HEAVY IONS

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Abstract

The scenario of high energy heavy ion collisions is described. Selected experimental results are discussed in terms of our present understanding of the physics and future hopes and goals.

1. INTRODUCTION

The aim of high energy heavy ion physics is to establish the existence of a new state of matter, the Quark Gluon Plasma (QGP) and ultimately to study the properties of this state of matter in detail. This search is and will be not easy and will be going on for still a long time to come. QGP is a natural part of our understanding of the big bang, i.e. the state of the universe at approximately a microsecond. Thus this physics is strongly linked to astrophysics. Recently multi GeV heavy ion beams have become available at Brookhaven and CERN making it possible to study scenarios never before possible under laboraty conditions.

At these new experimental conditions a typical collision looks like this :

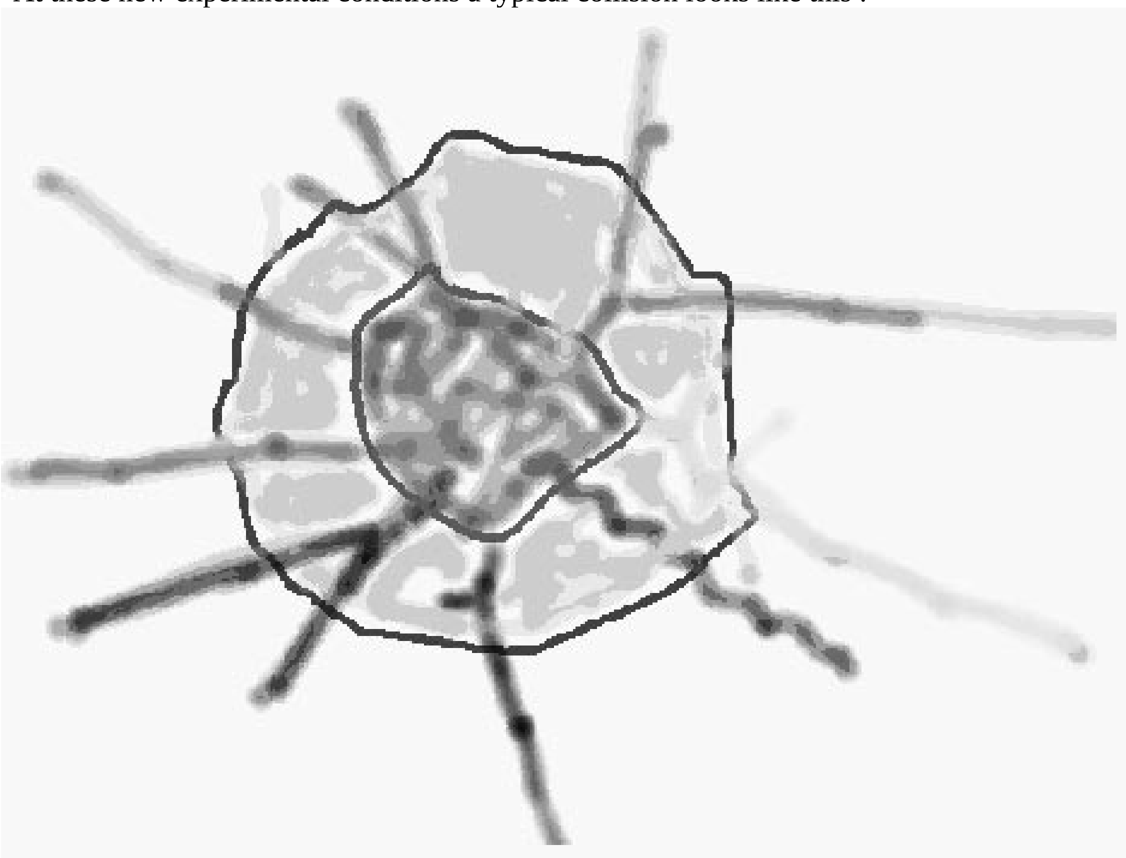

Fig. 1. A ‘typical’ heavy ion collision

It is not too hard to imagine that what we see here is an initial state, which may or may not be a quark gluon plasma. Outside it (or rather later in time) a dense fireball of hadronic matter expands and finally hadrons freeze out, e.g. have no more scatters. The big problem is studying the inside through the outside which will tend to wash out the potential signals. In the above picture everything possible happens :

- *Transverse energy is radiated signalling the energy density available, if high enough formation of a quark gluon plasma is possible - section 2.*
- *The deep probes, direct photons get out to us observers, unfortunately the photon background from ^{1o} decays is very big - section 3.*
- *Virtual direct photons, i.e. low mass lepton pairs, have no background from ^{1o} decays. The low rate makes experiments hard, anyhow a promising signal - section 4.*
- *Lepton pairs with heavy masses, signalling J/ψ - or ψ' - production have been predicted to be most promising probes, the suppression of the J/ψ due to disintegration of the c-cbar system - section 5.*
- *Strangeness enhancement, high energy density / temperature restoring the up- , down- and strange chemical equilibrium - section 6.*
- *The transverse mass spectra may be effected by the expansion during the collision and reflect properties of the expanding system - section 7.*
- *HBT - two particle intensity interferometry can, at least in principle, give information about the space time evolution in heavy ion collisions - section 8.*
- *Conclusion - section 9.*

2. GLOBAL SIGNATURE

The transverse energy spectrum from NA49 [1] shown in fig 2 tells us (using Bjorkens formula [2]) that we are in a regime of energy densities around 3 GeV/fm^3 where theoretical estimates say quark gluon plasma is likely to be formed at an early time during the collision.

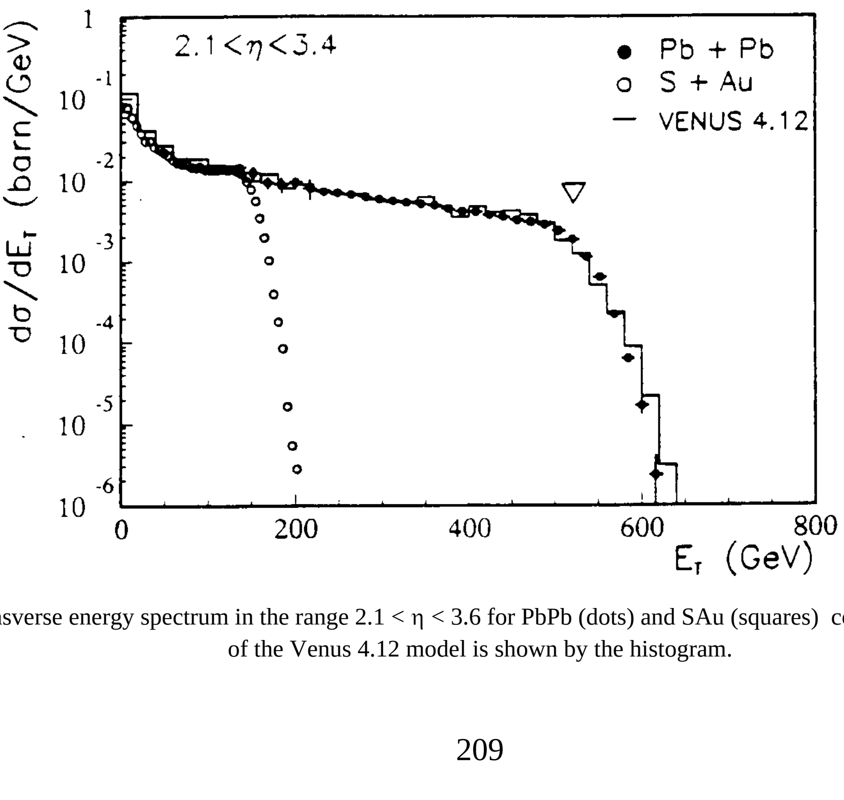

Fig. 2. Transverse energy spectrum in the range 2.1 < η < 3.6 for PbPb (dots) and SAu (squares) collisions. The prediction of the Venus 4.12 model is shown by the histogram.

Taking into account the size of the nuclei involved the energy density is a factor 2.5 higher for central PbPb compared to SAu collisions (i.e. 3.2 compared to 1.3 GeV/fm^3) indicating that we are closing in on a promising scenario !

3. DIRECT PHOTONS

Experiment WA80 has been a pioneer in the search for a positive signal, concluding [3] that a weak signal may be there. The CERES experiment [4] (NA45) also at CERN now presents an upper limit of 10% of the possible extra photons not accounted for by known hadronic sources.

At present this signal does indeed not seem very promising. However nature sometimes has surprises in hand. Indeed if there is a hot initial thermal equilibrium photons ought to be radiated. The search will go on.

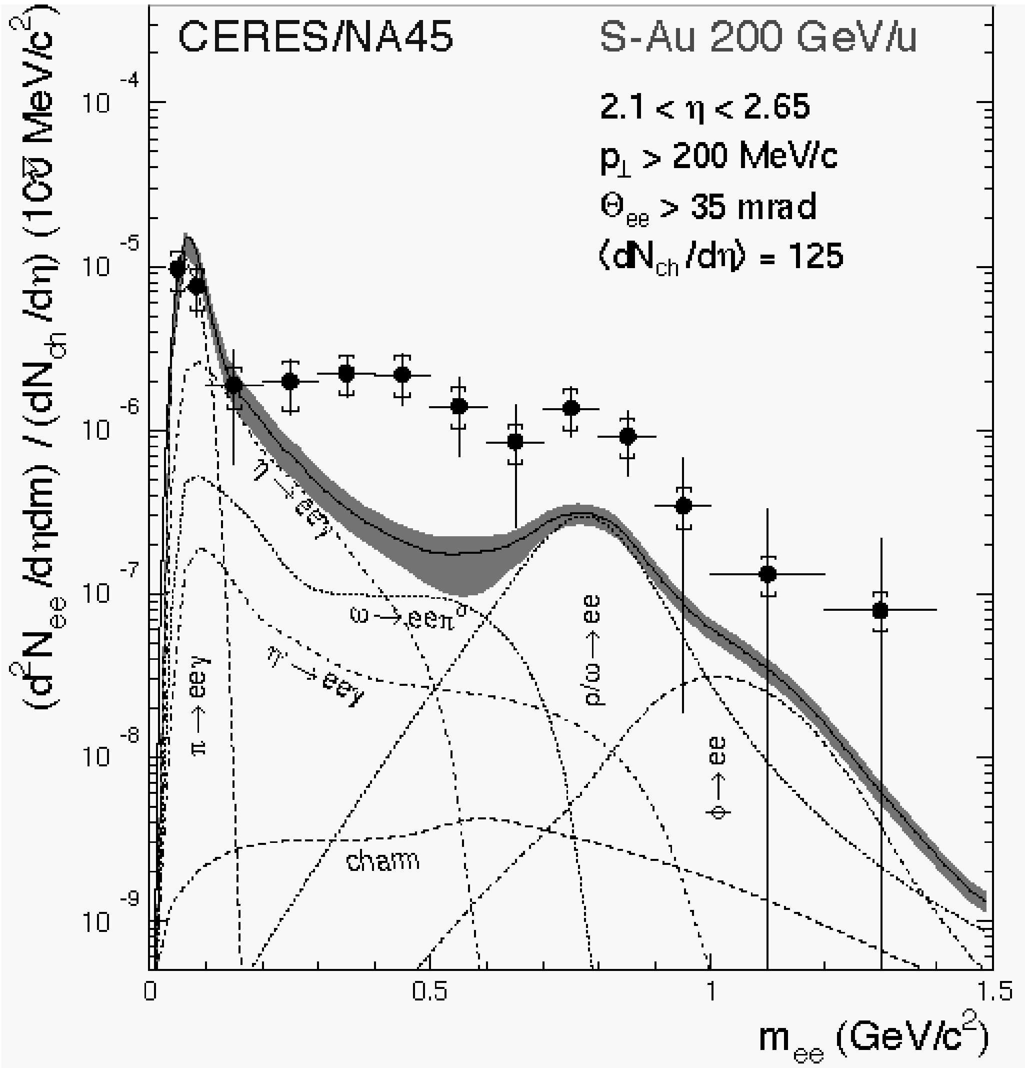

Fig 3. The mass spectra of electron positron pairs from the CERES experiment [4] for S-Au, normalised to the charged particle density

4. LOW MASS LEPTON PAIRS

Looking at virtual photons through low mass lepton pairs the situation is also experimentally difficult, though quite different. When the lepton pair mass gets above the ^{1o} -mass the overwhelming background from Dalitz decays of ^{1o}'s is away. Still a very careful analysis is necessary because the signal is small and all background sources have to be pinned down before a signal can be claimed [5,4]. Fig 3 and 4 shows the e^+e^- mass spectrum measured by the CERES experiment [5], in S-Au and p-Be collisions normalised to the charged particle density. The figures illustrates the necessary very careful calculations of all known hadronic sources to make sure a possible deviation is really something new.

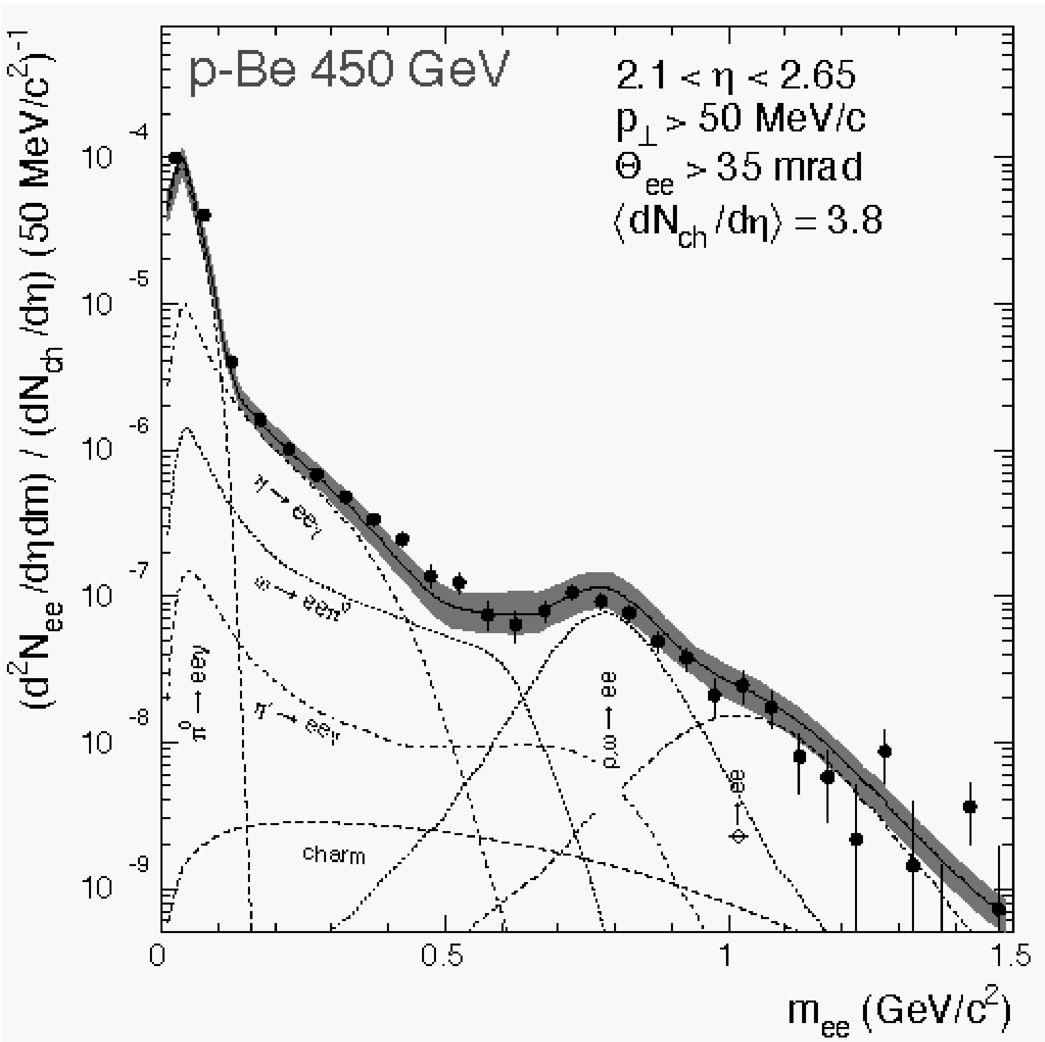

Fig 4 The mass spectra of electron positron pairs from the CERES experiment [4] for pBe, , also normalised to the charged particle density.

For the lighter ion collisions the descriptions turn out to be adequate, but for S-Au a special new source seems to be present above 200 MeV/c.This enhancement is not presently theoretically understood, It is suggested that the rho and omega masses in the high energy density medium is shifted downwards indicating that the quark - antiqoark states are breaking up. It will be very interesting to see similar results from the PbPb data and their theoretical interpretations.

5. J/ψ - AND ψ' - SUPPRESSION.

J/ψ suppression was indeed predicted [6] as a signature for a quark gluon plasma. When the temperature (e.g. energy density in a reasonably large volume measured by the total transverse energy E_T) is high enough the charm-anticharm quarks are screened away from each other. This effect has also been unambiguously found [7]. The problem is that afterwards other more conventional explanations could be constructed [8]. More precise experiments were needed and in particular experiments in the new experimental scenario, i.e. PbPb. Fig 5 shows the $\mu^+\mu^-$ mass spectrum found in 158 GeV Pb-Pb collisions from NA50 [9]. The different contributions to this distribution are shown. The J/ψ signal can be extracted and compared with the Drell-Yan contribution at high mass. A parameter L, measured in fermi can be constructed as a measure of the reaction volume or length. The more central the collision is the larger is L. Fig 6 shows the ratio of J/ψ's compared with Drell-Yan as a function of L. At low L the decrease observed can be explained by known effects, basically the re-absorption of produced J/ψ's, but at large L a sudden drop is observed, exactly what is expected from a Quark-Gluon plasma,. However at this moment all sorts of alternative explanations are persued and we have to wait some time for a final concensus.

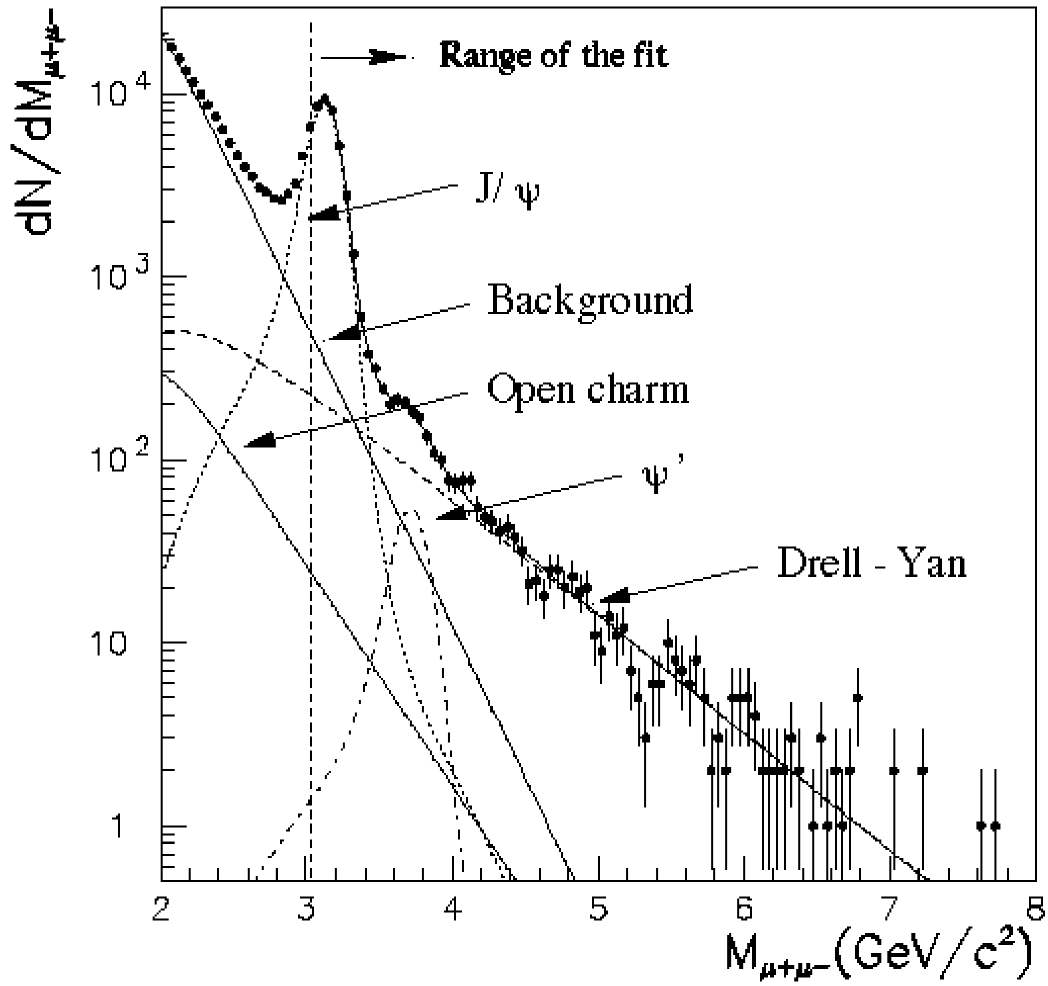

Fig 5 Mass distribution of opposite sign muon pairs from PbPb collisions in NA50 [9].

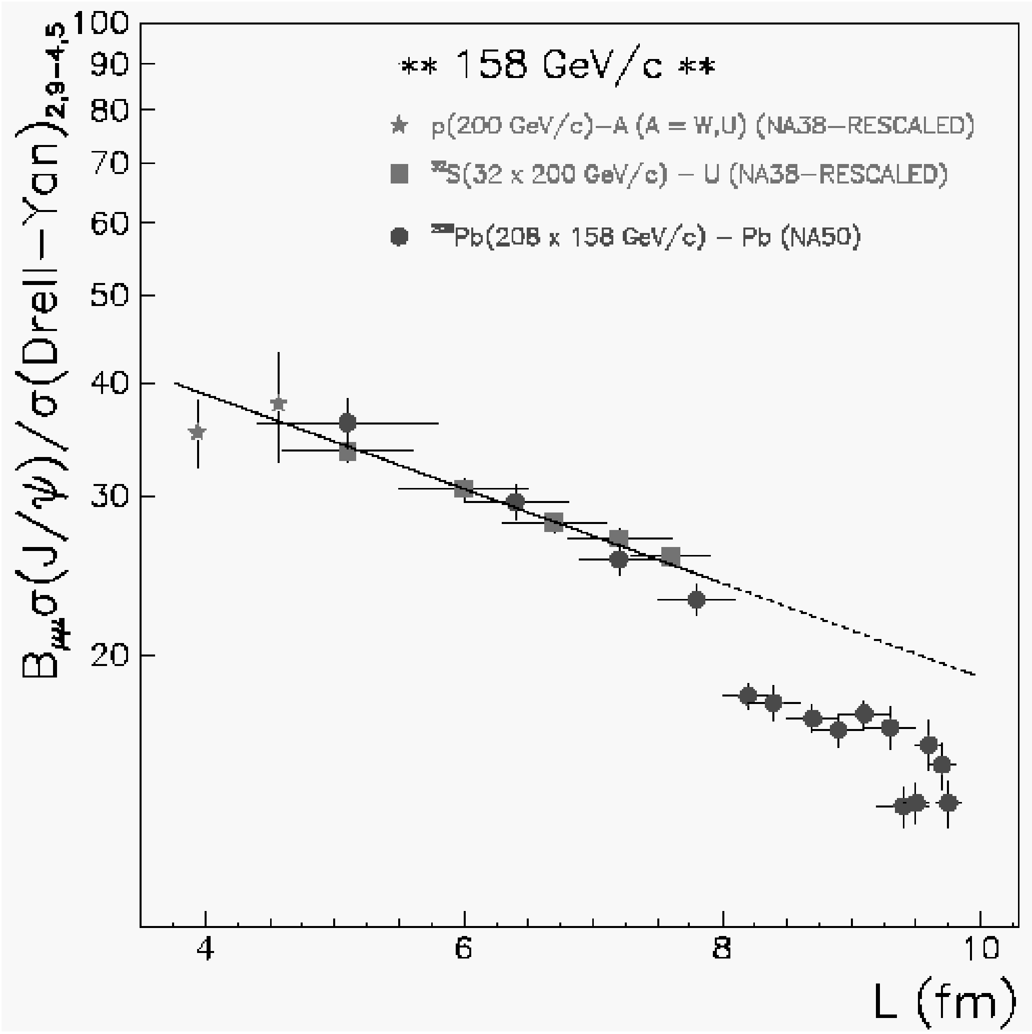

Fig 6. J/ψ /Drell-Yan cross section ratio at 158 GeV versus L from NA50 [9]

The same ratio has also been studied for pA collisions as a function of A and of Ãs and no change is observed [10].The search for a convincing set of results is certainly not given up, NA50 at the CERN SPS is busy with PbPb collisions and future higher energy experiments will undoubtedly continue the quest.

Another expectation from a hot state of matter is that the ψ' breaks up more easily than the ψ because of the larger size, smaller binding energy. This is indeed found by NA38 i.e. the ψ'/ ψ ratio is found to be decreasing when the total transverse energy increases [10].

6. STRANGENESS ENHANCEMENT

When the energy density is so high that the mass difference between up/down versus strange quarks becomes less important the number of the different (light) quarks should be in chemical equilibrium. therefore strangeness enhancement is predicted [11] and also found. The $K^+/1^+$ ratio typically doubles compared with pp collisions, the $K^-/1^-$ increase as well, but less. Again hadronic explanations are found. Also expected is that the more strange the larger the increase. This is clearly observed by the WA85 collaboration [12] comparing the change from pW to SW collisions. The double ratio K^o_s /(h^-, negative hadrons) ratio SW to pW is above 1.3 and when increasingly strange baryons and antibaryons are studied the effect is increasing, e.g. for Ξ/h^- around 3.0.

It is also observed [13] that the ϕ meson is indeed enhanced, being build by light strange quarks and not heavy charm quarks

7. TRANSVERSE MASS SPECTRA.

The transverse mass spectra do indeed change when the energy density and the volume becomes large. Fig 7 shows the m_T distributions from NA44 [14] and fig 8 how the inverse slopes ('temperature') from the exponential fits to dN/dpt = Kexp($-m_T/T$) changes with mass and collision type. For pp collisions the inverse slopes are independent of particle mass, for SPb and PbPb they increase remarkably with the particle masses.

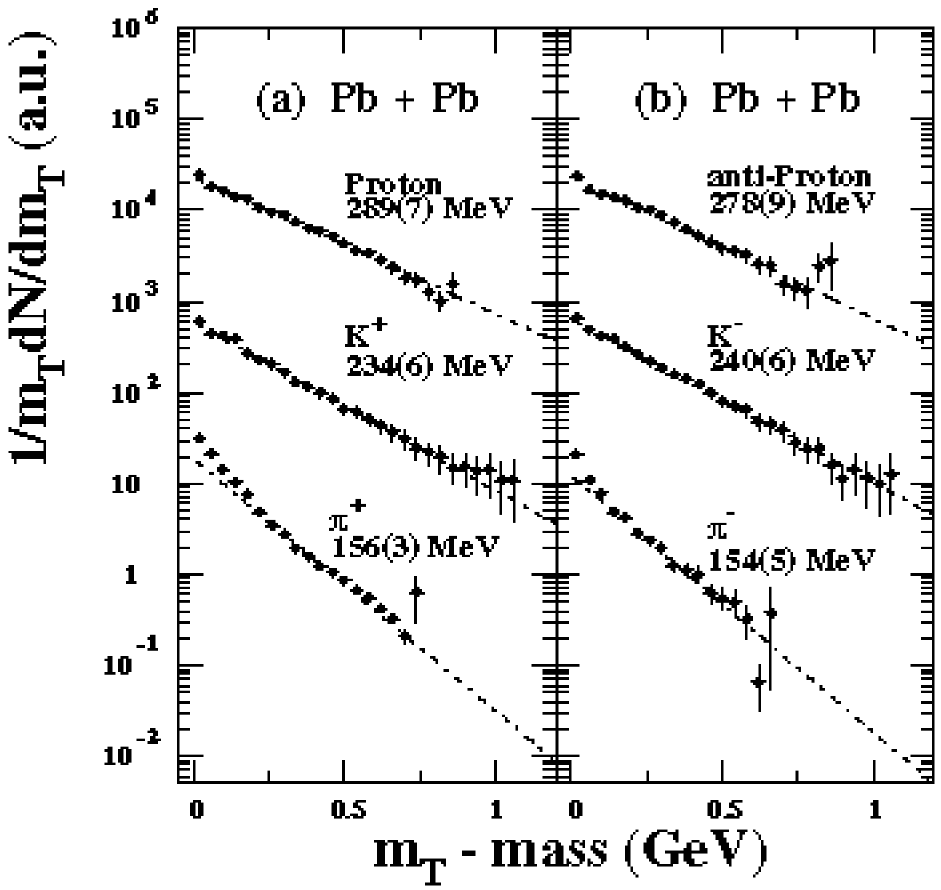

Fig 7. The transverse mass spectra for 160 GeV/n PbPb and 200 Gev/n SS from NA44

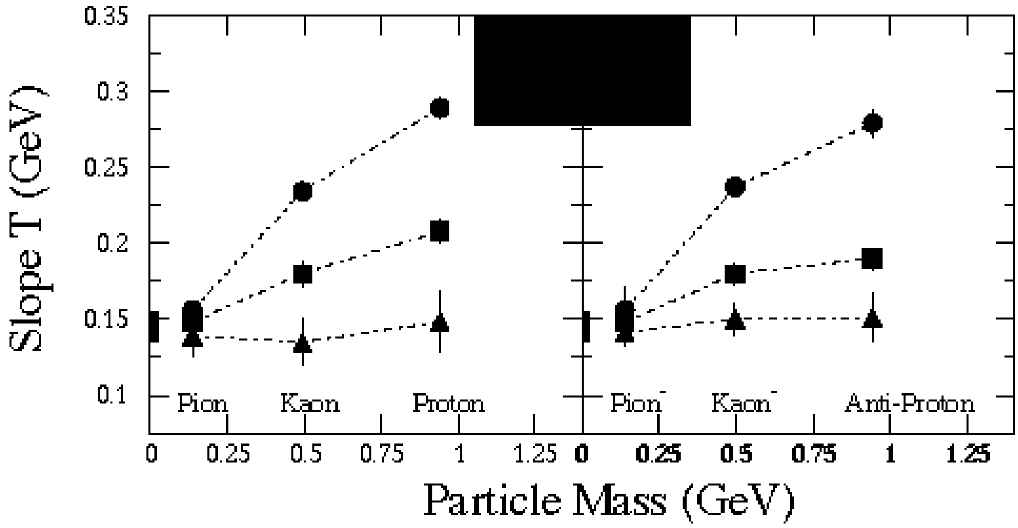

Fig 8. Transverse slopes as a function of mass for pp, SS and PbPb.

This is consistent with a picture [15] of an initial production state with a certain temperature followed by an expansion giving the heavier particles a larger boost, i.e. increasing m_T. The systematic behaviour seen in fig 8 indicates strongly a collective behaviour in the final state. This is important because the existence of such a state makes it possible to consider it as a candidate for a quark gluon plasma.

8. HBT - TWO PARTICLE INTENSITY INTEFEROMETRY.

Hanburry-Brown Twiss intensity interferometry [16] was introduced in stellar astronomy to study scales of parsec - it turns out that the same quantum mechanical effect can be used in hadron physics to study the space time evolution in hadron collisions on the scales of fermi's. The effect is a consequence of boson statistics, two identical bosons emitted from a source cannot be distinguished from each other by the observer, the final state wave function has to be symmetrized. The effect is an enhancement at small differences in momentum of the two bosons, the width of which depends on (through a fourier transformation) the spatial extension of the source. A correlation function can be constructed, i.e. the probability of observing two particles at specific momentum differences, Q, divided by the product of the probabilities of seeing these independently. Usually this correlation function is called C2 - the value of C2 for small q should ideally, for a completely incoherent source, approach 2. In reality smaller values are found and a parameter, λ, is introduced, the so-called incoherence parameter. Typically C2 is fitted to functions like C2 = $K\exp(-R^2Q^2)$, where R (in fm) represents a measure of the size, ‘Radius’, of the emitting source. Fig 9 shows as an illustration the correlation function for ^{11} and for KK pairs, measured by NA44. It is clearly seen that the KK peak at low Q is wider that the ^{11} peak leading to a smaller radius parameter for KK, see below.

The momentum difference vector can have several components, longitudinal, transverse. In the transverse plane two different components are defined, one parallel to the vector sum of the two transverse momenta, q_{Tout}, and one transverse to the sum, q_{Tside}. The 'side' component is predicted to reflect the transverse geometrical size, whereas the 'out' component also carries information on the time development in the collisions.. From the extracted source parameters, e.g. radii one can compare the results for different particle types, colliding particles and production energies.

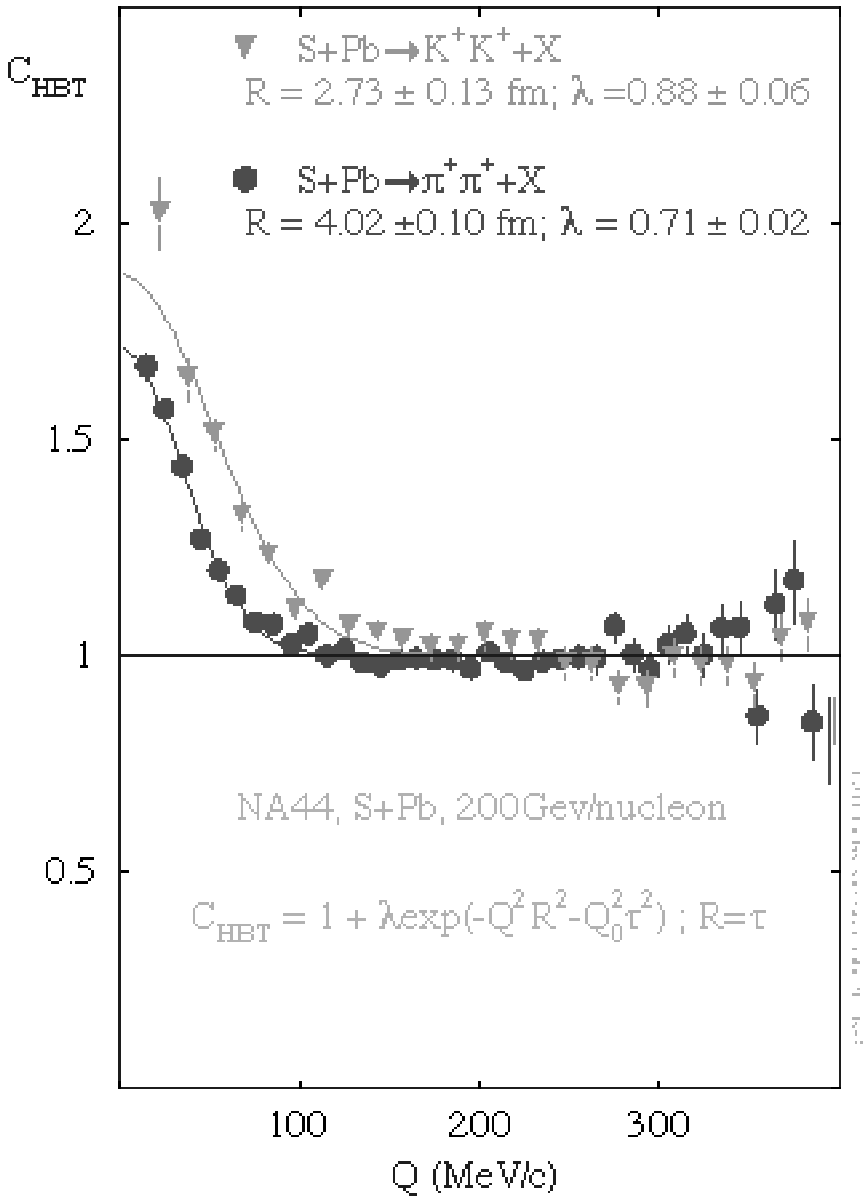

Fig 9. The correlation function C2 for ^{11} and KK pairs from NA44

Fig 10 shows a compilation of results from NA44 [17] at CERN (200 GeV per nucleon) and E802 [18] at Brookhaven (14.6 GeV per nucleon).

The following features can be observed : 1) The radius parameters are found larger at the CERN energies for almost the same size nuclei colliding. This means that the higher hadronic density at the higher energy must have lead to an expansion, and thus to the existence of a hadronic final state of interacting particles. 2) The radii for kaons are smaller than for pions, i.e. it looks as if kaons decouple earlier 3) The radii for pions at large p_T are smaller than for small p_T. 4) For pA collisions the radii are also small as expected.

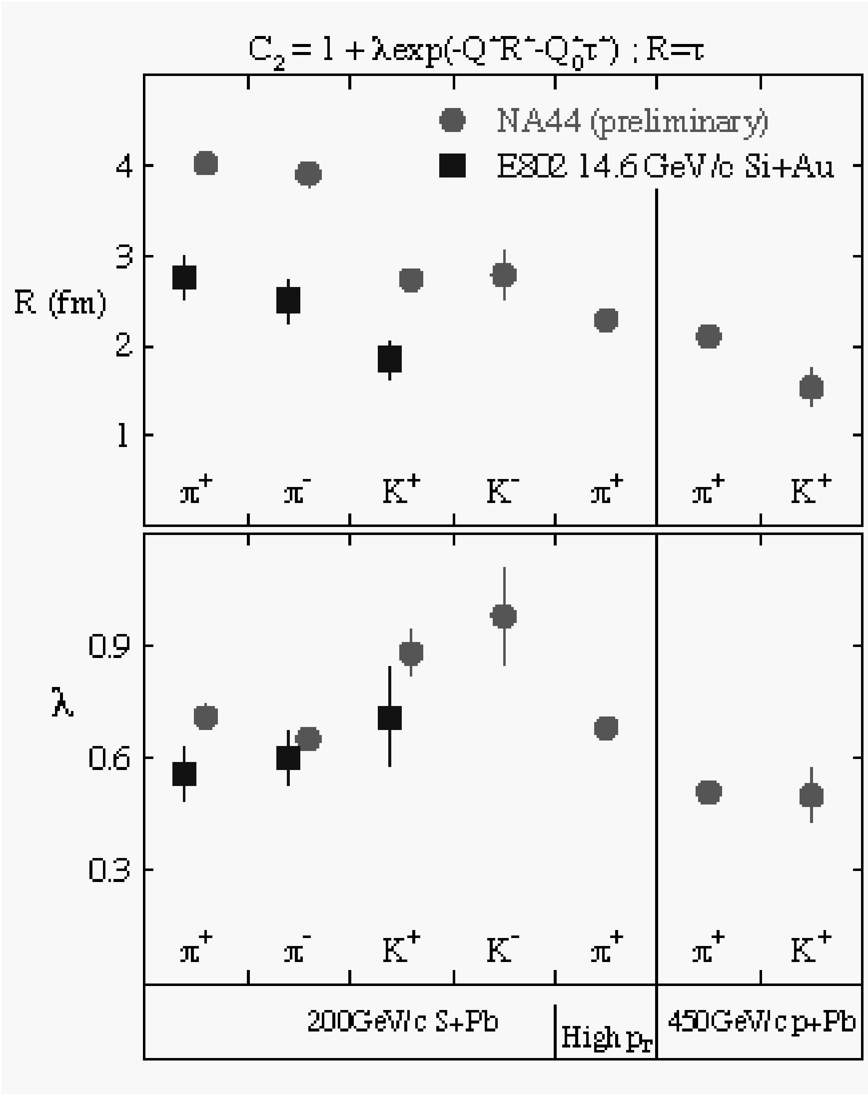

Fig 10. A compilation of HBT results from CERN,NA44 and Brookhaven, E802

It turns out that the NA44 SPb results [19] lead to a simple scaling of the radii by 1/Ãm_T , see fig 11. A similar result is found by NA35 [20] This can be interpreted in terms of a hydrodynamical expansion of the final state .

8. CONCLUSIONS.

The conclusion at this point is that we are still underway with several promising positive signals found, but still no real proof of a (shortlived) existence of a new state of matter, the *quark gluon plasma*. The picture is however consistent with such a state of matter and we are allowed to look optimistically forward to what we find around the next corner. In the near future a new generation of experiments will start at RHIC, Brookhaven, where where heavy nuclei at 100 GeV per nucleon collide. This will give a large step in energy density and the potential for new discoveries is large. On a longer scale the LHC will start in 2005 and will include a heavy ion programme. Here the energy per nucleon will be many TeV, probably this will for a long time be the ultimate machine for high energy heavy ion physics. A possible scenario is that at the SPS strong signals are found, at RHIC the existence of a QGP is finally pinned down and finally at the LHC the properties of QGP can be studied in detail. This will in turn teach us important information about conditions in the early universe.

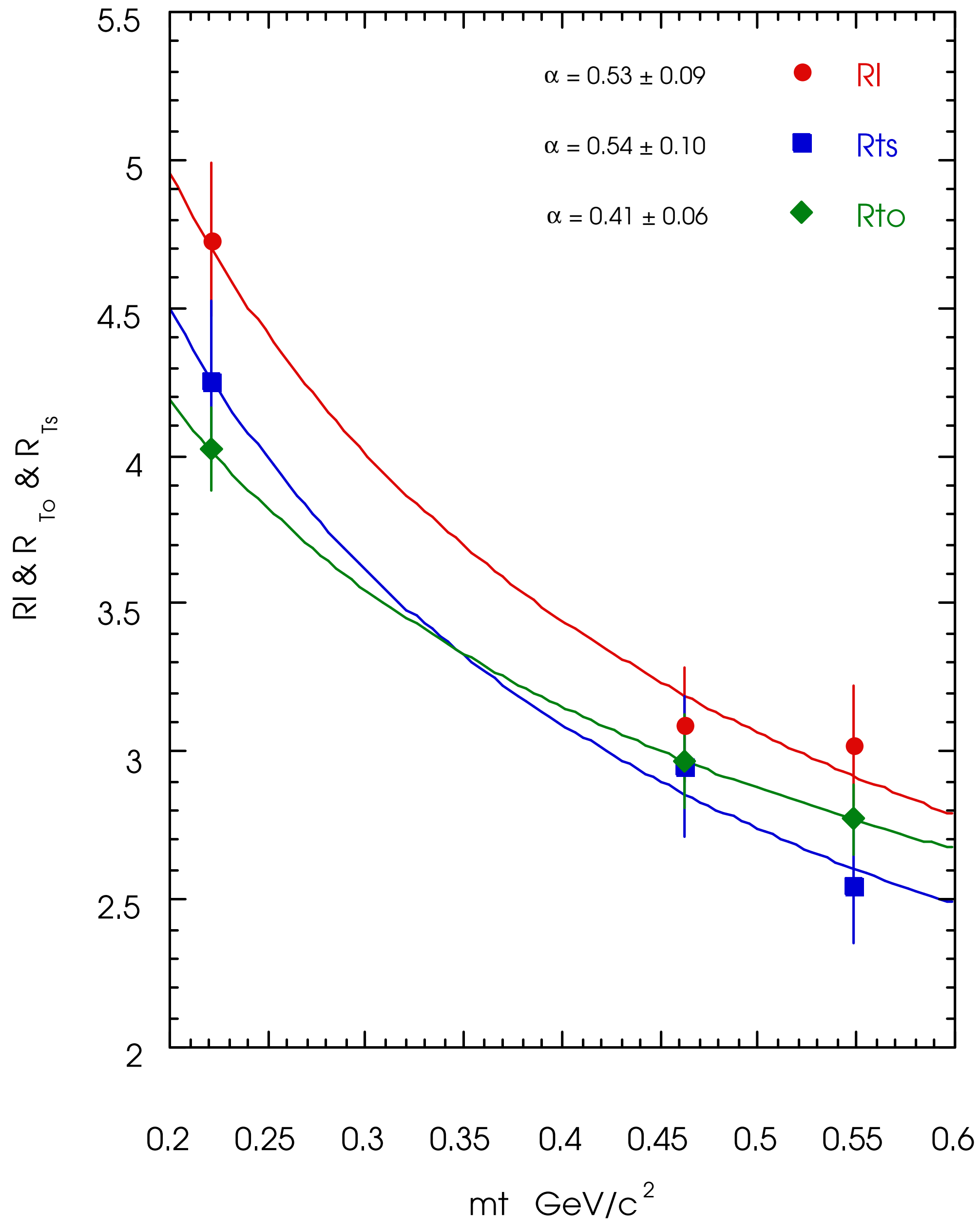

Fig 11 The radii parameters of the three component fits as a function m_T . The α values are fits to const. / m_T^{α}.

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