NA49 Experimental Results Relevant to the Question of QGP Formation

The NA49 Collaboration,November 23,1999

Experiment NA49 was designed to study central Pb+Pb interactions at the top CERN SPS energy (158 A·GeV) with the aim of discovering signals due to a transient deconfined state (ultimately the Quark Gluon Plasma (QGP)) which is expected to be created at the early stage of the collisions. Numerous hadronic observables are measured in a large part of phase space making it possible to determine their values in individual Pb+Pb collision events. This gives NA49 the capability to determine event–by–event fluctuations and to search for distinct event classes, in addition to performing inclusive analysis.

The unique features of NA49 are large phase–space acceptance, excellent momentum resolution, good particle identification capability and high statistics of collected events. This is achieved by employing four large volume Time Projection Chambers and four Time of Flight Walls. A large variety of observables are measured, notably total multiplicities and rapidity–transverse momentum spectra of stable hadrons (π, p, K, Λ, Ξ and antiparticle) and hadronic resonances (ϕ, Δ, Λ^*), small scale momentum correlations (e.g. Bose–Einstein and Coulomb correlations between two identical pions or protons) and global event–by–event fluctuations of kinetic (e.g. transverse momentum) and flavor composition (e.g. kaon/pion ratio) variables.

The properties of the NA49 detector in addition make it an excellent tool for the study of soft collision processes in elementary nucleon–nucleon and nucleon–nucleus collisions. This program will allow NA49 to compare nucleus–nucleus reactions not only to inelastic elementary collisions but to perform such a comparison at a more profound level with controlled inelasticity and centrality of the elementary processes.

From the analysis of the NA49 experimental results on central Pb+Pb collisions at the top SPS energy and the comparison with inelastic p+p reactions we conclude:

- the average energy density reached in central Pb+Pb collisions significantly exceeds the threshold value predicted for the deconfiment phase transition by lattice QCD calculations,
- the properties of the produced hadronic system (distribution of hadron yields) are surprisingly well described by the statistical/hydrodynamical models applied to subsequent stages of the collision,
- the space–time evolution of the produced particle system shows features of hydrodynamic expansion,
- the properties of the produced hadron system are consistent with the hypothesis that matter in a deconfined state (ultimately QGP) is created in A+A collisions at the top SPS energy.

In the following part of this report we will show and discuss the measurements on which we base our conclusions concerning the compatibility with the existence of a transient deconfined phase in central Pb+Pb collisions.

The estimate of the energy density in the early phase of the reaction is based on the backward (in space–time) extrapolation of the measured transverse energy flow (Fig. 1). Using the assumption of scaling longitudinal expansion the resulting energy density is about 3 GeV/fm^3 in central Pb+Pb collisions at a time of 1 fm/c after the initial reaction.

This exceeds the threshold for the deconfiment phase transition of $\approx$1 GeV/fm^3 predicted by lattice QCD calculations.

The conclusion concerning the statistical features of strong interactions is based on three observations:

- in central A+A collisions particle yields increase in proportion to the volume of the interacting matter as expected in the thermodynamical limit of the statistical approach (Fig. 2),

- the mean multiplicities of the produced hadrons follow the pattern given by the hadronic phase–space determined by the hadronization temperature T = 170–180 MeV and a strangeness suppression parameter (Fig. 3). The value of T is common for various interactions (e^++e^-, p+p, p+$\bar{p}$, A+A) and independent of the collision energy. The reduction of the strangeness suppression is a charactristic feature of nucleus–nucleus collisions (see also Fig. 7),

- event–by–event fluctuations of kinetic (average transverse momentum in the event) and flavor composition (kaon/pion ratio) observables studied for central Pb+Pb collisions are consistent with purely statistical fluctuations(Fig. 4). This suggests that equilibration has been reached at some stage in the evolution of the produced particle system.

The collective, hydrodynamic–like expansion of the produced particle system is suggested by the following results:

- the transverse momentum dependence of the correlation length measured via two–pion Bose–Einstein correlations and the particle mass dependence of the inverse slope parameter of transverse mass distributions provide evidence for strong radial collective flow in central Pb+Pb collisions (Fig. 5),

- azimuthally non–uniform particle distributions are produced in non–central Pb+Pb collisions which are most likely due to pressure driven expansion (Fig. 6).

The supporting evidence for the creation of a transient QGP state in A+A collisions at the top SPS energy is provided by the following features of the data:

- theoretical model estimates of relaxation times have shown that it is unlikely that the factor 2 strangeness enhancement(Fig. 7 top) observed by NA49 in Pb+Pb relative to elementary collisions can be produced in a short–lived system of confined hadrons by rescattering; the enhancement is found to be even stronger for the hidden strangeness ϕ meson (Fig. 7, bottom),

- enhanced total pion (Figs. 2 and 9) and strangeness (Figs. 7 and 8) yields in A+A collisions at the SPS are consistent with those expected in the statistical model of the QGP,

- the collision energy dependence of pion and strangeness production established by the NA49 measurements and results at low energies (AGS and below) indicates in accordance with expectation that the transition to a reaction scenario which proceeds via a transient QGP phase appears to take place between top AGS (15 A·GeV) and top SPS (158 A·GeV) energies, (Figs. 8 and 9).

The event–by–event analysis of central Pb+Pb collisions at the highest SPS energy did not reveal distinct event classes down to the 10^{-3} level of admixture with respect to total produced particle multiplicity, average transverse momentum or ratio of kaons to pions. Large fluctuations or appearence of event classes may be expected in the vicinity of the transition region. Therefore measurement of purely statistical fluctuations in central Pb+Pb collisions at 158 A·GeV is consistent with the previous indication that the threshold for the creation of a deconfined state lies at a lower energy and smaller size of nuclei.

Also first results have been obtained on the impact parameter dependence of hadronic observables for which Fig. 10 shows as an example particle ratios. No distinct threshold is apparent in the studied range. Since there is no unique signature of the QGP and its identification necessarily relies on circumstantial evidence, NA49 is persuing a comprehensive program of measuring the energy and nuclear size dependence of relevant observables in both nucleon and nuclear collisions in an effort to find further supporting or disproving evidence for the expected deconfinement transition and to locate its threshold.

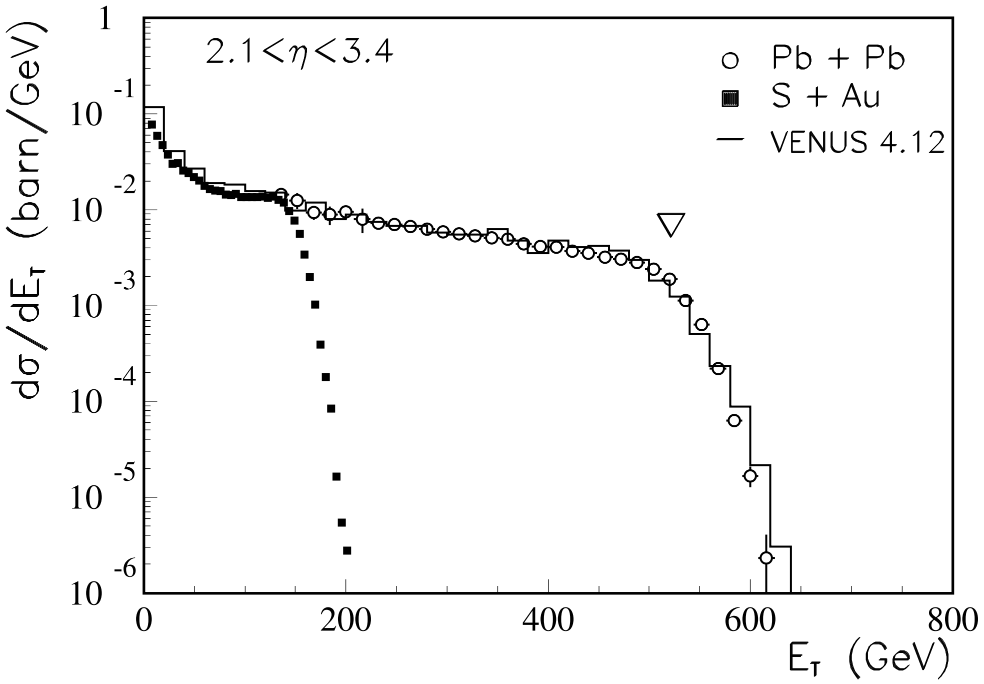

Figure 1: Cross sections as a function of transverse energy E_T in Pb+Pb (NA49) and S+Au (NA35) collisions near midrapidity. The highest values of E_T are reached in central collisions. Using the Bjorken hydrodynamical model one obtains an estimate of about 3 GeV/fm^3 for the energy density in the early phase of central Pb+Pb collisions.

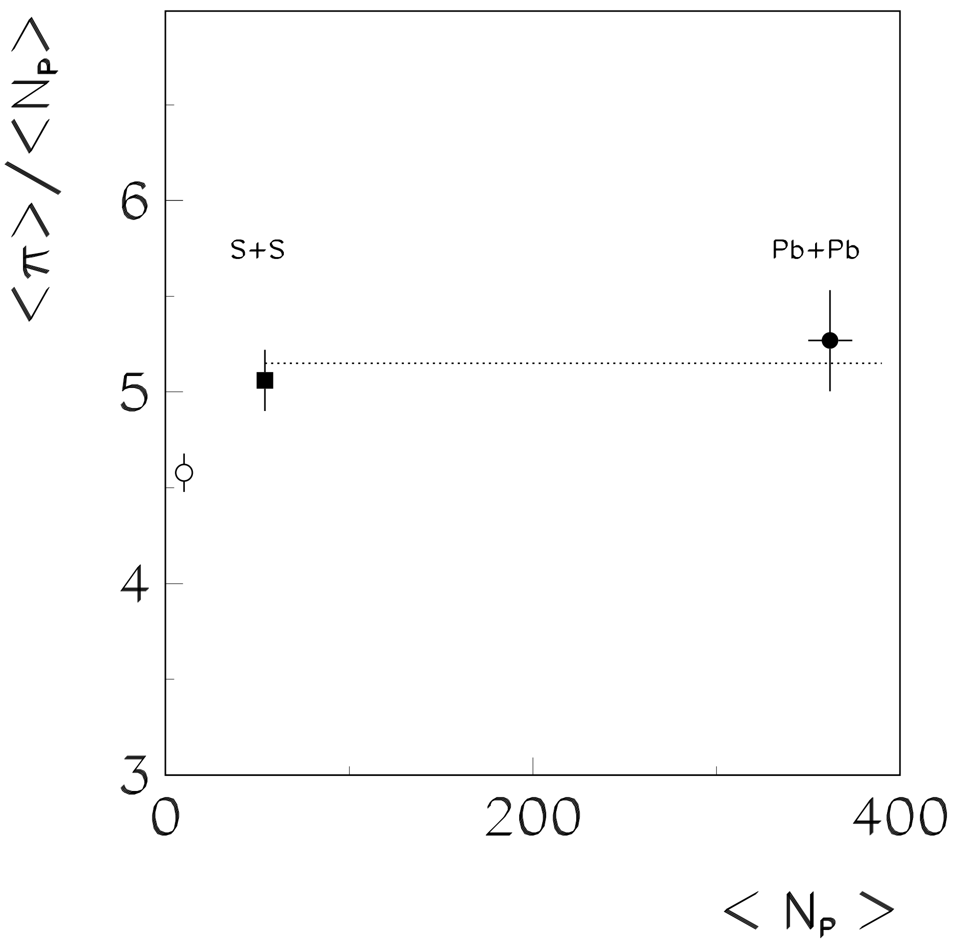

Figure 2: Total number of pions produced per participant nucleon plotted versus the number of participant nucleons N_P in central Pb+Pb (NA49, full circle), central S+S (NA35, full square) and inelastic p+p (open square) collisions. In central nucleus-nucleus collisisons $\langle\pi\rangle/\langle N_P\rangle$ is constant, indicating that pion production is proportional to the volume of the interaction region.

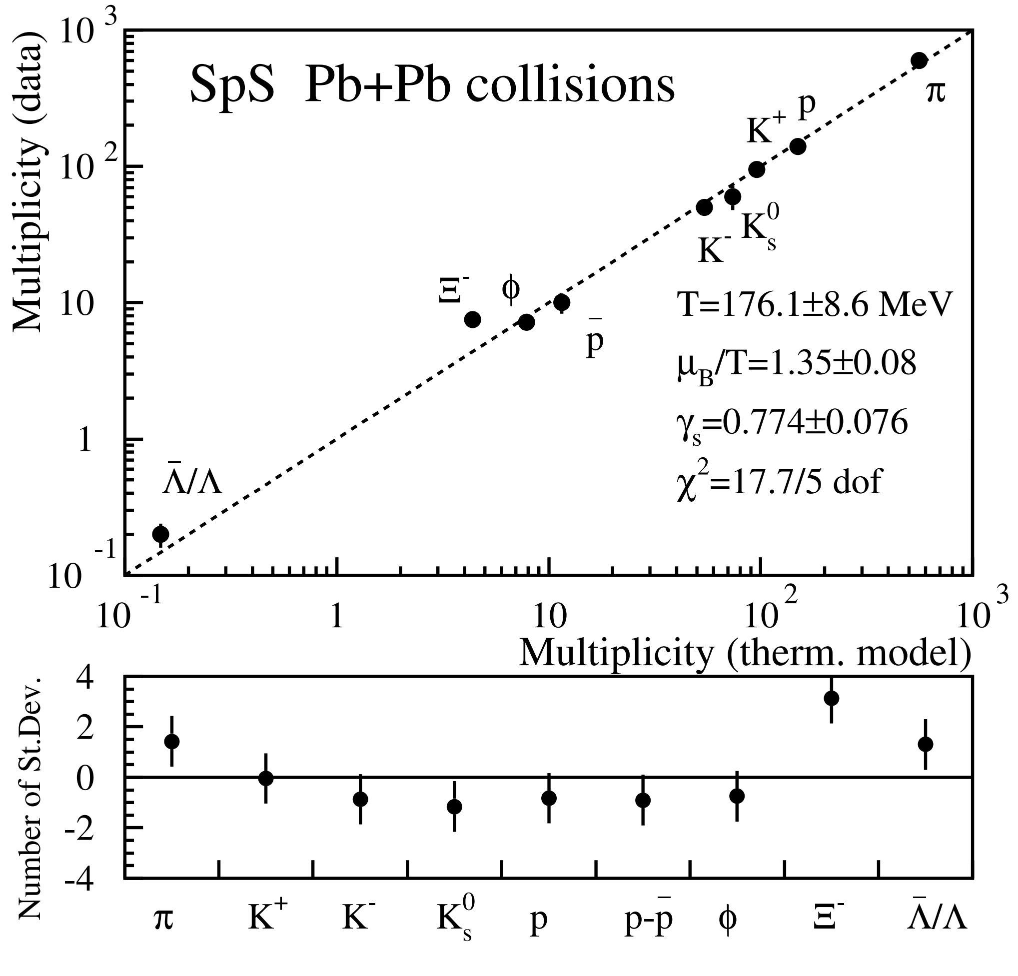

Figure 3: Phase space integrated multiplicities of various identified particle species measured by NA49 in central Pb+Pb reactions at 158 A·GeV are compared to a statistical model fit (performed by F.Becattini). Fitted parameters of the model are the temperature T, the baryochemical potential μ_B, the strangeness suppression parameter γ_S and the fireball volume V.

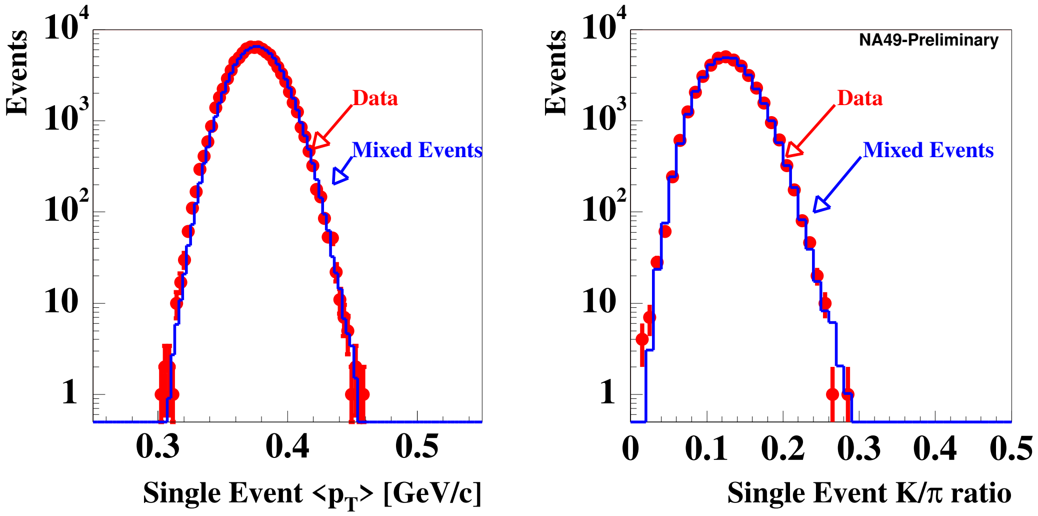

Figure 4: Event-by-event fluctuations of the average transverse momentum $\langle p_T \rangle$ (a measure of the temperature in the event) and of the ratio of the produced numbers of charged kaons and pions (a measure of the strangeness content of the event) in central Pb+Pb collisions at 158 A·GeV (data points) are reduced to the level of finite particle number statistics (histograms). This lack of dynamical fluctuations (upper limits at 90% C.L. 1.2% for $\langle p_T \rangle$ and 2.8% for kaon/pion fluctuations) indicates equilibration of the produced matter, as may be expected if the reaction proceeded through a QGP stage.

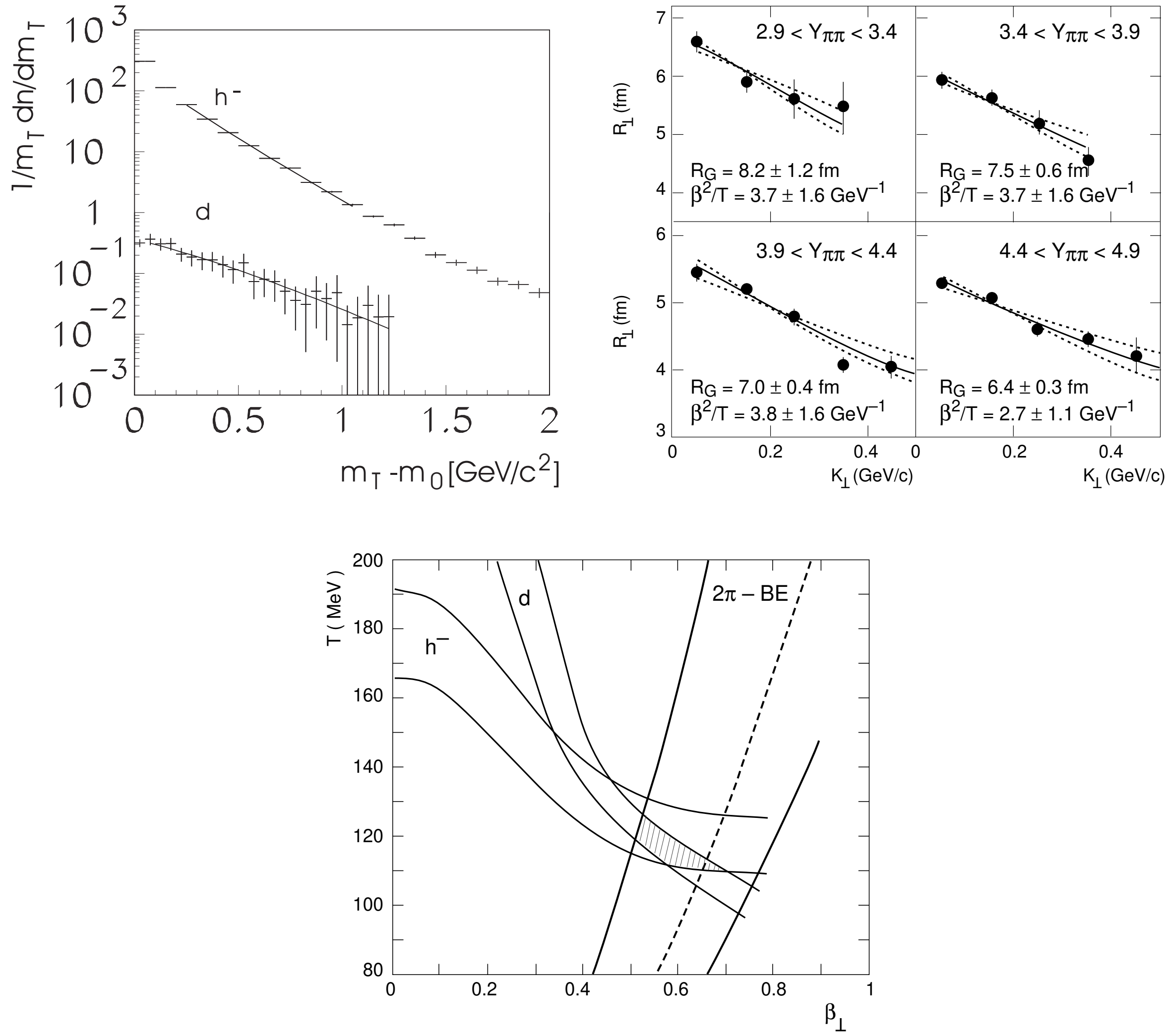

Figure 5: Determination of the collective radial flow velocity and the freezeout temperature of the fireball produced in central Pb+Pb collisions at 158 A·GeV (NA49 data). The top left panel demonstrates for negative hadrons (mostly pions) and deuterons that the transverse mass distribution flattens with increasing particle mass. The top right panel shows that the transverse radius R_T of the pion emitting fireball region as determined from Bose-Einstein correleations of negative pions decreases with average transverse momentum of the pion pair. Both observations are signatures of strong radial flow. Fitting to a fireball model with such features one obtains the displayed curves and the limit bands for T and β_T shown in the bottom plot. The freeze–out temperature T, when inelastic and elastic collisions among produced hadrons cease, is found to be about 120 MeV.

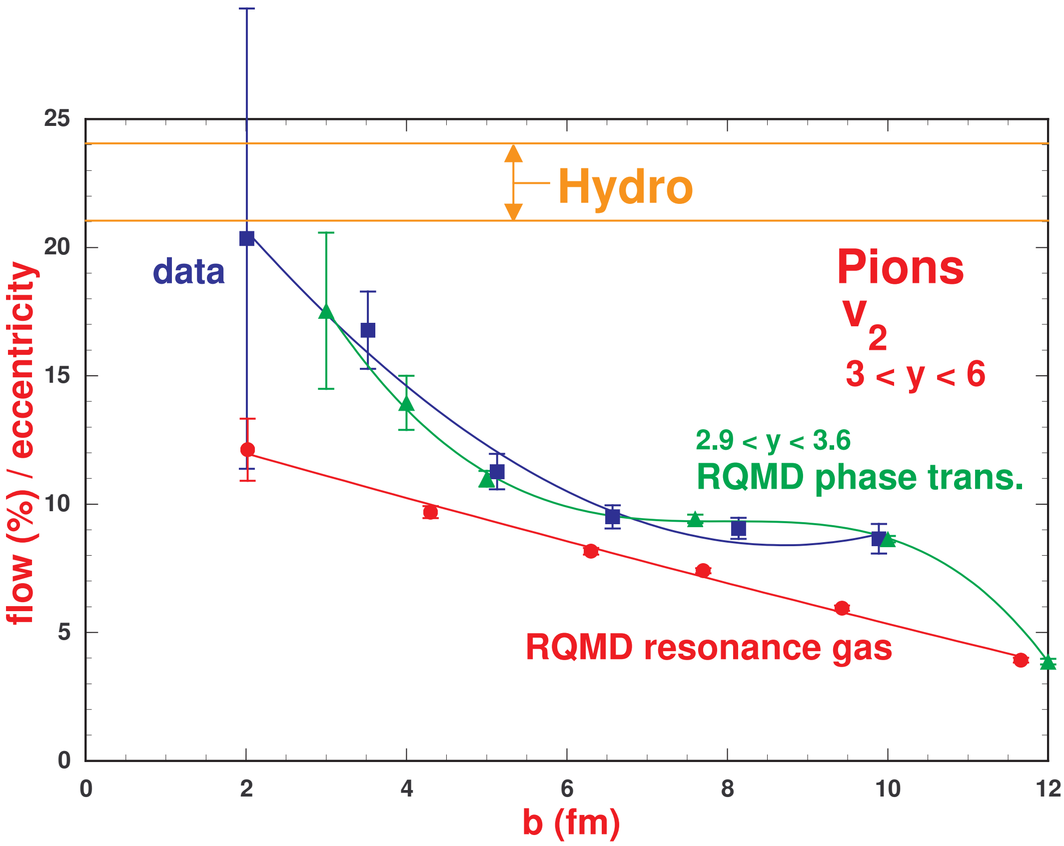

Figure 6: Azimuthal anisotropy of the produced pion distribution in Pb+Pb collisions as a function of impact parameter b. The measure of anisotropy used is the ratio of the second Fourier coefficient of the azimuthal distribution (v_2 in percent) divided by the eccentricity of the overlap region of the colliding Pb nuclei. The experimental results are shown by the squares and are compared to model calculations.

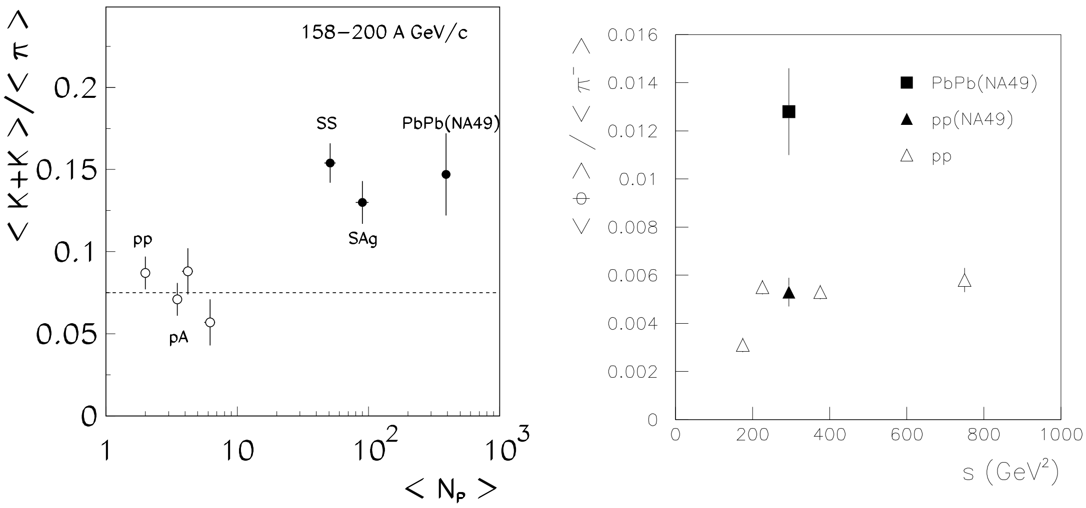

Figure 7: Evidence for strangeness enhancement in nucleus–nucleus collisions. The left panel shows the ratio of phase space integrated kaon to pion multiplicities produced in central nucleus–nucleus and inelastic proton–proton and proton–nucleus collisions. About 75% of strange and antistrange quarks in the final state hadrons are contained in kaons. Thus kaon production is a good measure of strangeness production and is seen to increase by a factor of two from inelastic elementary collisions to central nucleus–nucleus collisions at the top SPS energy. The right panel shows the ratio of phase space integrated ϕ meson to pion multiplicities. The ϕ meson is composed of an $s - \bar{s}$ quark–antiquark pair and is overall strangeness neutral. Its enhancement factor is found to be even larger, consistent with the assumption that the enhancement occurs at the quark constituent level.

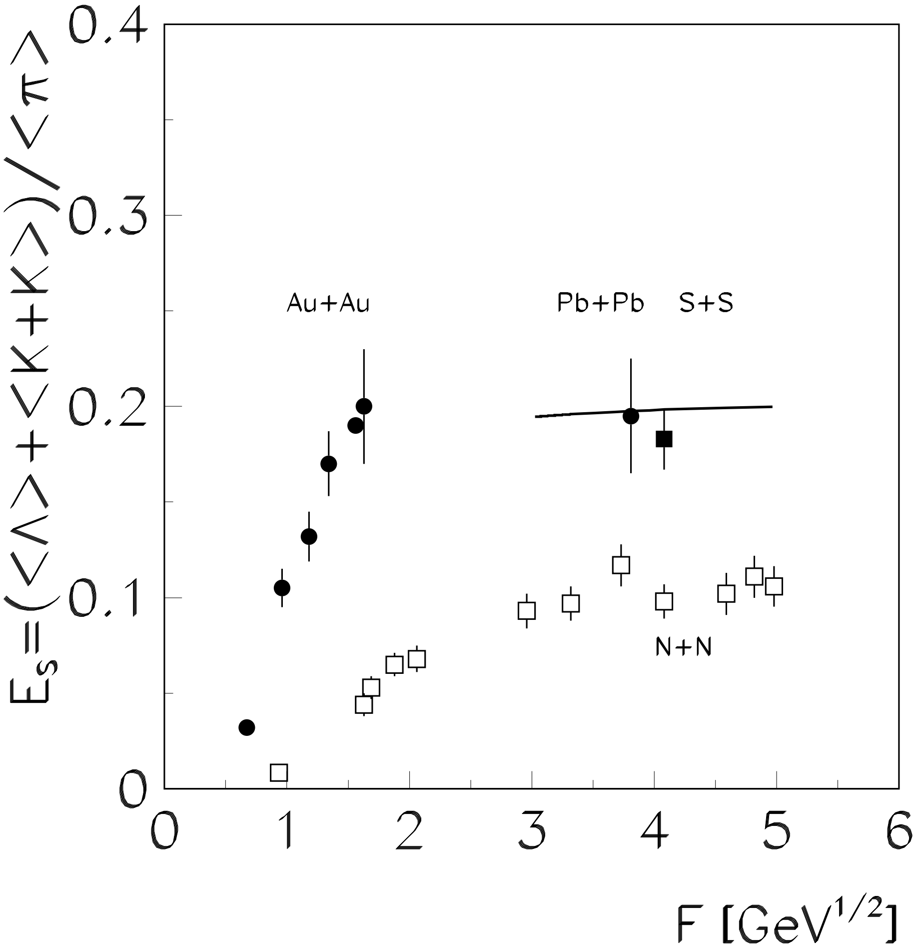

Figure 8: The strangeness content E_S of the produced hadronic final state plotted versus the Fermi energy variable $F \approx s^{0.25}$ for central nucleus–nucleus (full circles) and inelastic p+p collisions (open squares). The solid curve shows the prediction (M.Gazdzicki and M.Gorenstein) of a statistical model with a QGP phase in the early stage of the reaction.

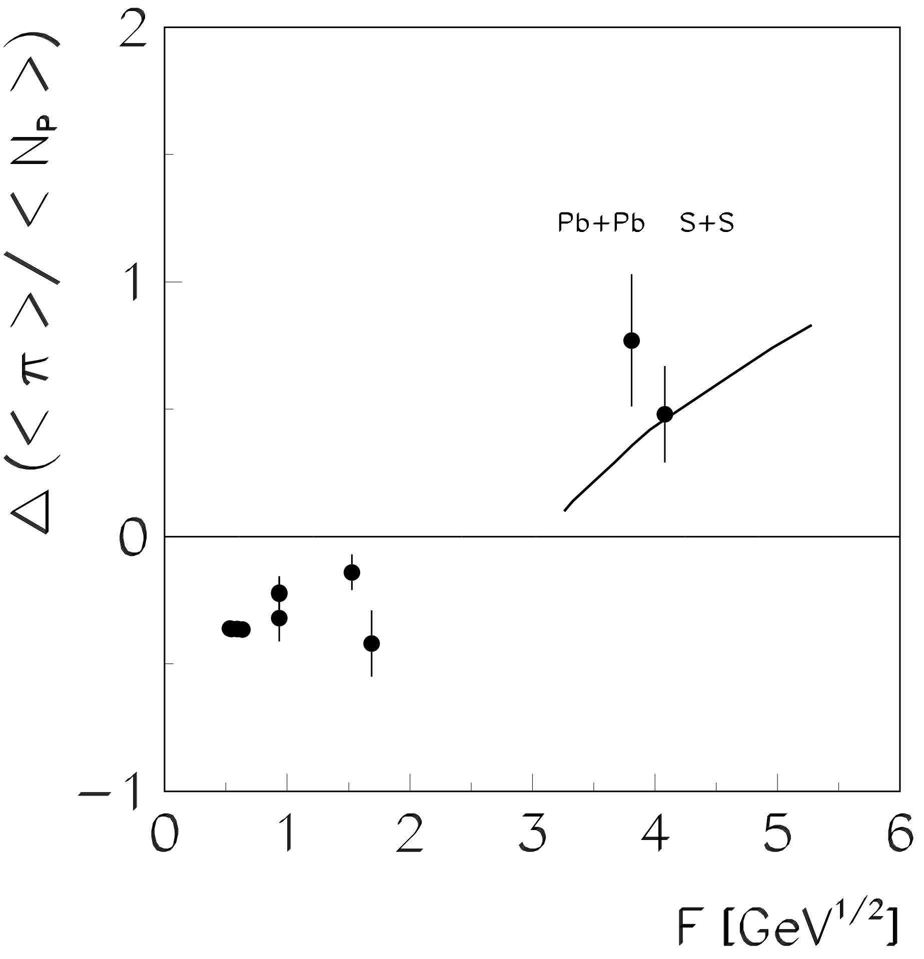

Figure 9: Difference of the numbers of pions produced per participant nucleon between central nucleus–nucleus and inelastic nucleon–nucleon interactions as a function of the Fermi energy variable $F \approx s^{0.25}$. The solid curve shows the prediction (M.Gazdzicki and M.Gorenstein) of a statistical model with a QGP phase in the early stage of the reaction .

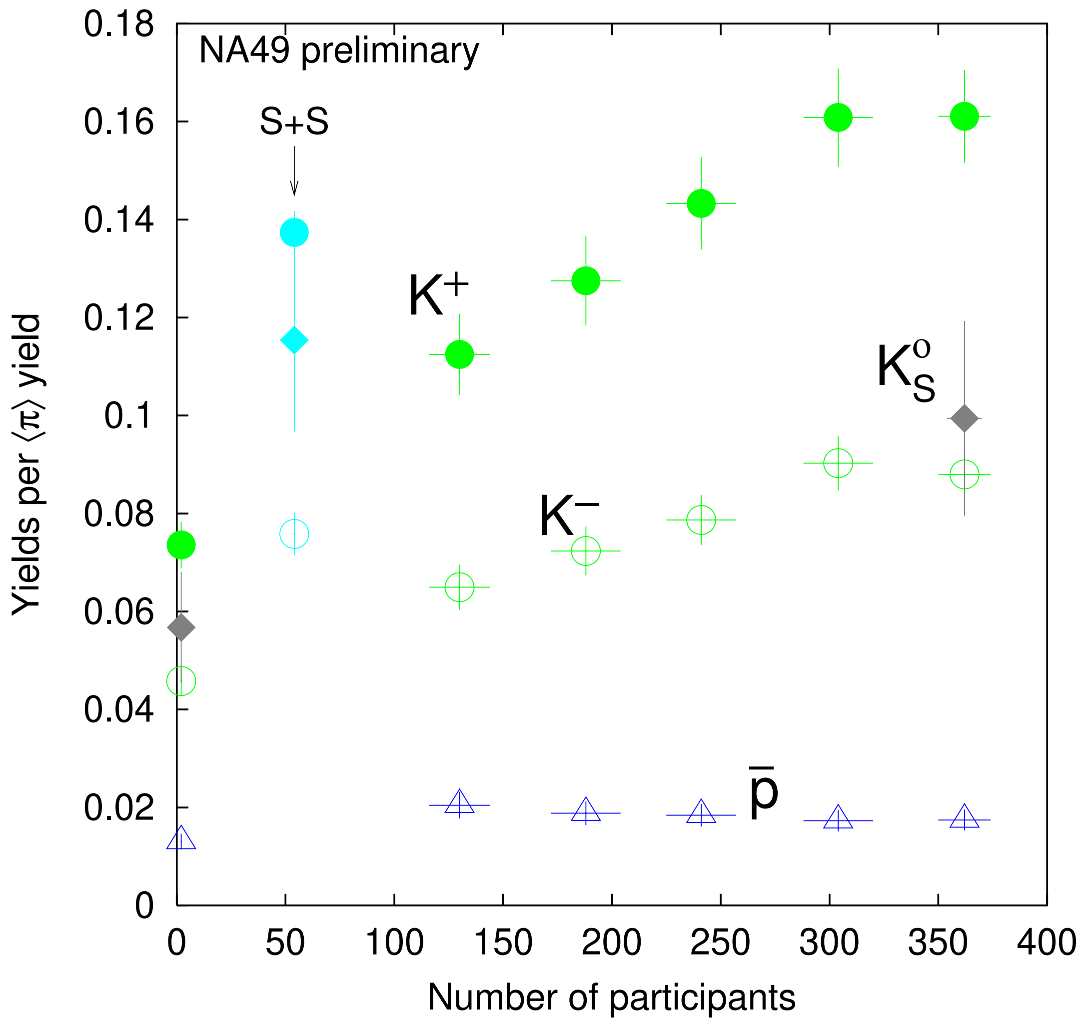

Figure 10: Ratio of phase space integrated multiplicities of kaons and antiprotons to pions as a function of the number of participants in Pb+Pb collisions at 158 A·GeV energy. Also shown for comparison are the NA49 results from inelastic p+p collisions and the NA35 results from central S+S reactions.

References to results of NA49 measurements:

Energy density:

Transverse Energy Production in ^{208}Pb+Pb Collisions at 158 GeV per Nucleon, T.Alber et al.,Phys.Rev.Lett.75(1995)3814

Pion production and baryon stopping:

Baryon Stopping and Charged Particle Distributions in Central Pb+Pb Collisions at 158 GeV per Nucleon, H.Appelshaeuser et al.,Phys.Rev.Lett.82(1999)2471

Hadron production in nuclear collisions from the NA49 experiment at 158 GeV/c.A, F.Sikler,Proceedings of Quark Matter 99,Nucl.Phys.A661,45c

Stopping: from peripheral to central nuclear collisions at the SPS, G.Cooper,Proceedings of Quark Matter 99,Nucl.Phys.A661,362c

Strangeness production:

Strangeness measurements in NA49 experiment with Pb projectiles, S.Margetis, J.Phys.G,25(1999)189

Strangeness production in nuclear collisions C.Hoehne, Proceedings of Quark Matter 99, Nucl.Phys.A661,485c

Phi emission in central Pb+Pb collisions at 158 GeV/u, F.Puehlhofer et al., Nucl.Phys.A638(1998)431c

Fireball properties (size,lifetime,expansion):

Hadronic expansion dynamics in central Pb+Pb collisions at 158 GeV per nucleon, H.Appelshaeuser et al.,Eur.Phys.J.C2(1998)661

Directed and elliptic flow:

Directed and Elliptic Flow in 158 GeV/Nucleon Pb+Pb Collisions, H.Appelshaeuser et al.,Phys.Rev.Lett.80(1998)4136

Centrality dependence of directed and elliptic flow at the SPS, A.Poskanzer,Proceedings of Quark Matter 99,Nucl.Phys.A661,341c

Event to event fluctuations:

Event-by-event fluctuations of average transverse momentum in central Pb+Pb collisions at 158 GeV per nucleon, H.Appelshaeuser et al.,Phys.Lett.B459(1999)679

Hadron production in nuclear collisions from the NA49 experiment at 158 GeV/c.A, F.Sikler,Proceedings of Quark Matter 99,Nucl.Phys.A661,45c