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FUTURE PLANS OF THE NA49 COLLABORATION

The NA49 detector with its wide acceptance coverage and extensive particle identification capabilities, offers a general purpose instrument for the study of hadronic interactions which is today unique in the SPS energy range.

After a first phase of exploratory investigation of lead-lead interactions at the highest SPS energy, the collaboration is planning to extend its experimental programme into a systematic survey of hadronic phenomena in proton-proton, proton-nucleus, and nucleus-nucleus reactions. This programme should explore the range of beam momenta available at the SPS as well as different target and projectile nuclei, with the aim at establishing a consistent set of data obtained with the same experimental apparatus.

In the course of this programme, several additions to the present detector layout are foreseen in order to enhance its physics potential:

- Impact parameter trigger detector using multiplicity of low-energy target fragmentation products
- Enhanced particle identification in the backward rapidity hemisphere by adding Pestov counter arrays inside the vertex magnets
- Forward detector for the study of projectile fragmentation products and for extension of acceptance to the kinematic limit for beam momenta above 80 GeV/nucleon
- Microvertex detectors for extended particle spectroscopy

Most of the anticipated detector upgrades serve at the same time as a testbed for detector developments in the framework of the ALICE experiment at LHC. It should be stressed that this synergy is essential for the proper evaluation of detector performance in the correct range of experimental boundary conditions (e.g. track density and overall detector load) to be expected at LHC.

1. Intermediate energy Pb+Pb collisions

Analysis of experimental data from NA35 and NA49 on central S+S and Pb+Pb collisions at the CERN SPS (nucleon-nucleon $\sqrt{s} = 19.4$ and 17.2 GeV respectively) and of complementary data from AGS heavy ion experiments (nucleon-nucleon $\sqrt{s} \sim 5$

GeV) shows that relative pion and relative strangeness production in central nucleus-nucleus collisions undergo an apparent qualitative change as a function of bombarding energy between these two energy regimes. The gap in bombarding energy is large, however, and understanding of this phenomenon would be greatly advanced by additional experimental data at some intermediate bombarding energies. To this end, the NA49 collaboration proposes to study central Pb+Pb collisions at one intermediate energy ($E_{\rm lab}$ ~40A-GeV, nucleon-nucleon $\sqrt{s} = 4.3$ GeV) as soon as possible. Further studies (different energies and collision systems) would be contingent upon results of this initial study.

One possible interpretation of the relative change in pion and strange particle production (see attached NA49 note for a more detailed discussion) is that a significant degree of color deconfinement occurs between AGS and SPS energies, which would be an indication of the formation of a quark-gluon plasma (QGP). However, prior to claiming the existence of a new state of matter we must exhaust the ability of conventional, i.e. hadronic, physics to explain the data. Because of the theoretical uncertainties in interpolating hadronic physics between the two energy regimes, this task is made difficult by the lack of available experimental data. At least one intermediate energy (40A GeV) should be explored at the SPS to provide a basis for interpolation. Evidence for QGP formation would then consist of differential phenomena not explainable by the energy dependence of hadronic phenomena over the whole energy interval from AGS to SPS, including the results of this intermediate energy study.

At the end of the 1997 Pb-beam period a machine development test run with 40 GeV/nucleon Pb ions is forseen. If the beam would then be extracted into the North Hall for a few days NA49 could address the question of possible sudden qualitative changes in this energy regime. A data sample of 100 K events would suffice for a first analysis and could be collected within two days.

2. Impact parameter trigger detector

For an extrapolation of the effects of rescattering in cold nuclear matter from pA collisions to AA collisions it is desirable not to be restricted to a minimum bias event sample but to perform an appropriate impact parameter average.

Small impact parameter pA collisions represent a few percent of the total inelastic cross section. In order to obtain a statistically significant sample an impact parameter selection at the trigger level is necessary. A special multiplicity detector around the target is being constructed for this purpose.

This detector will consist of a cylindrical array of proportional counters, surrounding the nuclear target with 256 elements covering production angles up to 1 unit of pseudorapidity. Proton momenta down to about 150 MeV/c will be detected. A fast majority coincidence should allow an impact parameter selection, at trigger level, with a resolution of better than 2 Fermi. This should allow a suppression of peripheral events between one and two orders of magnitude and thereby greatly enhance data taking efficiency.

3. Pestov Time-of-Flight arrays (PesTOF)

Operation and longterm stability of several PesTOF detector units had been extensively tested both at the CERN PS and with cosmic rays at GSI. Stable operation of 9 detectors was maintained over a period of 9 months. A time resolution of 35 ps was found in coincidence studies at CERN. It is foreseen to have 32 detector units, each with 32 electronic channels, installed in the NA49 experiment for the heavy ion

run 1997. A total of 1024 electronic channels will be used to readout the detector. Double threshold discriminators (DTD) are of a novel design and will be tested for the first time in a data production environment. The remaining part of the electronics will consist of custom made QDC's and standard TDCs. The study and optimisation of detector performance in terms of two particle resolution, electronic channel cross talk, pile up and timing resolution is one of the goals of this project.

Secondly, the position of the detector modules was selected in order to extend the particle identification capabilities of the NA49 setup for charged kaons in view of increasing the number of identified kaons per event and extending the acceptance for kaons into the rapidity interval $1.2 < y < 2.2$. The latter improvement is essential for the determination of the complete rapidity distribution and thus 4π multiplicity of K^+ and K^- mesons. A possible byproduct is the detection of additional Φ mesons through their decay into $K^+ + K^-$. The regions in phase space of Kaons and Φ's newly accessible by means of the Pestof detectors comprise $1.2 < y < 2.2$ for transverse momenta up to 1.3 GeV/c.

In a second step a total of 88 counters (2816 readout channels) will be made available to NA49 for the run in 1998. It is planned to employ custom made TDC ASIC's in this run.

It should be noted that the configuration both in terms of the detector setup (the counters are located in a magnetic field at 3.5 m distance from the interaction point behind a TPC) and layout of the frontend readout is of ALICE-type and constitues therefore a first approach to conditions expected for ALICE collider runs.

4. Forward detector

A small Time Projection Chamber will be placed in front of the Main TPC's of NA49 behind the vertex magnets, centered on the beam line. This TPC will cover the range of longitudinal momenta above about 90 GeV/c, thus complementing the acceptance of the standard NA49 detectors up to the kinematic limit. The TPC will have 40 cm vertical drift length (corresponding to a transverse momentum coverage of 2 GeV/c) and a readout chamber of dimension 30×40 cm^2. The study of nuclear fragments in the projectile frame will also be possible.

For NA49, the ability to study the longitudinal and transverse momentum spectra of leading mesons and baryons as well as spectator particles in conditions of controlled centrality and in correlation with more centrally produced identified hadrons, will help to expand the physics programme.

According to the high track densities and extended energy loss range to be expected, this TPC serves at the same time as prototype detector for the development of the ALICE barrel TPC. Several new features will be included in its design:

- new pad structure (Ring Cathode Chamber, developed in the RD32 project)
- new gating scheme
- new front end electronics and digitization scheme
- new electronics mounting technology (TAB)
- new readout chamber construction.

The installation in NA49 will enable a sensitive study of space and two-track resolution as well as dynamic range and occupation density problems in electronics performance.

The long-range operational stability in terms of wire aging and induced self-stable discharges will also be clarified. These latter aspects are of major concern in the ALICE environment.

5. Microvertex detector

The feasibility of a micro-vertex-detector for the study of open charm production in Pb+Pb collisions within the NA49 experiment has been under investigation for some time. Present plans are based on the use of a pre-production batch of Si-drift chambers produced for the Silicon-Vertex-Tracker of the STAR experiment at RHIC. A telescope of 4 planes of 4 detectors each would be placed with 8 cm spacing downstream of the target. The detectors of 6.3×6.3 cm^2 sensitive area have a measuring accuracy of $\sigma_x = \sigma_y < 25\mu$ and a double hit resolution of about 350 μ. Monte Carlo simulations of neutral D-meson decays in the detector look encouraging; they indicate that several hundred D^0 and $\bar{D}^0$ decays into K and π will survive the selection cuts in 10^6 central Pb+Pb events. With an estimated mass resolution of 20 MeV they would represent a signal of $S/N = 2/1$ in the $K\pi$ mass distribution. The situation is expected to be even more favorable for the charged D into $K\pi\pi$ channels.

Negotiations are under way on the availability and compatibility of the use of these STAR detectors in NA49 considering the constraints of the startup of the STAR experiment at RHIC. Similar Si-drift chambers are planned for use in the ALICE inner tracking detector. For this reason the Italian groups lead by L. Riccati have expressed an interest in participating in such a project within NA49.

Searching for QCD Phase Transition

Proposal of NA49 for a low energy Pb–run at the SPS

May 23, 1997

1 Introduction

An analysis of results of the experiments NA49 [1] and NA35 [2] on central Pb+Pb and S+S collisions at CERN SPS energies (158 A·GeV and 200 A·GeV) and AGS experiments ($\approx$ 15 A·GeV) show that the collision energy dependence of the relative pion and strangeness production in central nucleus–nucleus (A+A) interactions changes between these two energies [3]. The most exciting of the possible interpretations of these observation is that a transition to a new form of strongly interacting matter, the Quark Gluon Plasma, takes place somewhere in the above energy range. This interpretation is plausible because estimated initial energy density in A+A collisions at SPS is larger than the critical energy density obtained from lattice QCD calculations. Therefore, we suggest to confirm such an interpretation with a search for the transition energy. *For this purpose the NA49 Collaboration proposes to study central Pb+Pb collisions at the intermidate collision energy (around 30 A·GeV) as soon as possible.* Further studies (selection of different collisions energies and smaller colliding nuclei) will depend on the results from the intermidiate energy run.

This note presents the justification for this proposal. The experimental and theoretical motivations are reviewed in Section 2. The expected signals of the QCD transition are summarized in Section 3. The performance of the NA49 experiment and the required statistics and quality of data are discussed in Section 4.

2 QCD Phase Transition and High Energy Nuclear Collisions

The fundamental theory of strong interaction, quantum chromodynamics (QCD), predicts a phase transition at high temperature (density), approximately when the energy density reaches about one GeV/fm^3. The high temperature state of matter conjectured long ago [4] was called Quark Gluon Plasma (QGP) [5] because it has color charge *screening* rather than confinement. The transition to QGP is such that the QCD vacuum – a very complicated and dense medium by itself – is melted. In contrast to the low temperature (density) matter it consists of independent quarks and gluons. The basic feature of the transition from hadronic matter to QGP is an increase of the effective number of degrees of freedom and a reduction of their effective masses.

Theoretical studies of the properties of strongly interacting matter at nonzero temperature are performed by the QCD lattice simulations [6]. The results [7] for QCD with

dynamical quarks indicate that the transition temperature is about T_C = 140–160 MeV, and takes place in a narrow range of temperature, Δ T $\approx$ 20 MeV. The calculated change of energy density and pressure as a function of temperature [7] is shown in Fig. 1.

In the experimental studies of the properties of strongly interacting matter, high energy nuclear collisions play a unique role [8]. They make it possible to create, in the laboratory, 'macroscopic' space–time regions with high energy density. The volume and the energy density are controlled by the sizes of the colliding nuclei and the collision energy. Nucleus–nucleus collisions are studied at the SPS at the highest presently available energy (200 A·GeV for S beam and 158 A·GeV for Pb beam).

Let us now address the widely debated question whether the matter created in central nucleus–nucleus collisions at SPS energy is in the state of Quark Gluon Plasma. The experimental data on transverse energy spectra [9] allows to estimate [10] that the early stage energy density in central collisions of large nuclei is in the range of 1–3 GeV/fm^3. This is *above* the critical energy density obtained using lattice QCD simulations. Among the proposed signals of the QGP are strangeness enhancement [11], J/Ψ suppression [12] and significant dilepton production [13]: and indeed they are observed experimentally [14, 15, 16]. However these results do not allow to conclude on the discovery of the QGP because secondary hadronic processes produce qualitatively similar (and sometimes larger) effects.

A new dimension in the interpretation of the data is given by systematic studies of the *energy dependence* of the collision properties. The data on nuclear collisions at lower energies (BNL AGS: $\approx$15 A·GeV, JINR Dubna: $\approx$4.5 A·GeV, Bevelac LBL and SIS GSI: below 3 A·GeV) together with the existing data at the highest SPS energy allow two search for these effects in pion [17] and strangeness [18] production. In the following we outline the main experimental results interpreted in a simplest thermodynaical framework.

Most of the entropy created during a high energy nuclear collision is carried away by the produced pions. Thus the increase in the number of degrees of freedom at the early stage of the collision due to the creation of QGP should be reflected in abundant pion production. In fact, the energy dependence of the difference between the mean pion multiplicity per participant baryon for central A+A collisions and nucleon–nucleon (N+N) interactions shows a significant change (Fig. 2 [3]). Up to the AGS energy the pion production in A+A collisions is suppressed by about 0.3 pion per baryon relatively to N+N interactions, approximately independent of collision energy and the size of colliding nuclei. This suppression is not continuing at SPS energies. The data on central S+S and Pb+Pb [2, 17] collisions show an enhanced pion production by about one pion per baryon.

The transition from suppression to enhancement occurs between AGS and SPS energies.

The appropriate variable to study the collision energy dependence is the Fermi variable [19, 20]:

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

where $\sqrt{s}_{NN}$ is the c.m. energy for a nucleon–nucleon pair and m_N is the mass of the nucleon. Within the Landau model [20] the early stage entropy is proportional to F. The initial temperature of matter is also approximately (for $\sqrt{s}_{NN} > 2m_N$) proportional to F for the fixed number of degrees of freedom. Because of these simple 'thermodynamical' features the F variable is used to present energy dependence of pion and strangeness production in Figs. 1 and 2.

A reduction of the mass of strangeness carriers during the transition from hadronic matter ($m_K \approx 500$ MeV/c^2) to QGP ($m_S \approx 150$ MeV/c^2) as well as a change in the effective number of strange degrees of freedom should be reflected in the energy dependence of strangeness production. The ratio of the multiplicity of strange particles to pions is shown in Fig. 3 [18] for central A+A collisions and N+N interactions. Both ratios show a rapid increase from Dubna to AGS energies. The ratio for N+N interactions increases further when going from AGS to SPS energy. No such increase is observed for central A+A collisions, indicating a change of the energy dependence of the relative strangeness (to pion) production again occuring between AGS and SPS energies. On a qualitative level this change can be interpreted as following [18]. In hadronic matter due to the large mass of strange hadrons relative to the temperature the ratio of strangeness to pions (approximately equal to the ratio of strangeness to entropy) grows with the temperature (collision energy). Much weaker energy dependence of the strangeness to entropy (pion) ratio is predicted for the QGP phase where the mass of strangeness carriers is similar or smaller than the temperature of matter. At high temperatures the strangeness/entropy ratio is larger in hadronic matter than in QGP. Therefore the *non–monotonic* behaviour of the strangeness/entropy ratio as a function of the collisions energy can be expected in the transition region [21]. Note that this simplified interpretation is based on the assumption that the entropy and the number of strangeness carriers reach equilibrium in the early stage of the collision and are conserved during the system evolution.

As mentioned above the early stage energy density estimated on the basis of transverse energy measurements at the SPS using Bjorken initial conditions [10] is higher than the critical energy density of QGP obtained in lattice QCD calculations. This yields an upper limit for the transition collision energy $E_C < 160$ A·GeV. An estimate of the lower

limit of E_C performed using Landau initial conditions [20] yields $E_C > 30$ A·GeV [22]. These estimates of E_C limits based on the energy density arguments agree well with the experimental localization of E_C using pion and strangeness data.

The observed energy dependence of pion and strangeness production together with the detection of other signatures of QGP suggest that at the CERN SPS energy the matter created in A+A collisions is initially in the state of Quark Gluon Plasma. Consequently we should search for the collision energy at which the transition occurs and study the transition properties.

The program should be started with a study of central Pb+Pb collisions at around 30 A·GeV. From the previous considerations one expects that collisions at 30 A·GeV are below or at the threshold for the QCD phase transition. In the case that $E_C > 30$ A·GeV one will observe a further increase of the strangeness/pion ratio to values above the AGS and SPS results (see Fig. 3). A *non–monotonic* energy dependence of the ratio should be obvious from the data. If $E_C \approx 30$ A·GeV *unusual* behaviour in the space–time evolution of the matter and large event–by–event fluctuations are expected (see next Section). Thus the results at this energy would be more conclusive than those at $E > E_C$ where no such anomalies are expected.

3 Further Signals of the QCD Phase Transition

In the following we describe two other signatures of the QCD phase transition which can be measured by the NA49 experiment at the collision energy near to the transition energy.

Close to the transition energy a "softening" of the equation of state (EOS) is expected [23, 24]. The drop of the ratio of pressure to energy density, which defines acceleration of matter, (see Fig. 4 [22]) should influence the space–time evolution of the initially created fireball. In the extreme picture of Landau initial conditions discussed in Ref. [22] a stationary *slow–burning fireball* is created. Strong longitudinal and transverse expansion of matter observed at AGS and SPS energies should then be suppressed. Moreover the life time of the fireball increases significantly.

This should significantly influence inclusive spectra of the produced hadrons. Details of the space–time evolution of the matter created in nuclear collisions is "measured" by the analysis of two particle correlations. Large acceptance, high statistics and high momentum resolution of the NA49 experiment allow for an estimation of flow velocities and duration of particle emission. We should be able to observe a hypothetical non–monotonic energy dependence of these parameters when crossing the "softest" point of

the EOS. The longitudinal flow rapidity and the duration of pion emission obtained for central Pb+Pb collisions at 158 A·GeV are shown in Fig. 5 [25] as a function of the pion pair rapidity. In the extreme case of a *slow–burning fireball* the longitudinal flow rapidity (y_{YKP}) should be independent of pion pair rapidity and equal to the rapidity of the fireball ($y_{YKP} = 2.9$, dotted line in Fig. 5a). The duration of particle emission may reach 10–20 fm/c in comparison to the few fm/c measured at 158 A·GeV (see Fig. 5b).

The large acceptance of the NA49 experiment allows to study event–by–event fluctuations of global observables like particle multiplicity, total transverse energy or transverse momentum. Due to the fact that particles originating from decaying strings or resonaces are correlated one expects nonstatistical event-by–event fluctuations in A+A collisions provided that the freezeing–out matter consists of strings and/or resonances [26]. Preliminary results of the NA49 experiment [27] show that such fluctuations are not present in central Pb+Pb collisions at 158 A·GeV, see Fig. 6. As in the Quark Gluon Plasma the string–resonance structure is dissolved the study of the above fluctuations as a function of collision energy may serve as another signal of the onset of the QCD phase transition.

Close to the transition energy large event–by–event fluctuations (pion multiplicity, strangeness content) are expected due to fluctuations in the plasma creation processes: nucleation [29] or percolation [30]. At collision energies below the transition energy one may expect appearence of the fluctuations due to the string–resonance structure of the decaying matter. Thus characteristic changes in the event–by–event fluctuation pattern provide an additional signature of the QCD phase transition which can be measured by the NA49 experiment.

4 The Performance of NA49 for 30 A·GeV Pb+Pb collisions

In two weeks of data taking about $7{\cdot}10^5$ central Pb+Pb collisions can be registered by the NA49 detectors. This estimate is done assuming 50% overall run efficiency. As the mean particle multiplicities at 30 A·GeV are reduced by a factor of about two in comparison to the multiplicities at 158 A·GeV the collected statistics corresponds to about $3.5{\cdot}10^5$ events for single particle spectra and $1.5{\cdot}10^5$ events for two particle correlations at 158 A·GeV. This is sufficient for the analysis of all observables discussed in this proposal.

The acceptance of the NA49 tracking TPCs in rapidity–transverse momentum space is plotted in Fig. 7 for the standard NA49 magnetic field–target configuration. The center of mass rapidities for 30 A·GeV and 158 A·GeV collisions are indicated by dashed lines. It is

seen that using the standard NA49 configuration the NA49 TPCs cover fully the forward hemisphere for 30 A·GeV Pb+Pb collisions which is enough to perform an analysis for all necessary observables. The NA49 acceptance at 30 A·GeV, and specially Time–of–Flight acceptance needed for particle identification, can be further optimized by decreasing the magnetic field in the NA49 Vertex Magnets. The search for an optimum configuration is in progress.

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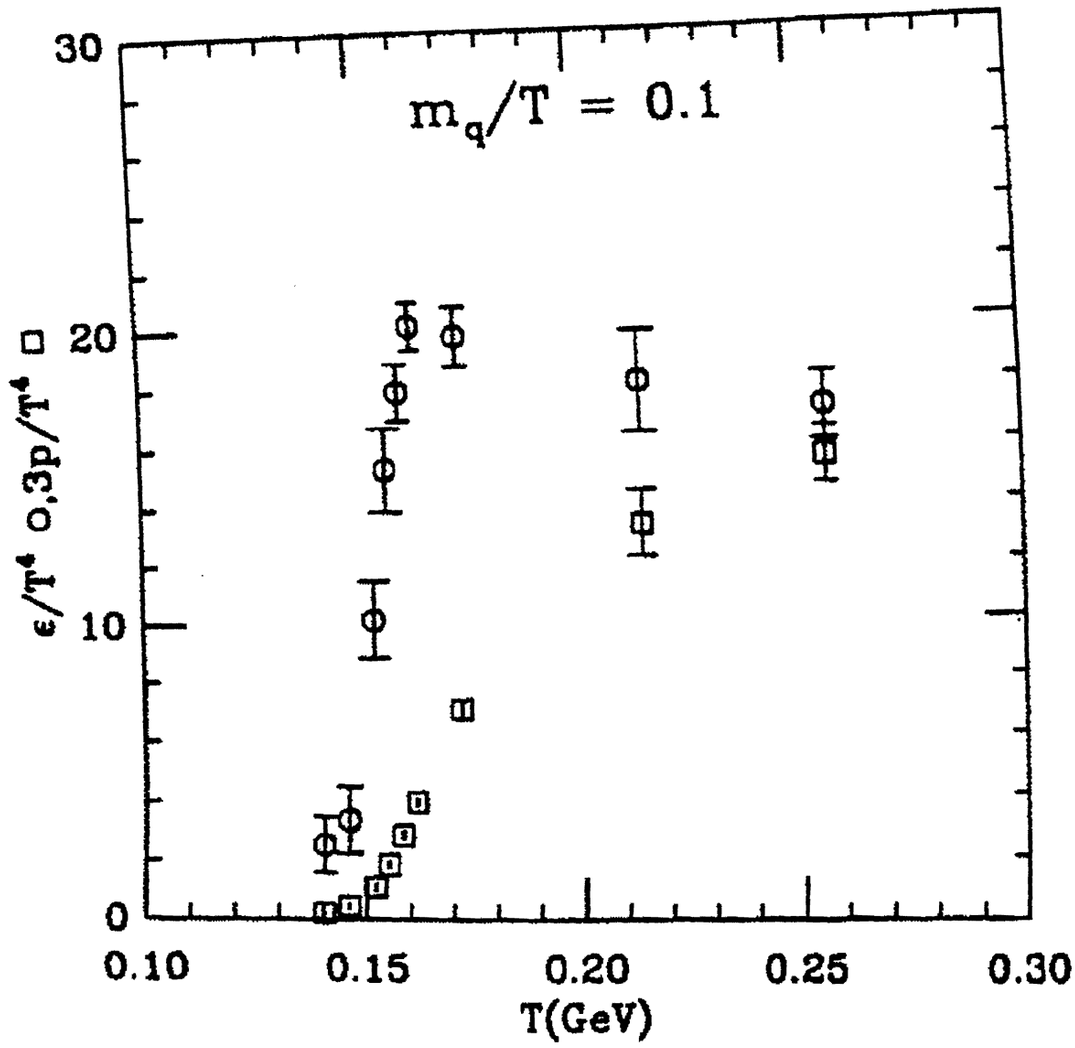

Figure 1: Energy density and pressure for two–flavour QCD on the lattice as a function of temperature[7].

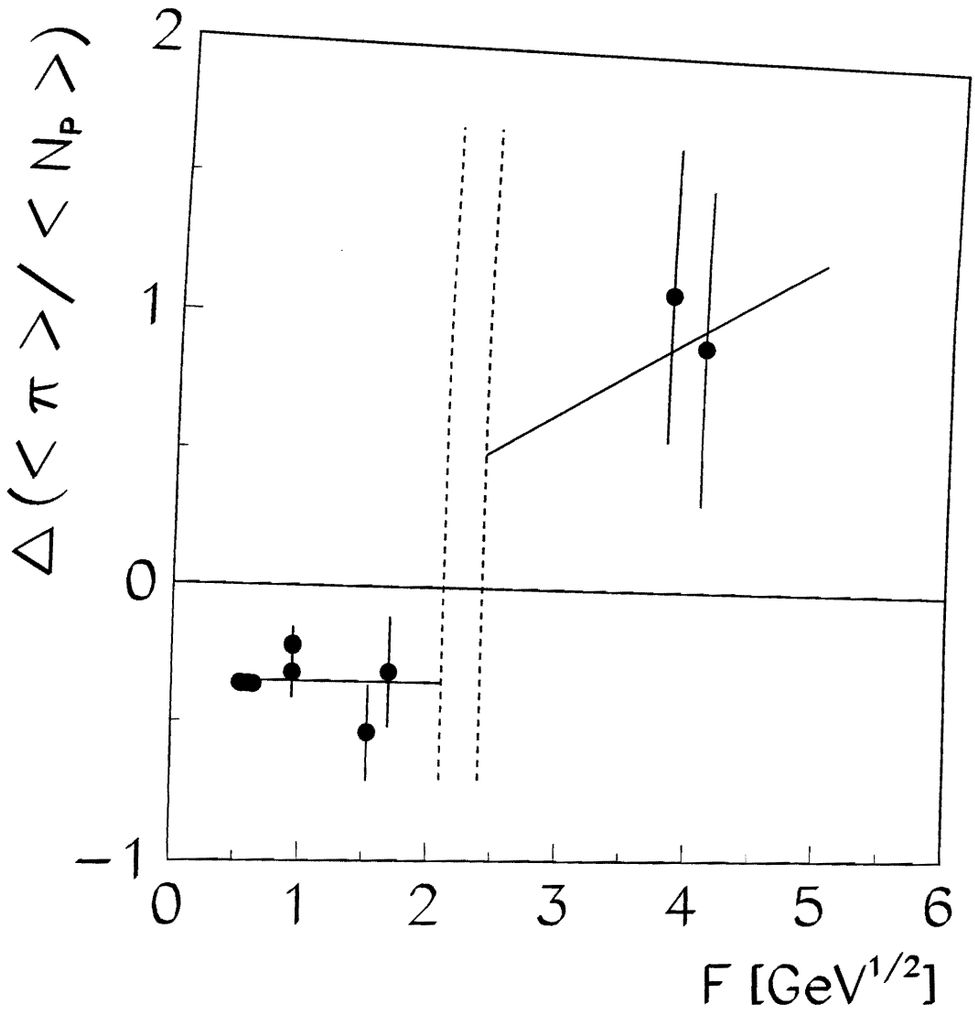

Figure 2: The dependence of the difference between pion/baryon ratios for central nucleus–nucleus collisions and nucleon–nucleon interaction at the same energy per nucleon on the collision energy measured by the Fermi energy variable, F (see Eq. 1) [17, 3]. The soild lines indicate the hypothetical energy dependence based on generalized Landau approach [3] assuming transition occuring in the energy region 25–40 A·GeV (dashed lines).

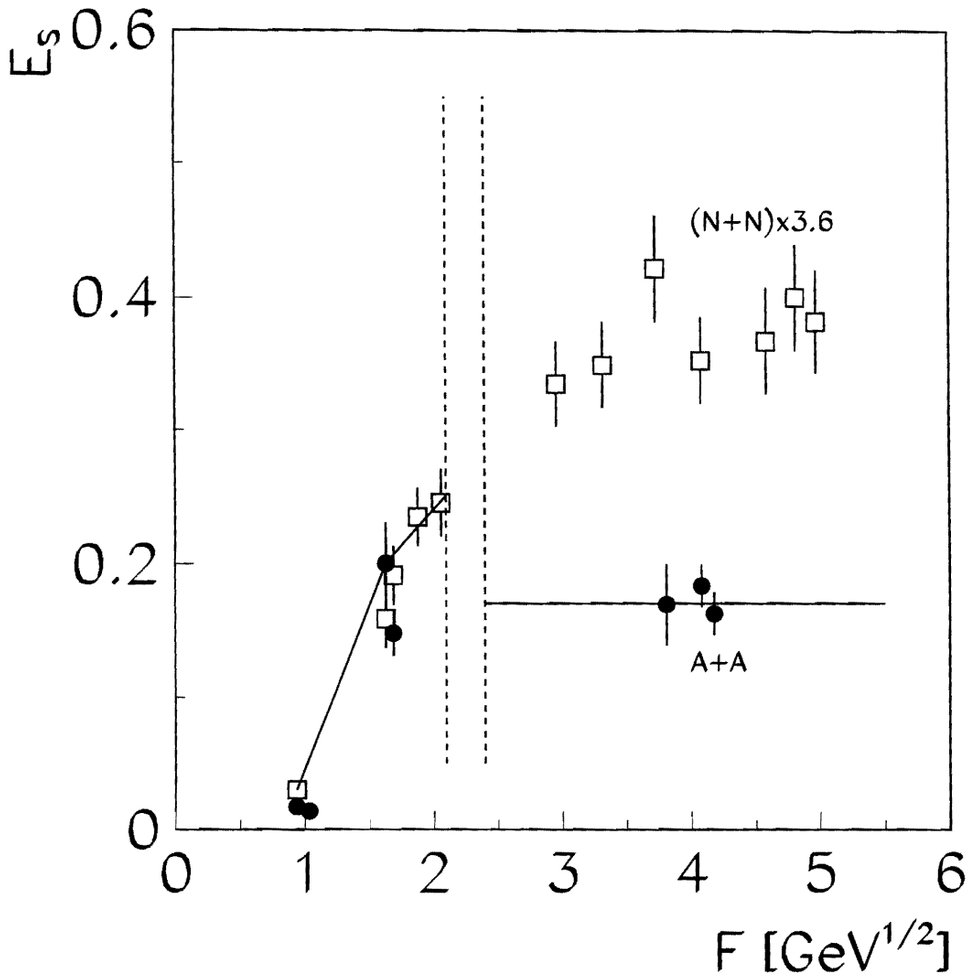

Figure 3: The dependence of the strangeness/pion ratio ($E_S = (\langle\Lambda\rangle + \langle K/\overline{K}\rangle)/\langle\pi\rangle$) for central nucleus–nucleus collisions (close circles) and nucleon–nucleon interaction (open squars, scaled by a factor 3.6 to match A+A data at AGS energy) at the same energy per nucleon on the collision energy measured by the Fermi energy variable, F [18]. The soild lines indicate the hypothetical energy dependence based on a simple thermal approach [18] assuming transition occuring in the energy region 25–40 A·GeV (dashed lines).

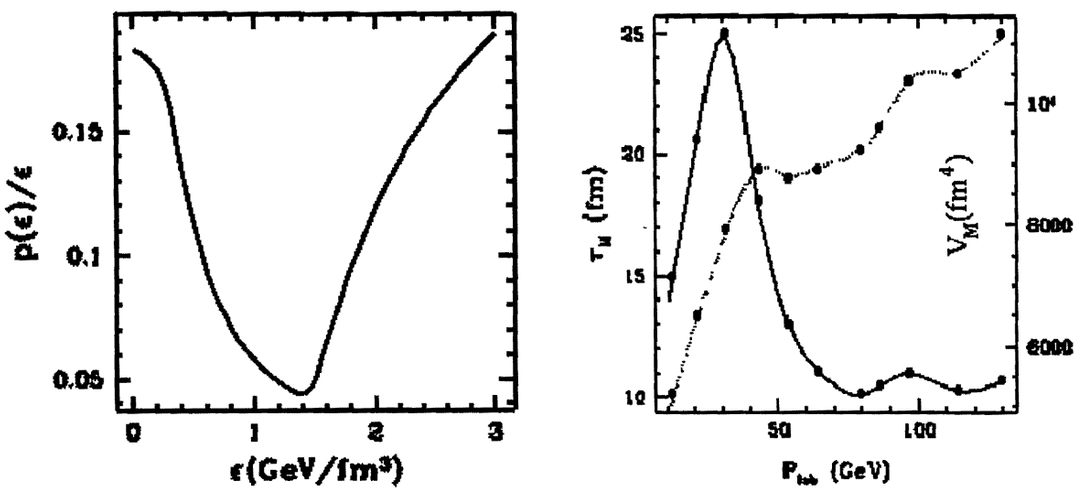

Figure 4: (a) The equation of state obtained assuming QCD phase transition at $T_C \approx$ 160 MeV shown as pressure to energy density ratio vs energy density [22]. (b) Lifetime τ_M of the mixed phase (solid line) and the corresponding space–time volume V_M (dashed line) as a function of collision energy [22].

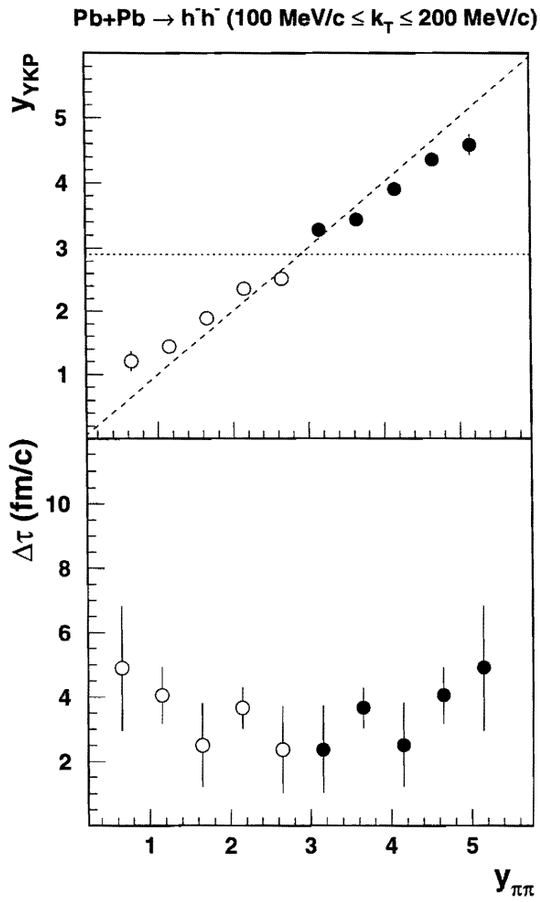

Figure 5: (a) Longitudinal flow rapidity y_{YKP} as a function of pion pair rapidity $y_{\pi\pi}$ for central Pb+Pb collisions at 158 A·GeV. The dashed line indicates dependences of y_{YKP} on $y_{\pi\pi}$ for boost invariant expansion. The dotted line shows dependence of y_{YKP} on $y_{\pi\pi}$ for stationary source created at $y = y_{cms} = 2.9$ [25]. (b) Duration of pion emission $\Delta\tau$ as a function of pion pair rapidity $y_{\pi\pi}$ [25]. The results are based on the analysis of 15000 central Pb+Pb collisions.

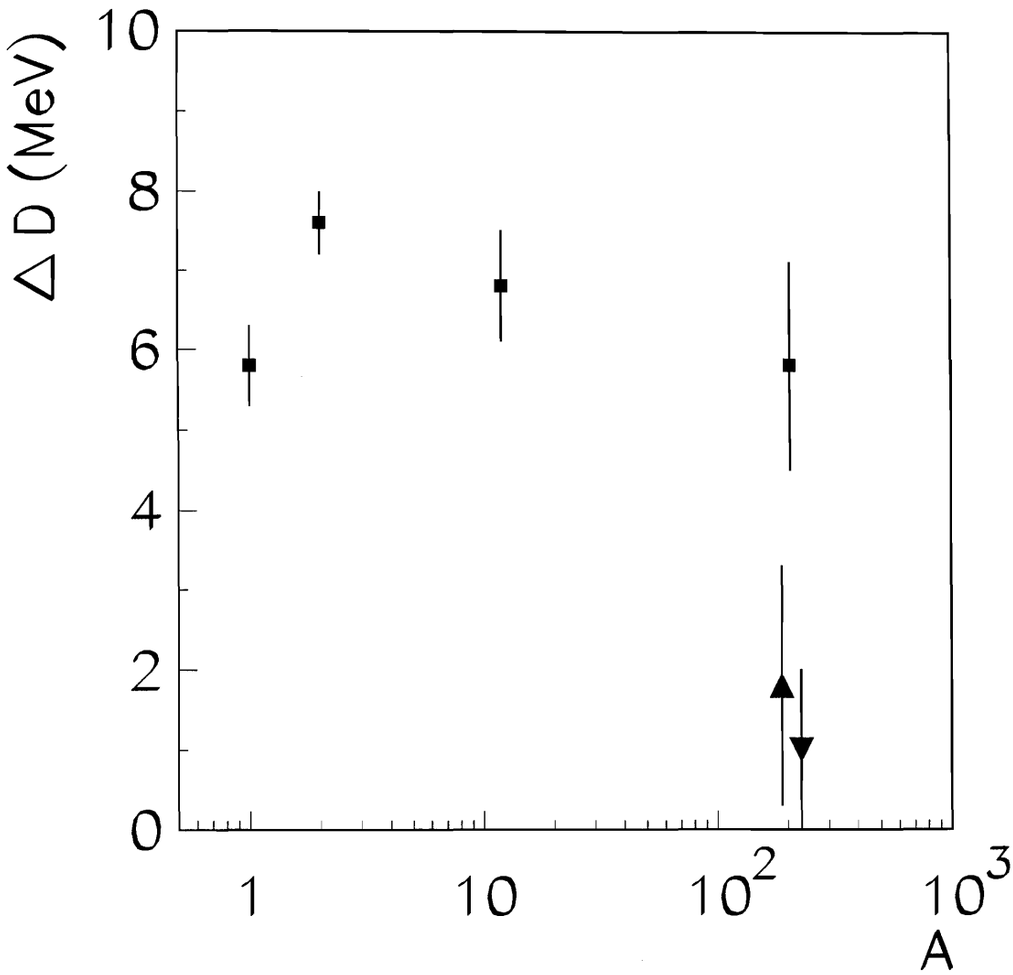

Figure 6: The measure of event–by–event fluctuations in transverse momentum ΔD [26] as a function of nuclear mass number A. The Fritiof model [28] predictions for p+p and central A+A collisions at 158 A·GeV are indicated by squares [27]. The results for central Pb+Pb collisions at 158 A·GeV obtained using data from two independet detectors (MTPC and VTPC2) are show by triangles (MTPC). [27].

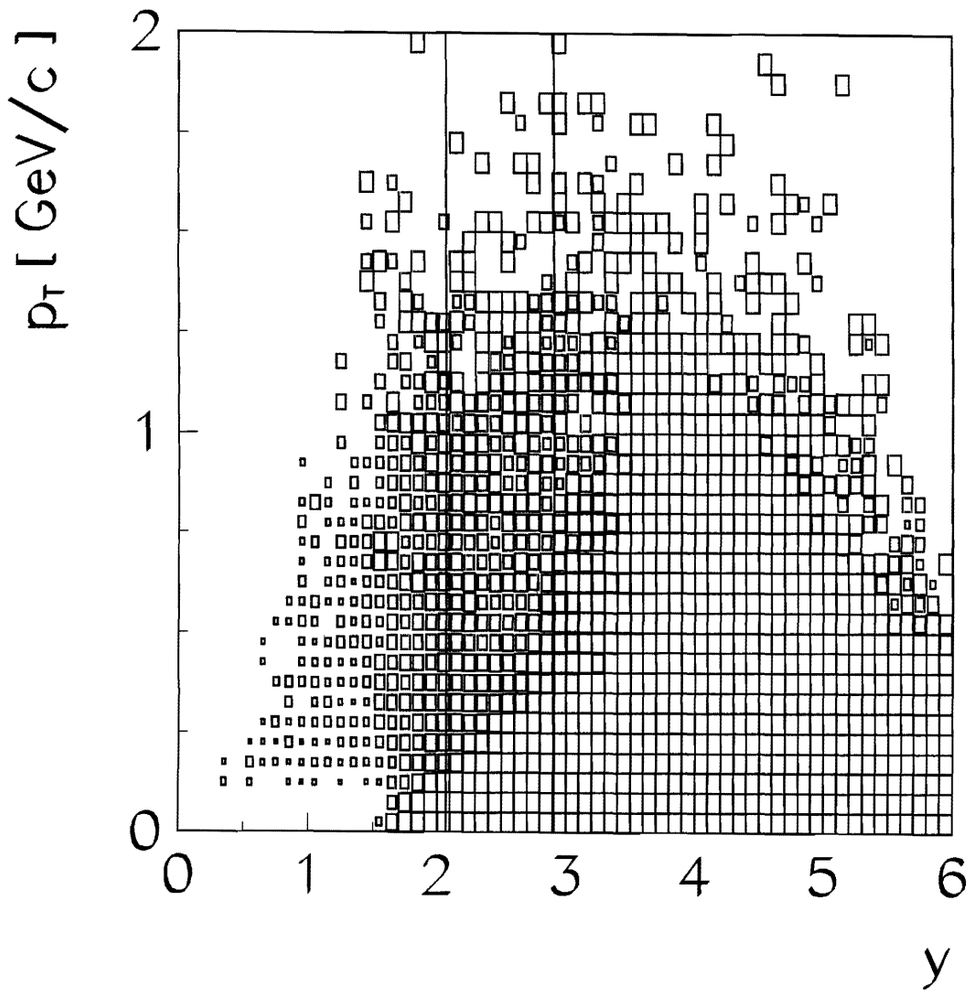

Figure 7: Geometrical acceptance of NA49 tracking detectors (TPCs) in transverse momentum (p_T) and pion rapidity (y). Vertical solid lines indicate center of mass rapidities for collisions at 30 A·GeV and 158 A·GeV.