NA49: A large acceptance tracking spectrometer at the CERN SPS Lead beam facility

1. The 33 TeV Lead beam at the SPS

The highest energy density ever produced in the terrestial laboratory, in highly excited and compressed "fireballs" of nuclear matter, has become accessible for research at the 33 TeV total energy SPS beam of highly relativistic nuclear projectiles: the isotope ^{208}Pb, one of the heaviest nuclear species, made up from 82 protons and 126 neutrons in a tight spherical packing that we call "nuclear matter", is accelerated to about 99.9% of light velocity.The CERN chain of successively higher velocity or energy accelerators (injector Linac, Booster synchrotron, PS synchrotron, SPS synchrotron) was initially built to provide high energy beams of electrons, positrons, protons and antiprotons for particle physics studies of the elementary constituents of matter: leptons and quarks. This accelerator complex was ingeniously adapted to the acceleration of heavy nuclei which, from their initially neutral atomic state, are getting successively stripped of their electrons in the course of passage through the accelerator chain, being shifted to higher ionization states (hence the term "heavy ions") until they are fully stripped down to bare ^{208}Pb nuclei of charge +82 upon injection to the last element of the accelerator chain: the SPS (Super Proton Synchrotron) is versatile enough to accelerate charge 82^+, mass 208 nuclei - instead of charge 1^+, mass 1 protons - to its maximal energy which, for this charge to mass ratio, is about 160 GeV per projectile nucleon. The term "nucleon" refers to the constituents of nuclei, e. g. protons and neutrons. The heavy nuclear species ^{208}Pb is built up of 208 nucleons, hence the final total SPS beam energy is 160 x 208 GeV $\approx$ 33 TeV, the highest accelerator energy reached world wide.

Extraction of the circulating beam, at top SPS energy, feeds beam splitter systems that distribute the Pb projectiles into several external beam transport lines ending on target in up to seven concurrently operating experiments. Such targets are thin foils of metallic Lead: the Lead beam projectiles hit stationary Lead nuclei in the foils creating violent Pb+Pb nuclear collisions if they hit head-on. The 33 TeV beam energy gets consumed in a process of heating and compressing the extended, initially cold volumes of nuclear matter, thus creating "fireball" matter through the strong interaction, occurring initially in violent nucleon collisions at the microscopic level that stop down the relative motion and sap the beam kinetic energy into a collective excitation of an emerging volume of fireball matter. All the initial content of the nucleons from target and projectile, in terms of internal quarks and gluons, might melt away under such heating and compression, to give rise to a continuous extended state of strongly interacting matter made up by quarks and gluons propagating freely in this fireball of extreme energy density. Such a primitive "Urzustand" of matter under the influence of the elementary strong force/interaction was predicted by Quantum Chromodynamics theory (QCD) to occur in extended volumes of extreme temperature and energy density - that is why we collide extended nuclear matter volumes here, instead of investigating the small volume elementary collisions of protons or electrons that probe into the properties of elementary particles. The Lead beam experiments thus analyze extended quark-gluon **matter** properties, not the properties of individual elementary particles. Thus the term "Quark Matter research".

2. The NA49 Spectrometer at the SPS Lead beam

In a typical head-on collisions of two Lead nuclei about 2500 particles are created: the whole zoo of different hadrons but predominantly pions, kaons and protons. About one-third of these particles are neutral and thus invisible in magnetic spectrometers and gas-filled tracking detectors.

NA49 is a large acceptance magnetic and tracking spectrometer, covering about 70% of all created charged particles simultaneously: about 1200 hadrons are recorded and identified in each collision event. This is formidable challenge to experimental technique! It requires:

- A large volume of magnetic dipole fields in order to disperse the orbits of the produced particles and enable one to record their tracks and to measure their momenta.

- Large volumes of gas-filled high resolution tracking detectors inside the magnetic fields and behind the huge dipole magnets - to make ionization trails ("tracks") along the trajectories of the charges particles that are recorded electronically.

- An enormous array of electronics. The total readout surface of the tracking gas detectors amounts to about 40 m^2, but in order to achieve high spatial resolution these surfaces must be granulated into pixels of one square centimeter dimension. Each readout pixel feeds a separate electronic circuit, an electronic "channel": NA49 has 180.000 electronic channels.

- In order to identify the various hadrons, i. e. tell a negative pion from a negative kaon, or from a negative antiproton, it is not sufficient to know the momenta from tracking but one wants, likewise, to measure the velocity of each particle. This determines the mass and, thus, the particle species.

The layout thus consists of two 450-ton superconducting coil dipole magnets. Four large volume gas tracking detectors are deployed employing the Time Projection Chamber (TPC) technique to electronically record the ionization tracks of the 1200 charged particles. After a flight path (from the collision target across the tracking detectors placed inside and at the exit of the two magnets) of about 12 m the particles hit scintillator walls of fine granularity that record their flight time, thus determining the velocity.

One single Pb+Pb head-on collision event is reflected in about 100 megapixels of information that is electronically encoded. After rejecting the empty pixels we have an information flux of about 10 Megabytes per event that we write to special high speed recording tapes. An elaborate computer program performs the so-called "off-line analysis" in which the raw pixel data get transformed into particle tracks by automatic track pattern recognition algorithms, then the momenta etc. are determined and a complete digital image of each event is created. This information, gathered for a few million events, forms the basis of physics analysis.

3. NA49 physics results

We want to comment here about four experimental NA49 results which, in particular, have the most immediate connection to the search for the QCD phase transition between partons (i. e. quarks and gluons) and hadrons (i.e. pions , kaons, protons etc.).

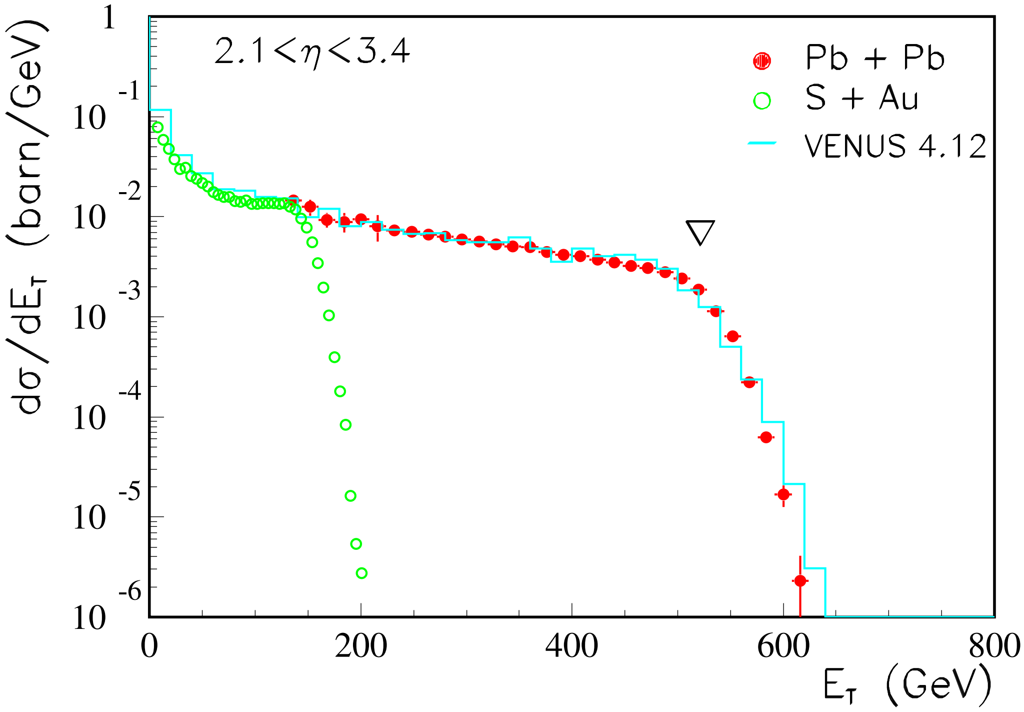

Figure 1: Cross sections as a function of transverse energy E_T in Pb+Pb (NA49) and S+Au (NA35) collisions near midrapidity. The highest values of E_T are reached in central collisions. Using the Bjorken hydrodynamical model one obtains an estimate of about 3 GeV/fm^3 for the energy density in the early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

a. Estimate of the primordial energy density in the fireball

How can we know that the energy density created in head-on Pb+Pb collisions at 158 GeV per nucleon in the projectile nucleus suffices to get beyond the "critical" energy density ϵ_c at which the transition occurs - i. e. beyond 1-1.5 GeV per cubic fermi which is the QCD estimate for ϵ_c? To this end one first measures the total internal energy content at the center of the fireball, then employs an estimate for the corresponding volume - to get an energy density. This approach was suggested almost 20 years ago by J. D. Bjorken of Fermilab. NA49 adapted a large calorimeter inherited from former SPS experiments to measure the so-called transverse energy E_T radiated outward from the primordial interaction zone created in Pb+Pb collisions: Fig: 1. The range of created E_T extends from mere grazing collisions, with low E_T, to near head-on collisions which show more than 500 GeV of transverse energy. The Bjorken estimate of that fraction of the primordial volume which is covered by the calorimeter acceptance amounts to 150-200 cubic fermis.

The transverse energy density can thus be estimated to be about 3 GeV per fm^3: well sufficient to let the system enter the domain above the QCD estimate for ϵ_c. The SPS energy thus appears to be just high enough to probe into deconfined partonic matter.

b. Explosive expansion of the primordial fireball matter

The primordial fireball volume develops an enormous pressure that drives it into expansion. This pressure is related to its energy density (it is proportional to ϵ). We have estimated the latter above, albeit in the units of GeV/fm^3 that are appropriate to microscopic physics. Translated into our more familiar classical physics terminology the initial pressure amounts to about $3x10^{32}kg/cm^2$, again past any imagination but it may help to realize that this amounts to about the weight total of 150 solar masses pressing on one square centimeter. From our above argument this should be the pressure prevailing at an instant of time before the pressure driven expansion enters the QCD parton to hadron phase transition. The above findings are relevant to the dynamics of the cosmological expansion at the early microsecond stage, whence the Big Bang is about to undergo the parton to hadron phase transition. Likewise, in our mini-bangs, the primordial pressure drives the interaction volume into an expansion mode. The characteristics of this "explosive" mode is recaptured in the experimental observation of a radially symmetric "blast wave" collective velocity field which drives the fireball particles into free space. Fig. 2 shows the result, from NA49 analysis of the spectra of emitted particles, combined with an analysis of the constructive interference effect imposed on emitted pion pairs by their Bose statistics, which provides for an alternative microscope of their collective, blast wave mode emission. We see that all data coincide at a collective emission velocity of hadrons, driven by the primordial high energy and pressure, of $\beta \approx 0.6$, i. e. at 60% of light velocity: the final remnant of the initial high density fireball explosion.

c. The multi-hadron thermometer of the parton-hadron phase transition

The two above examples of NA49 data illustrate, first the primordial energy density in the collision fireball which is well above the QCD prediction for the critical energy density of the parton to hadron phase transition, and

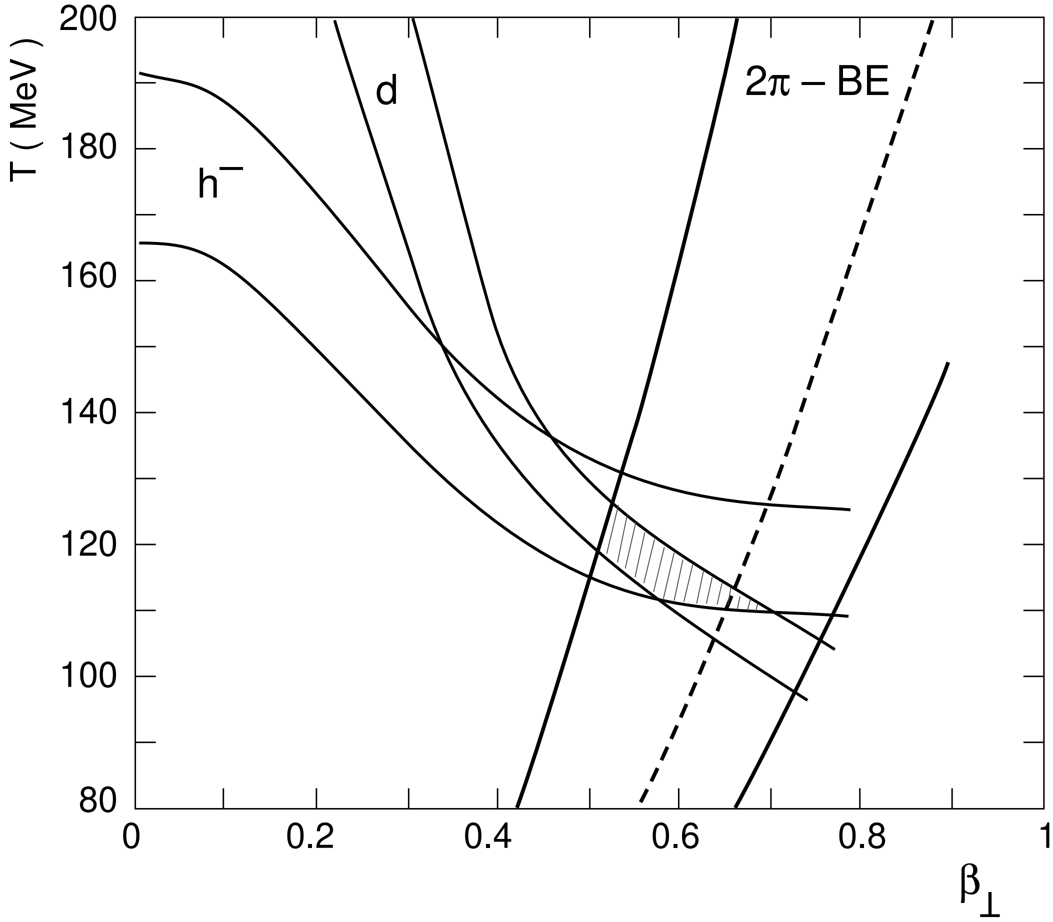

Figure 2: Determination of the collective radial flow velocity and the temperature at freezeout of the fireball produced in central Pb+Pb collisions at 158 GeV per nucleon. The negative hadrons (mostly pions) and the deuterons transverse mass distributions can be fitted in a fireball model by any set of parameters T and β_T within the bands labeled h- and d shown in the figure. The observed systematics in the measurement of the two-pion Bose-Einstein interferometry in the same events can be fitted by the same fireball model by an other set of parameters as given by the band labeled 2π-BE. The region where there is a common solution for the three different observables is given by the hatched area. From this we find that the freeze–out temperature T, when inelastic and elastic collisions among the produced hadrons cease, is about 120 MeV and that the system at this stage is expanding at 60% of the light velocity.

the final emission of produced particles in a "blast wave" explosive expansion mode. This captures a moment far below the critical density, as the hadrons decouple from the strong interaction force fields and travel into free streaming - eventually to be detected in the experimental apparatus. Under guidance from recent Lattice QCD results, that predict the transition from deconfined quarks and gluons to the finally observed hadrons to occur at an energy density of about 1 GeV/fm^3 we now entertain the hypothesis that the initial fireball volume, estimated to reach up to about 3 GeV/fm^3, is indeed in a state of partonic matter. It expands toward lower energy density and should thus hit the critical QCD point, at which hadrons are to be formed that continue to expand, giving rise to the observed final "blast wave" collective expansion mode. In order to recapture the conditions at phase transition we need an observable quantity which is sensitive to this special point in the expansion dynamics of the fireball. This point falls in between of the primordially formed state reflected by the Bjorken estimate (which marks the beginning of expansion), and the very end of this expansion phase in collectively ordered velocity fields.

We now employ the "hadron thermometer" idea. Measuring all hadronic production rates, in central Pb+Pb collisions, for pions, kaons, antiprotons etc., up to the doubly strange Xi-hyperon makes use of the large acceptance and the high particle discrimination provided by the NA49 setup. The set of the production rates, or their ratios contains essentially one single information - but a very valuable one: the temperature and energy density prevailing at the birth of the hadronic phase. This should be very close to the critical values T_c and ϵ_c of the phase transition. Fig. 3 shows the data and an analysis by F. Becattini of Florence University who employs a thermodynamic model, in the footsteps of R. Hagedorn of CERN, obtaining T=176$\pm$10 MeV corresponding to ϵ=1.1$\pm$0.2 GeV per fm^3. These are, thus, our results concerning the critical parameters, and the outcome agrees with the prediction of lattice QCD. The parton-hadron phase transition is thus located.

d. The nature of the parton-hadron phase transformation

Big Bang theorists wold consider our mini-bang physics complete if we could not only pin down T_c and ϵ_c but also obtain insight into the nature of the phase transformation. The lattice QCD model is still uncertain about this question. For Big Bang dynamics it would be of particular importance to know

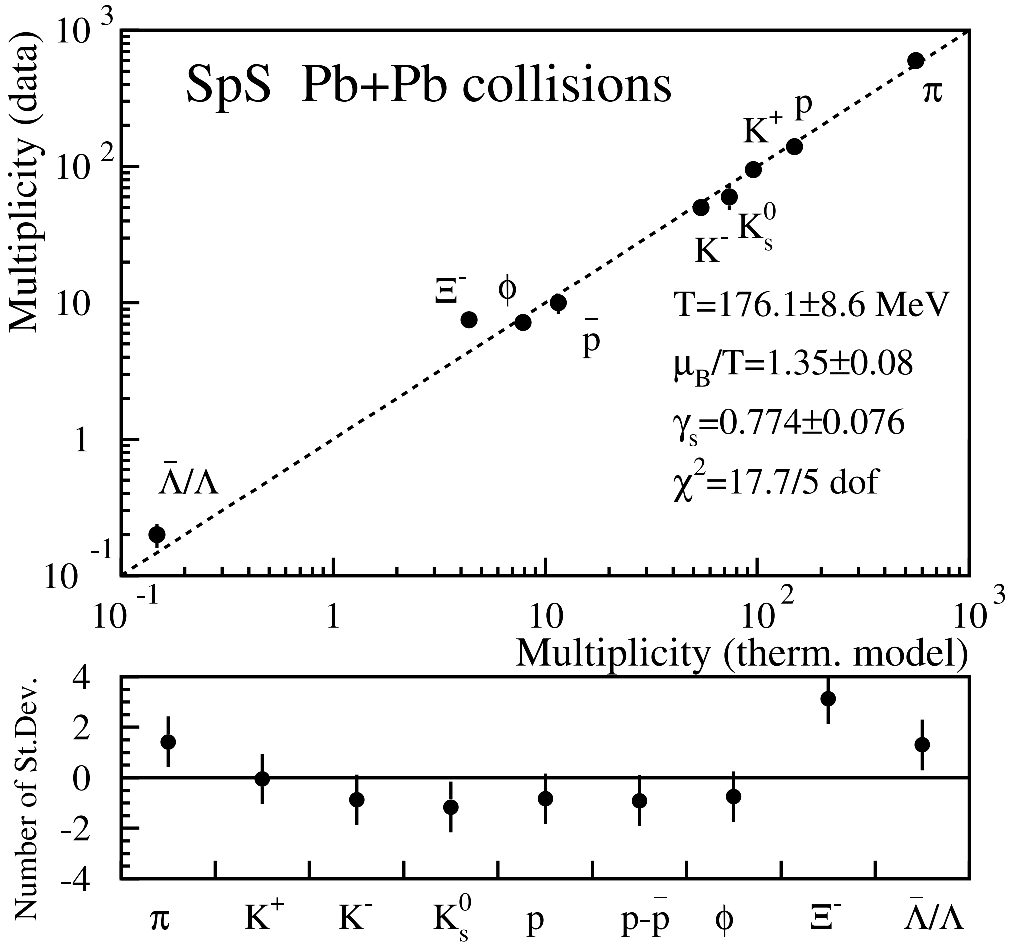

Figure 3: Phase space integrated multiplicities of various identified particle species measured by NA49 in central Pb+Pb reactions at 158 GeV per nucleon are compared to a statistical model fit (performed by F.Becattini). Fitted parameters of the model are the temperature T, the baryochemical potential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

whether or not the transformation is a first order phase transition because that would be of influence to the early synthesis of light nuclear species (helium, lithium, beryllium) in the Big Bang. In the Pb+Pb collisions a first order phase transition with a large latent heat jump might manifest itself by a long life-time of the fireball at the transition point. In principle, the pion Bose correlation effect provides for a reaction time estimate but the NA49 data do not show a slowing of the expansion rate (to the contrary as we have seen in section b.). Also large fluctuations of the hadronization point would be expected due to supercooloing - reheating processes that vary from one collision event to the other. NA49 records about 1200 hadrons in each event which enable one to measure certain quantities for each single event, for example the kaon to pion ratio which is sensitive to the creation temperature of the hadronic phase (see the previous section). Fig. 4 shows the histogram of K/π ratios found in individual central Pb+Pb collision events. Its width and shape can be almost completely understood by a simulation that incorporates only the trivial effects due to finite number counting statistics, experimental K/π resolution etc.. Thus we might take this as a first indication that the transition is not first order or, at least, features no large latent heat jump. However, this conclusion is still subject to a vivid theoretical discussion.

We conclude that the SPS Lead beam program has led to very interesting data that give a first outline of the QCD deconfinement properties in extended matter of extreme energy density. The results of all experiments and theory have been intensively discussed at the recent Quark Matter99 Conference at Torino, and the interested reader is referred to the Proceedings of QM99 that have appeared as a special volume of the journal Nuclear Physics series A, volume 661 (1999), Elsevier Publishers.

Further Reading

- T. Alber et al. NA49 Collaboration, Phys. Rev. Lett. 75(1995) 3841.
- H. Appelshauser et al. NA49 Collaboration, Eur. Phys. Jour. C2(1998) 611.
- F.Sikler et al. NA49 Collaboration, Nucl. Phys. A611(1999) 45c.
- R. Stock Quark Matter 99 Summary, Nucl. Phys. A611(1999) 282c.

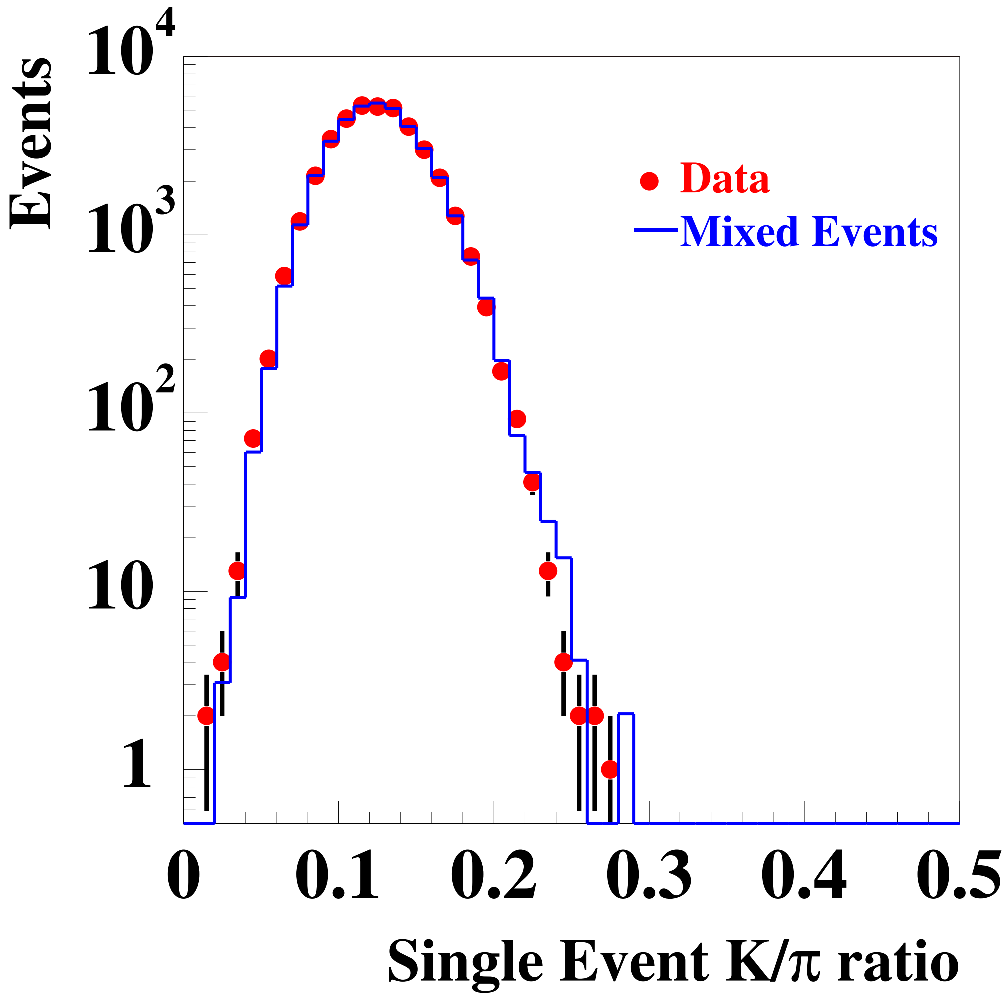

Figure 4: Event-by-event fluctuations of the ratio of the produced numbers of charged kaons and pions (a measure of the strangeness content of the event) in central Pb+Pb collisions at 158 GeV per nucleon (data points) are reduced to the level of finite particle number statistics (histograms). This lack of dynamical fluctuations indicates equilibration of the produced matter, as may be expected if the reaction proceeded through a QGP stage.