy dependence is observed for central A+A collisions. The rapid increase of the E_S between Dubna and BNL AGS energies is followed by a weak change of the E_S between BNL AGS and CERN SPS collision energies (Fig. 4b).

A possible interpretation of the **strangeness puzzle** – 'strange' energy dependence of the relative strangeness production in A+A collisions – is discussed in the next section.

5. Discussion

The saturation of the relative pion ($\langle\pi\rangle/\langle N_P\rangle$) and strangeness ($E_S$) production with the volume of the created system ($\langle N_P\rangle$) may be treated as an indication that both entropy and strangeness approached their equilibrium values. Thus the interpretation of the results in terms of statistical models is suggested by the data.

It can be argued [11, 17, 18] that both entropy and strangeness reach saturation at the early and hot stages of the collision and their values are only weakly affected by later stages of system evolution. Further interpretation of the present results is therefore based on the simplifing assumption that the measured final state entropy and strangeness reflect the equilibrium values at high temperature stage. Thus studing the entropy and strangeness production one can try to deduce the properties of matter (HM or QGP) at the early stage of the collision.

Transition from HM to QGP causes an increase of the effective number of degrees of freedom resulting in the increase of entropy production. As pointed out by Landau [11] the entropy of the system is approximately proportional to the pion multiplicity [19]. The entropy contained in baryons and generated during their thermalization process is not directly sensitive to the initial number of degrees of freedom and therefore should not be counted. Thus the relevant quantity is the entropy contained in the produced particles – the *inelastic* entropy. However during the expansion process a fraction of the initially created inelastic entropy can be transfered back to the baryonic environment. The experimental observation of pion suppression at low energies (see Figs. 1 and 2) can be interpreted as a result of the inelastic entropy transfer to baryons. Following arguments given in Ref. [8] one can estimate the inelastic entropy as:

$$S \sim \langle\pi\rangle + \alpha \cdot \langle N_P\rangle, \tag{4}$$

where $\alpha \cdot \langle N_P\rangle$ is a correction for the inelastic entropy transfer to baryons ($\alpha \approx -0.35$). For simplicity the contribution from other produced particles (mainly kaons) is neglected in Eq. 4, but it is included in the final evaluation of S presented in Fig. 5a [8].

The unusual increase of the relative pion production at CERN SPS energies may be interpreted as due to an increase of the effective number of degrees of

freedom. In fact, in the generalized Landau model [8] the inelastic entropy is proportional to:

$$S \sim g^{1/4} \cdot \langle N_P \rangle \cdot F, \tag{5}$$

where g is the effective number of degrees of freedom. Thus the observed deviation of the data for A+A collisions from the Landau scaling:

$$\frac{S}{\langle N_P \rangle} \sim F \tag{6}$$

can be interpretad as due to an increase of the effective number of degrees of freedom when crossing the transition collision energy. The magnitude of this increase can be estimated, within the generalized Landau model, as forth power of the ratio of slopes of straight lines describing (see Fig. 5a) low and high energy A+A data: $1.33^4 \approx 3$ [8]. A hypothetical dependence of $S/\langle N_P \rangle$ on F is shown by solid lines in Fig. 5a; the transition region is assumed to be at about $p_{LAB} = 30$ A·GeV/c [20].

The second dominant effect of the transition from HM to QGP is the reduction of the effective masses of degrees of freedom. Basic thermodynamics tells us that for massless particles the ratio *particle number/entropy* is independent of temperature. For massive particles the ratio increases with T at low temperature approaching saturation level (equal to the corresponding ratio for massless particles) at high temperatures, $T >> m$. This property can be used to study the magnitude of the effective mass of strangeness carriers in strongly interacting matter. The E_S ratio is approximately proportional to the ratio *number of strangeness carriers/entropy (strangeness/entropy)* and therefore its temperature (collision energy, F) dependence should be sensitive to the effective mass of strangeness carriers. Reduction of the mass of strangeness carriers should cause a weaker dependence of the E_S ratio on the collision energy.

The rapid increase of the E_S ratio in the energy range of $F < 2$ GeV$^{1/2}$ (see Fig. 4b) can be interpreted as due to large effective mass of strangeness carriers (kaons or constituent strange quarks, $m_S \approx 500$ MeV) in comparison to the temperature of matter, $T < T_C \approx 150$ MeV. At temperature above T_C matter is in the form of QGP and mass of strangeness carriers is equal to the mass of current strange quarks, $m_S \approx 150$ MeV, consequently $m_S \leq T$. Thus much weaker dependence of the E_S ratio on F is expected in the high energy region where the creation of QGP takes place.

The equilibrium value of the *strangeness/entropy* ratio is higher in HM than in QGP at very high temperatures. This is due to the fact that it is proportional to the ratio of the effective number of strangeness degrees of freedom to the number of all degrees of freedom. This ratio is lower in QGP than in hadronic matter. At low temperature, however, the *strangeness/entropy* ratio is lower in HM than in QGP. This is caused, as previously discussed, by the high mass of strangeness carriers in HM. Thus, in general, a transition to QGP may lead to an increase or a decrease of the *strangeness/entropy* ratio depending at which temperatures of QGP and HM the comparison is made. A quantative estimation of the *strangeness/entropy*

dependence on temperature within simple models of QGP and HM can be found in Ref. [6]. The estimated temperature of the crossover of QGP and HM dependences is about 130 MeV [6]. The measured low values of the E_S ratio at CERN SPS relative to the values at BNL AGS can be interpreted as due to reduction of the E_S value at the transition to QGP. The hypothetical dependence of the E_S ratio on F is indicated by the solid lines in Fig. 5b. The transition region is assumed to be at about $p_{LAB} = 30$ A·GeV/c [20].

6. Summary and Conclusions

The experimenal data on pion and strangeness production indicate:
(a) saturation of pion and strangeness production with the number of participant nucleons,
(b) change in the collision energy dependence occuring between 15 A·GeV/c and 200 A·GeV/c.
Within a simple statistical approach the observed behaviour can be qualitatively understood as due to:
equilibration of entropy and strangeness production in collisions of heavy nuclei (a), transition from hadronic matter to QGP occuring between BNL AGS and CERN SPS energies (b).
These observations hold already for the central S+S collisions, they are not unique to central Pb+Pb collisions.

A quantitative description of the existing data within theoretical models and experimental study of the energy dependence of pion and strangeness production between BNL AGS and CERN SPS energies are needed for a final clarification of the observed pion and strangeness puzzles.

Acknowledgments

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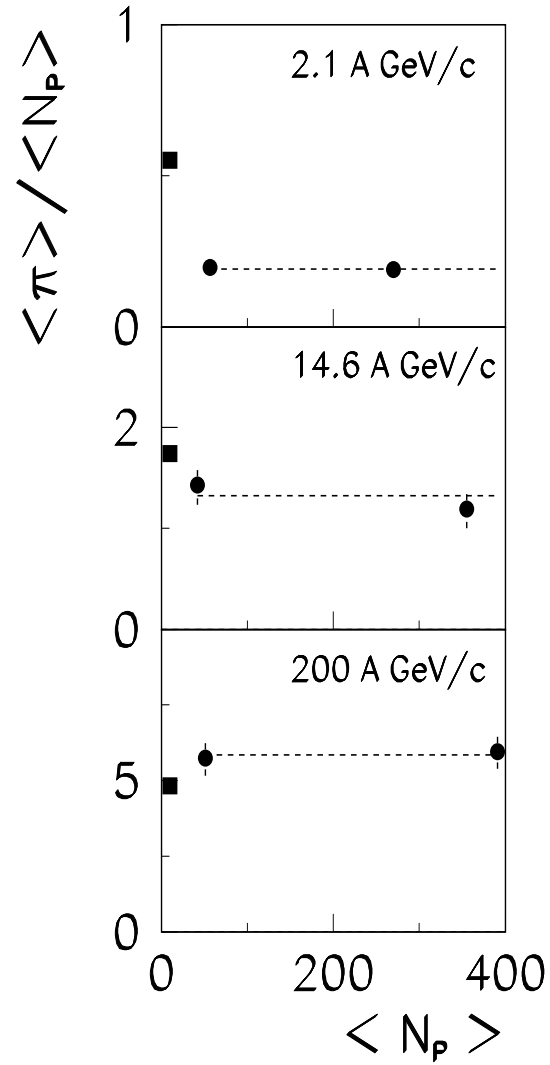20. C. M. Hung and E. V. Shuryak, Phys. Rev. Lett. **75** (1995) 4007

Fig. 1. The dependence of the ratio $\langle \pi \rangle / \langle N_P \rangle$ on $\langle N_P \rangle$ at three different collisions energies (p_{LAB} = 2.1, 14.6 and 200 A·GeV/c). The data for Au+Au at 11.6 A·GeV/c and Pb+Pb at 158 A·GeV/c were extrapolated to 14.6 A·GeV/c and 200 A·GeV/c, respectively. The data for central A+A collisions are indicated by circles and the data for N+N interactions by squares.
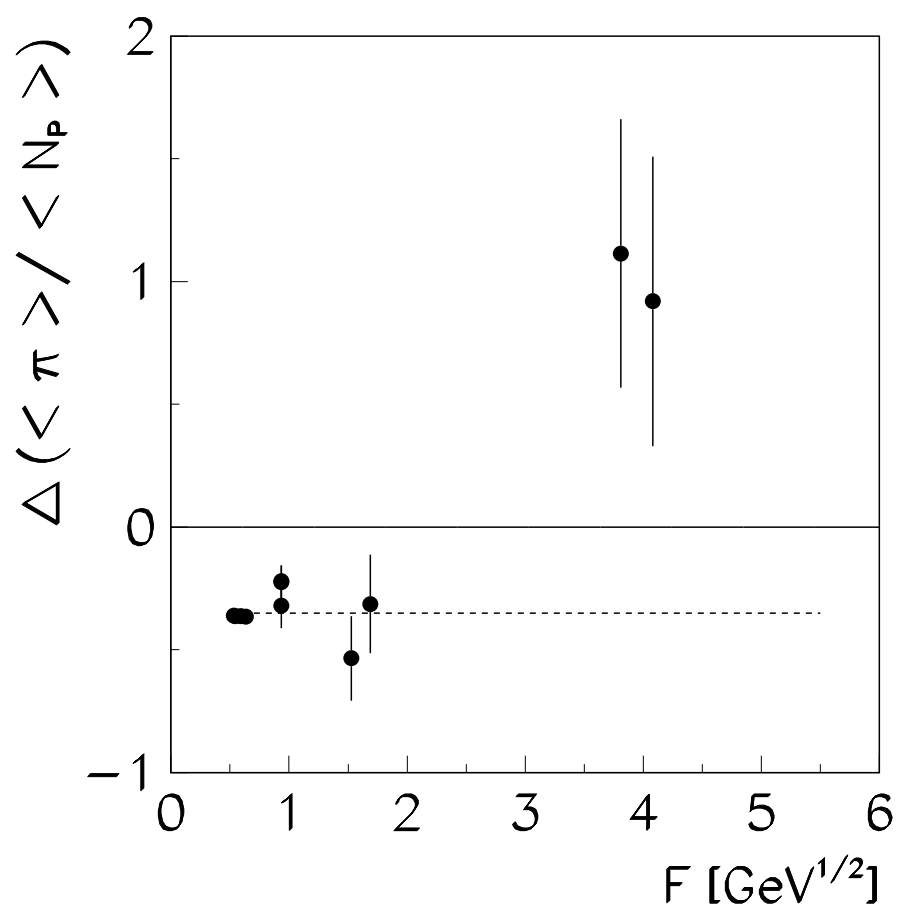
Fig. 2. The dependence of the difference $\Delta(\langle\pi\rangle/\langle N_P\rangle)$ (see Eq. 2) on the collision energy measured by the Fermi energy variable, F (see Eq. 1).
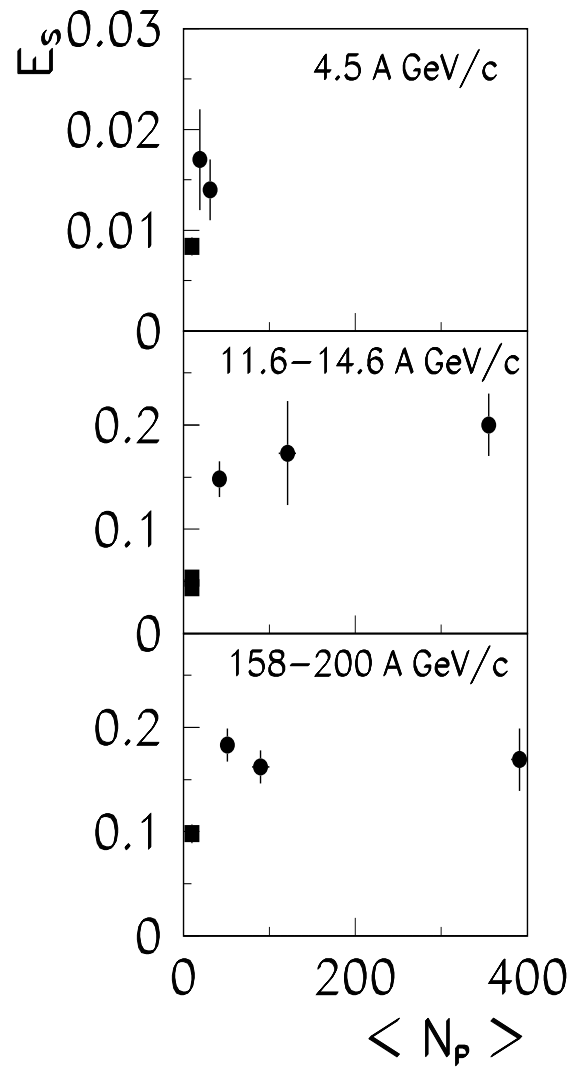
Fig. 3. The dependence of the E_S ratio (see Eq. 3) on $\langle N_P \rangle$ at three different collisions energies (p_{LAB} = 4.5, 11.6–14.6 and 158–200 A·GeV/c). The data for central A+A collisions are indicated by circles and the data for N+N interactions by squares.

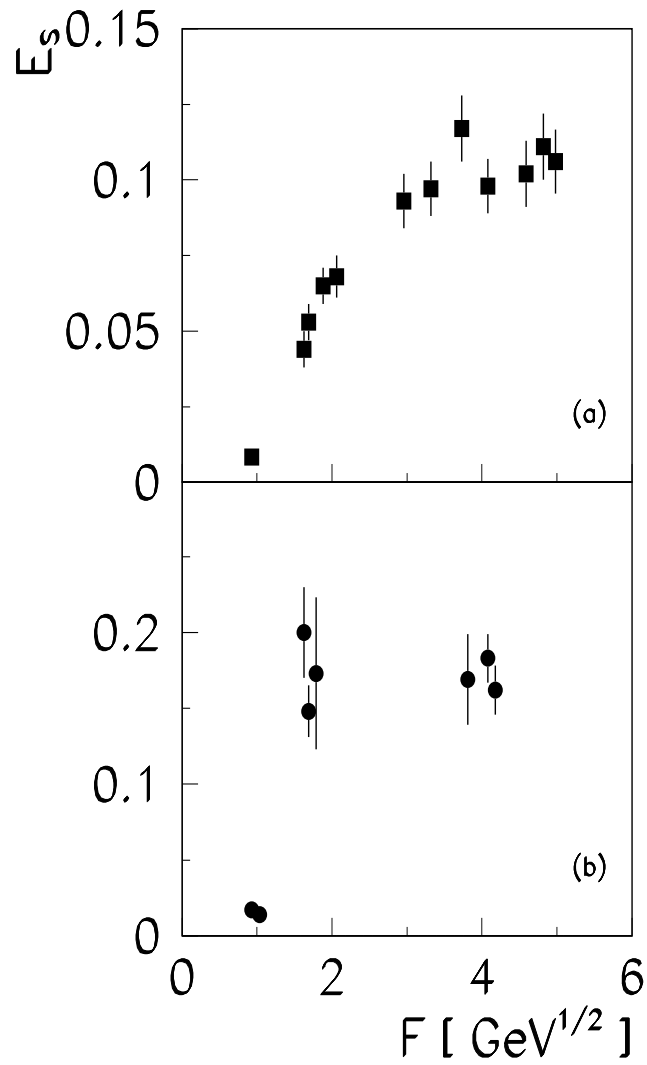**Fig. 4.** The dependence of the E_S ratio (see Eq. 3) on the collision energy measured by the Fermi energy variable, F (see Eq. 1) for N+N interactions (a) and central A+A collisions (b).
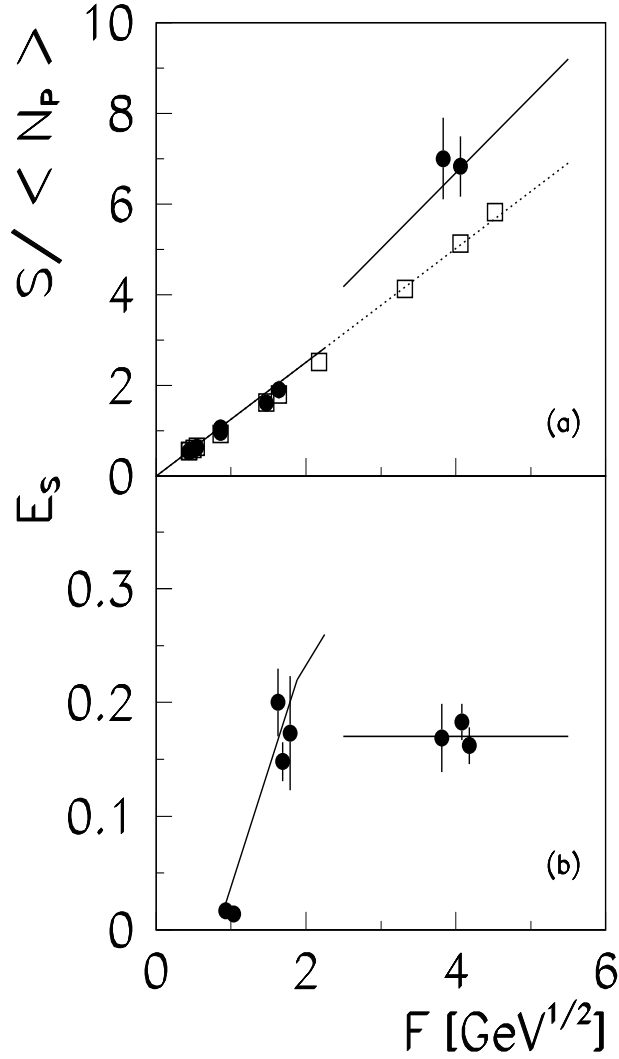
Fig. 5. (a) The dependence of the $S/\langle N_P \rangle$ ratio (see Eq. 4) on the collision energy measured by the Fermi energy variable, F (see Eq. 1). The entropy, S, is measured in units given by pion entropy at freeze–out. A hypothetical dependence of $S/\langle N_P \rangle$ ratio on F for central A+A collisions assuming transtion to QGP at $p_{LAB} = 30$ A·GeV/c is shown by solid lines. The data for central A+A collisions are shown by circles and the data for N+N interactions by squares. (b) A hypothetical dependence of the E_S ratio on F assuming transition to QGP at $p_{LAB} = 30$ A·GeV/c is shown by a solid lines. The data for central A+A collisions are indicated by circles.