Experimental Conference Summary

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1. Introduction

Within the history of our field, this Quark Matter Conference has been truly unique, and I am delighted and grateful to the organizers for the invitation to summarize it. First, RHIC has arrived, and the very fact and the way it did will surely make this meeting unforgettable to all of us. Second, the comprehensive programs at the AGS and the SPS have (with one exception) come to an end, and it therefore seems appropriate now to also look back and critically assess the old and the new at the same time.

Indeed, I cannot resist to start even earlier. It is now about 20 years ago that the scene was set by a series of workshops in Berkeley 1979 [1], Darmstadt 1980 [2] and, most important, Bielefeld 1982 [3], the start of the "official" series of Quark Matter Conferences (later labelled "2nd" to leave room for Darmstadt). In Bielefeld, particle physicists and nuclear physicists met for the first time in a systematic way to form a new community. Nearly everything was already there: first lattice results including the deconfinement transition, the chiral transition and indications for the soft equation of state, the astrophysical relevance, nuclear collision dynamics, most of the relevant observables including ρ-melting and hard probes like leptons and photons, the basic ingredients to the future experimental program (largely at the SPS) - and, most remarkably, the accelerator setting for the following 2-3 decades. As illustrated in Fig. 1, the preceding discussion on the LBL VENUS project [1]-[3] and the CERN ISR [2,3] had been superseded by a quickly converging discussion on SIS, the AGS, the SPS and RHIC, the latter in Barton's paper [3] still sailing under the traditional pp project name ISABELLE (the AGS came in through the backdoor of that). Indeed, only the LHC was not yet born at that time.

So now we celebrate the arrival of RHIC, delivering the highest center-of-mass energies ever made by mankind. The first day of the conference started with a grand firework. There were charged multiplicities, high-p_T spectra over many orders of magnitude, identified particles up to the exotica Ω^-/Ω^+, π°-spectra, flow, HBT correlations, single electrons, and the announcement of tens of more detailed contributions in the parallel and poster sessions. At the end of the day I had a headache, and it was only in the course of the week and after the 4 reviews of the final morning that I came to fully appreciate what we were all witnessing during these days. Personally, I am not aware of any other example within our field or beyond, which produced such a rich spectrum of (albeit preliminary) new and exciting physics results in such a short time after the first run, at a brandnew machine with a set of brandnew elaborate and complicated experiments. I express my

admiration, and I congratulate all of you, the management, the machine crew and the large number of enthusiastic young researchers who have made this miracle possible.

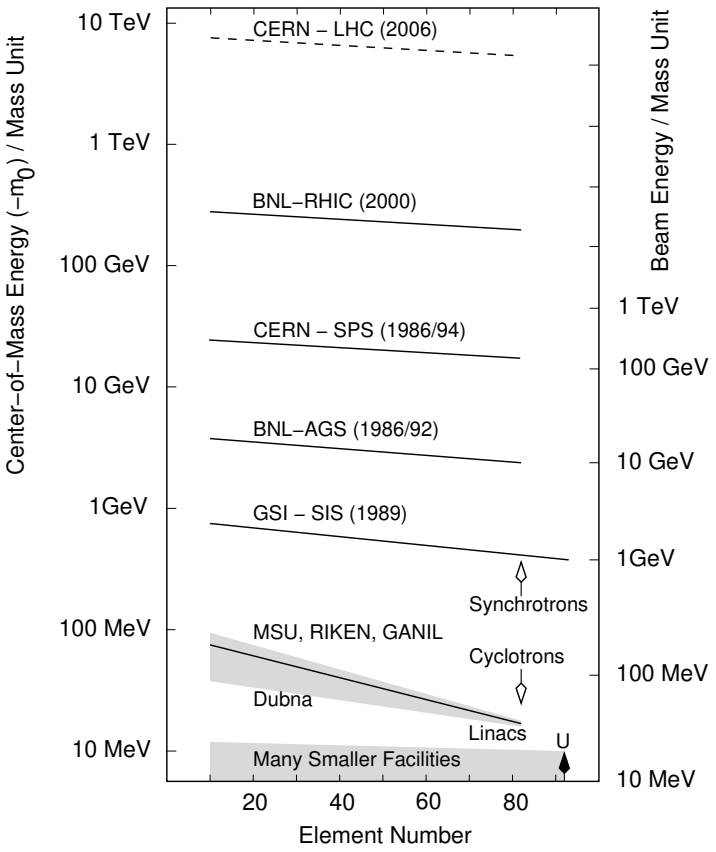

Figure 1. The major heavy ion accelerators worldwide. Nonrelativistic and relativistic, fixed target and collider facilities are put on a comparable basis by choosing the center-of-mass energy (minus rest mass) per nucleon for symmetric collision partners. Above 1 AGeV, the spacing progressively increases even on a log-scale. The years indicated for each machine refer to first operation with light ions (^{28}Si, ^{16}O/^{32}S) and very heavy ions (Au, Pb), resp.

2. What have we learnt?

The substance of what I wish to discuss is shown in Fig. 2 which can serve at the same time as an introduction, a guideline through the talk and a final summary. The figure is largely self-explanatory, confronting the fireball evolution after the collision impact with the experimental evidence for the interpretation and the conditions of the respective stage. With all due respect to RHIC, its first exciting results and its fascinating future potential, I will be courageous, use (what seems overdue) already at SPS energies the term "Quark Matter" rather than the nebulous "New State of Matter" of last year's CERN press release [4], and systematically integrate the new information from RHIC as reported during this conference. We then arrive at the following sequence of events: Heavy Nuclei collide and reach initial conditions in terms of energy density and temperature well above the critical values for deconfinement. Quark Matter is formed as evidenced by the hard probes J/ψ (SPS), high-p_T/intermediate mass photons/dileptons (SPS) and high-p_T hadrons (RHIC). The fireball then expands under pressure (more at RHIC than at the SPS), hadronizes with parameters close to the expected phase boundary, possibly shows the influence of chiral restoration at that boundary as evidenced by low mass dileptons (SPS), strongly expands further under pressure and finally, after thermal freeze-out, ends as a cloud of non-interacting hadrons. From hadronization onwards, the fireball evolution appears to show essentially no difference between the SPS and RHIC.

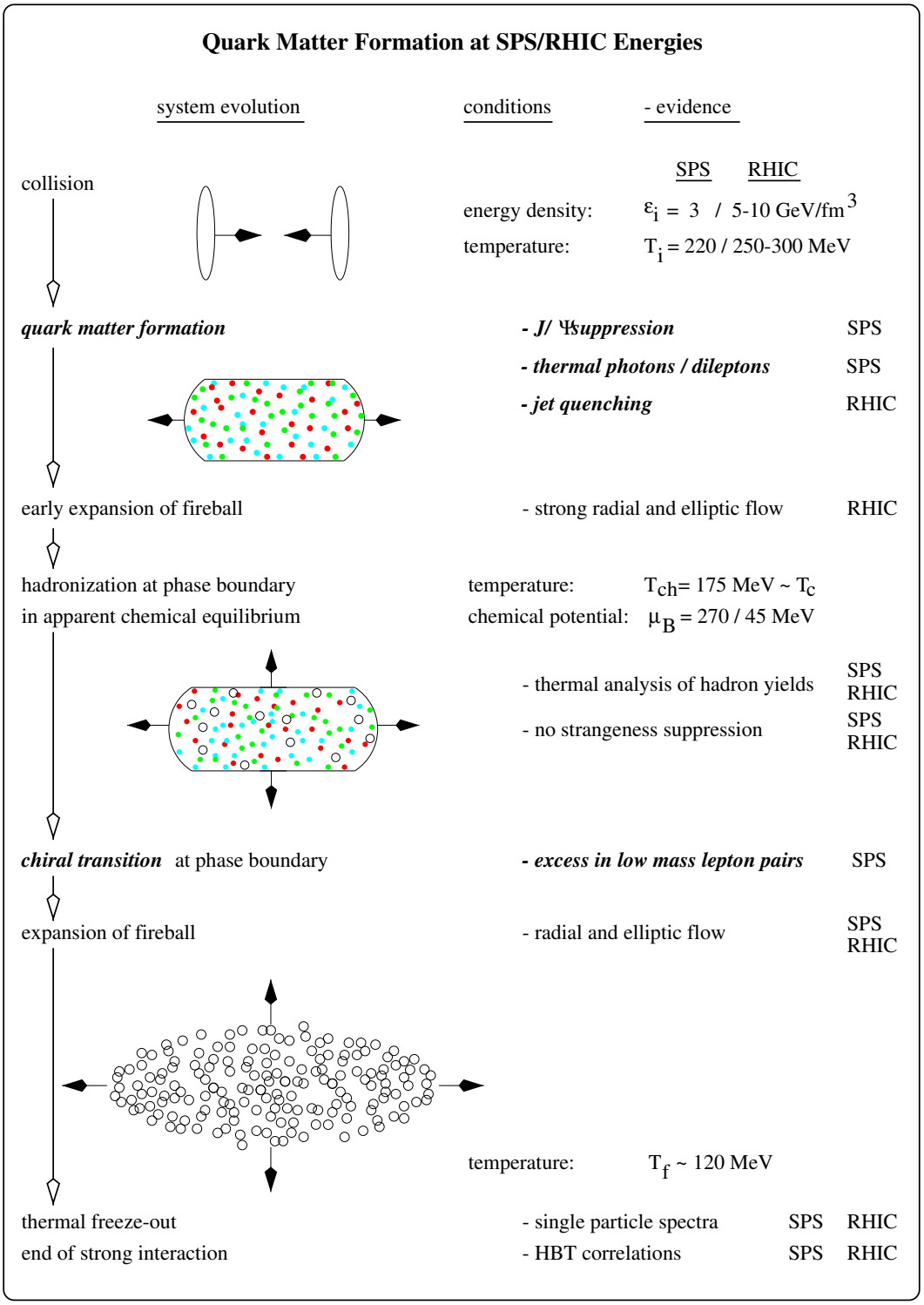

Figure 2. Fireball evolution following the impact of two heavy nuclei at ultrarelativistic energies. The various stages in the evolution are confronted with the experimental evidence and the experimentally determined conditions of the respective stage. Results (from mostly hard probes) related rather directly to quark matter formation are printed in *italics*. The labels SPS/RHIC refer to the energy regimes for which the respective evidence has thus for been observed.

2.1. Initial Conditions

Charged particle multiplicities measured by PHOBOS were the first published results from RHIC [5]. Fig. 3, taken from the review of Steinberg [6], shows the measurement of $dN_{ch}/d\eta/0.5N_{part}$ as a function of $\sqrt{s}$ for all RHIC experiments in comparison to NA49 at the SPS and various $\overline{p}p$ data; for the interesting discussion on the onset of contributions from hard processes and the associated theoretical model lines in Fig. 3 see ref. [6]. We use the fact that about 72 % more particles are produced at RHIC (at 130 GeV) than at the SPS and obtain, together with $<dE_T/dN_{ch}>$ = 0.8 GeV both at the SPS and at RHIC [6], initial energy densities of 3 and 5 GeV/fm^3, using the Bjorken formula [7]. However, the hadron formation time τ, taken as 1 fm for this estimate, may well decrease as a function of $\sqrt{s}$ as proposed, e.g., by models of particle production based on parton saturation [8]. If, conservatively, we allow for a factor of 2 at RHIC, we get a range 5-10 GeV/fm^3 and thus initial temperatures of T_i = 220 and 250-300 MeV at the SPS and RHIC, resp., both well above the critical values of 173±8 (2 flavors) and 154±8 (3 flavors) quoted by Karsch for lattice QCD during this meeting [9]. This argument alone, used of course by many people over many years, confirms that the SPS had a genuine chance, irrespective of the much more favorable conditions at RHIC.

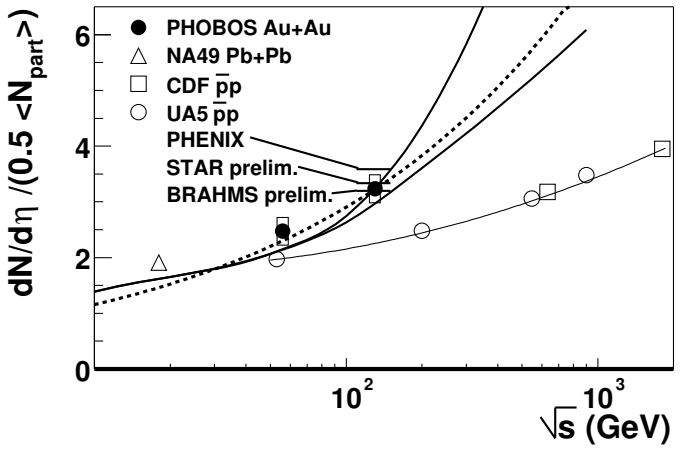

Figure 3. Dependence of $dN_{ch}/d\eta/0.5N_{part}$ for $|\eta| < 1$ on the center-of-mass energy with results from all four RHIC experiments at $\sqrt{s_{NN}}$=130 GeV (from [6]).

2.2. Quark Matter Formation

The evidence for quark matter formation at SPS and RHIC energies is essentially based on hard probes. This does not imply that soft probes like strangeness would not also be of relevance; consistency with quark matter formation is just not sufficient if alternate explanations persist. I will discuss the hard probes in the order indicated in Fig. 2.

J/ψ suppression

The study of J/ψ production, done by NA38/NA50, has been an integral part of the SPS program from the beginning. First signs for suppression were already reported after the very first data round (QM Nordkirchen 1987), when the appealing idea of melting in a deconfined phase as an existence proof for quark matter formation had just appeared [10]. In the nearly 15 years since then, 100's of theoretical papers have challenged the unambiguousness of the idea with various hadronic suppression scenarios, driving a continuous feedback with better and better data systematics up to the present impressive level. The breakthrough came with PbPb collisions and the recognition of "anomalous" suppression beyond the one understood as nuclear absorption. The controversy is still

continuing, however, sometimes now not even free from irrationalism. Today's situation as summarized by Bordalo [11] is illustrated in Fig. 4. The data are essentially those reported already at QM Torino 1999, while some of the model descriptions have only appeared more recently. Hadronic suppression based on conventional nuclear absorption is far off; hadronic suppression based on comovers and Qiu's [12] new approach to nuclear absorption fail at least in shape. The assumption of deconfinement clearly gives

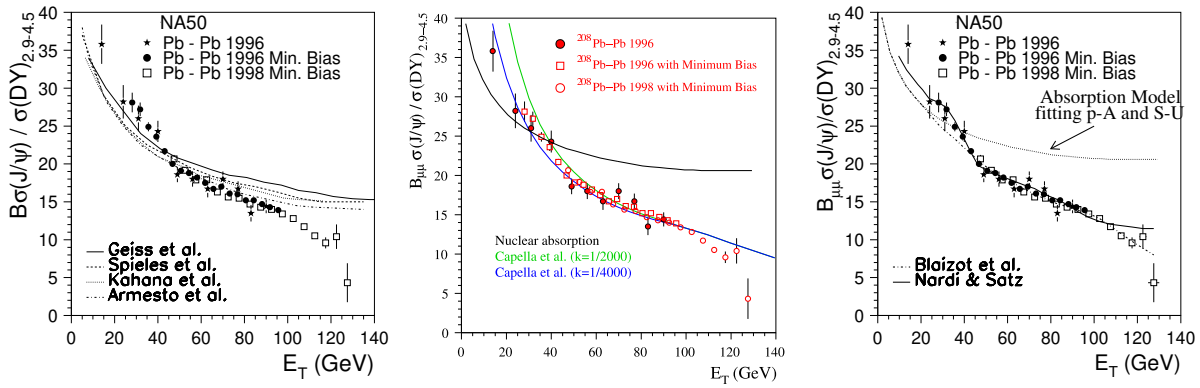

Figure 4. Experimental results on the ratio J/ψ/DY compared to different models: suppression by hadronic comovers (left and middle) and by quark matter formation (right) (from [11] which also contains all model references).

the best description. The still controversial stepwise suppression [13] with the apparent onset at $E_T \sim 40$ GeV will be confirmed if true by the improved data at low E_T taken in 2000, while the very natural idea of E_T-fluctuations at high E_T, coupled to complete suppression beyond a critical value of the local energy density [14], should perhaps be integrated with the onset- (or even stepwise-) suppression picture. New information on J/ψ transverse momentum distributions was also presented [11]; this still awaits critical modelling. Further experimental insight can be expected from NA60 which will e.g. look into the threshold behaviour (via a smaller collision system) and into the more open ψ' issue. In any case, J/ψ suppression as it stands at this moment should be taken as the most compelling piece of evidence in favor of deconfinement which the field has produced thus far.

In retrospect, J/ψ suppression at the SPS seems to be a fortunate accident of nature. Since only about 1 % of all charm produced appears in primary charmonia (the rest in open charm), it is conceivable that J/ψ's can also newly be created at the hadronization stage (see 2.3). Surprisingly, investigations along this line have only recently been done [15, 16], concluding that, although genuine thermal charm production is small, direct charm production by hard processes may lead to a level of statistically produced J/ψ's masking the suppression mechanism for the primary J/ψ's. At the SPS [15], the level does seem to come close, in particular if further charm enhancement is assumed (see below). However, the functional dependence on E_T (or N_{part}) with its peculiar shape (name it different "thresholds" or not) is not at all described, and the reduction relative to the primary level is in any case unchallenged. At RHIC [15,16], however, statistical production may be so effective as to lead to a net J/ψ enhancement. That would indeed be spectacular, greatly help precision experiments and provide an alternative tool to study quark matter formation [16] (if it does not suffer the fate of strangeness, hadronic phase space).

Thermal Photons/Dileptons

Dileptons and direct photons are among the earliest observables proposed for quark matter diagnostics. Unfortunately, the experiments are extremely difficult, and even 15 years after the start-up the situation has not even reached the level of relative maturity of the J/ψ. Dimuons with intermediate mass, i.e. in the mass window between the ϕ and the J/ψ, have been measured by HELIOS 3 and, very systematically, by NA38/NA50, and results on an enhancement relative to the sum of Drell-Yan dimuons and simultaneous semileptonic decays of D and $\overline{D}$ mesons (or relative to properly scaled pA which fits) have consistently been reported on several of the preceding Quark Matter Conferences. The present PbPb data from NA50 together with the options for interpretation are shown in Fig. 5 [17]. The data can be described either by artificially increasing the open charm yield,

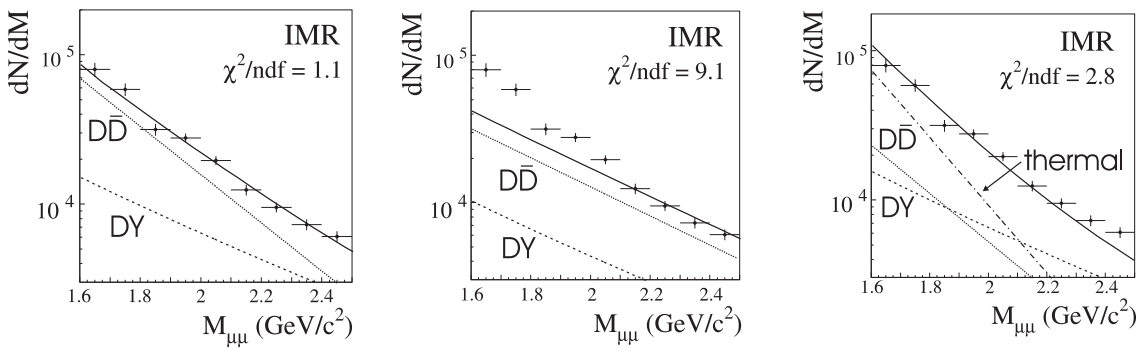

Figure 5. Dimuon mass spectrum in the intermediate mass region for central PbPb collisions compared to the prediction from different models: enhancement of charm production (left), D-meson rescattering (middle) and thermal radiation (right) (from [17]).

with a scaling factor rising with the number of participants up to a level of 3 for central collisions. If true, that would clearly be sensational, since thermal charm production has just been shown to be small [15], and production by hard processes is not easily modified towards such a dramatic enhancement. Alternatively (and more probably), the excess can be described by adding thermal radiation. The specific model used in Fig. 5 [18] is based on an expanding thermal fireball which explicitly includes an early (ideal) quark matter phase and a late hadronic resonance phase. The initial temperature required is about 190 MeV (not very sensitive up to 220 MeV), and the relative contribution from the deconfined phase is about 20-30 %. Final confirmation of thermal radiation obviously requires an experimental determination of the level of open charm (of direct relevance also for statistical J/ψ production, see above), and this is surely a primary motivation for the new NA60 experiment at the SPS.

The measurement of direct photons is even more tough, due to the overwhelming background from π° and η decay photons. All attempts with O and S beams, published by NA34/HELIOS, WA80 and NA45/CERES, have only resulted in upper bounds. The breakthrough came once again with PbPb collisions. The net photon p_T-spectrum, obtained by WA98 [19], is shown in Fig. 6. The model description of these data is presently quite open; an extensive review of the theoretical difficulties both in the high p_T and the low p_T region was given by Gale [20] during this conference. The high p_T part is usually believed to be dominated by hard QCD processes (like QCD Compton), somewhat anal-

ogous to Drell-Yan $q\overline{q}$ annihilation for high mass lepton pairs. The WA98 collaboration itself has added properly scaled pA results in Fig. 6 to argue that the PbPb data show an excess above hard processes up to very high p_T; indeed, the pQCD estimates [21] contained in the plot support that. As a consequence, Srivastava's description of the data as thermal radiation [22] requires initial temperatures of about 330 MeV, unrealistically high compared to any other values obtained for SPS energies. However, various effects like nuclear k_T broadening could add to increase the yield of hard processes at high p_T [20] suggesting, in lack of quantitative calculations, to fit the high p_T part to hard processes with an ad hoc scaling factor. This is the approach taken by Kämpfer [22], which

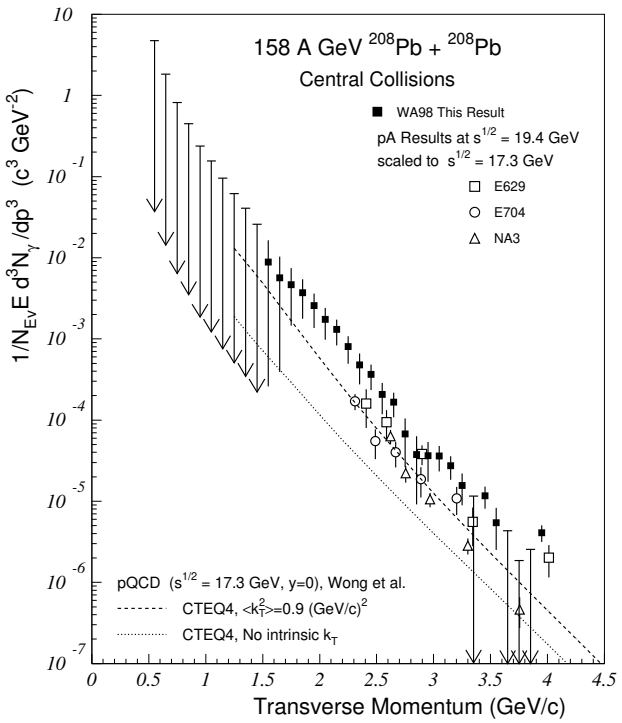

Figure 6. Invariant cross section for the production of real photons vs. transverse momentum. Data are from WA98 [19], the pQCD calculation from [21].

reduces the p_T-region requiring an excess description by thermal radiation to < 2.2 GeV. It is remarkable that the fireball model of this group is then able to describe the real photons of Fig. 6, the intermediate mass dimuons of Fig. 5 and the low mass dielectrons of CERES (see below) with an identical set of parameters; the initial temperature required is 210 MeV, reasonably consistent with Rapp/Shuryak [18] and the discussion of the initial conditions of section 2.1. All in all, direct photons obviously leave much room for improvements, and one can only hope that the situation at RHIC with higher initial temperatures will ultimately create a much more convincing case.

Jet Quenching

Out of all the impressive amount of new physics results from RHIC - the first evidence for jet quenching is *the* highlight of Quark Matter 2001! The idea, proposed about 10 years ago [24], is quite simple. In the initial stage of the collision, quarks or gluons can scatter with high momentum transfer. The scattered partons, though fast, sense the hot and dense phase in the time-evolution of the fireball, loosing before escape a significant fraction of their momentum by induced gluon bremsstrahlung. The final fragmentation of the partons into jets of hadrons is then modified relative to the situation in free space,

exhibiting reduced jet energies, i.e. reduced transverse momenta of the associated hadrons. Both STAR [25] and PHENIX [26]-[28] have reported first results on significantly reduced inclusive hadron cross sections at high p_T, and a critical summary of the results including a comparison to SPS energies has been presented by Drees [29]. Figs. 7 and 8 repeat his essence. Fig. 7 shows inclusive p_T distributions for negatively charged hadrons from STAR and all charged hadrons from PHENIX. The agreement of the data over a range of 7 orders of magnitude is most impressive, illustrating the high level of analysis quality which these "preliminary" data have already achieved.

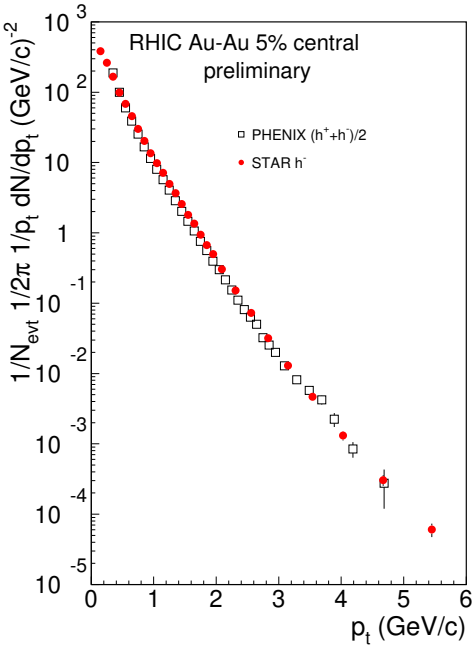

Figure 7. Inclusive cross sections for the production of negatively charged hadrons from STAR [25] and all charged hadrons from PHENIX [26] for the most central 5 % of the collisions. The data are independently normalized (from [29]).

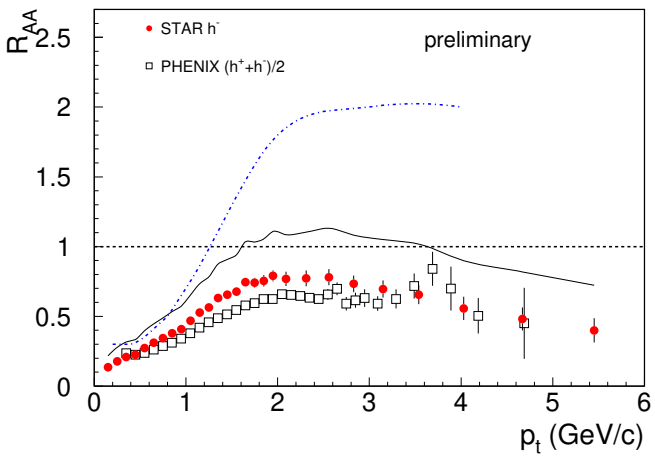

Figure 8. Data from Fig. 7 normalized to nucleon-nucleon data with $<N_{binary}> = 945$ (see text). The thin line is the upper limit of the systematical uncertainty. The dash-dotted line corresponds to the average of the SPS data from WA98, NA49 and NA45/CERES (from [29]).

To demonstrate jet quenching, one needs a comparison basis. This is provided by high energy pp and $p\overline{p}$ data from CDF and UA1 (see [29]), assuming that all high p_T particle production in AA (as in $pp/\overline{p}p$) results from binary hard collisions. A *nuclear modification factor* R_{AA} can then be defined as $R_{AA}(p_T) = d\sigma_{AA}/dydp_T^2/<N_{binary}>d\sigma_{pp}/dydp_T^2$ [29,30], where the average number of binary collisions $<N_{binary}>$ is obtained from the inelastic cross sections and the nuclear overlap integral. Results on R_{AA} as a function of p_T for the two data sets of Fig. 7 are shown in Fig. 8. Values < 1 are expected for low p_T, since the cross sections in this region should scale with the number of participating nucleons rather than with the number of binary collisions. However, the high p_T expectation of 1 for simple binary collision scaling is never reached, not to speak about the SPS level of 2 (due to the Cronin effect). Instead, a plateau is found at 0.6-0.8, followed by a decrease at still higher p_T. This is the evidence for jet quenching at RHIC. It finds support by the normalization of the central collision data to peripheral collisions rather than to pp [29]. It also finds support by the independent π° data of PHENIX [27]. These show a plateau value of only 0.4 suggesting that the reduction of R_{AA} for the mixture of charged

particles in Fig. 8 is less radical than it would be for charged pions alone. Indeed, identified particle spectra from PHENIX [28] show the ratios p/π^+ and $\overline{p}/\pi^-$ to be unusually large, i.e. nearly 1 for $p_T > 2$ GeV (possibly connected to the large radial flow observed at RHIC, see 2.5 below), while a value of only 0.2 is observed in pp. Accounting for the difference in (all charged)/π between AA and pp would give a downward correction of a factor of ~ 1.5 in Fig. 8 and thereby consistency with the π° results.

Theoretically, the size of the observed effect can be accounted for by requiring an average energy loss of 0.25 GeV/fm for the scattered partons [31]. It should be clear that this is only a phenomenological value averaged over the evolution history of the fireball. It does not separately reveal the specific energy loss of the partons and the characteristics and density of the medium the partons penetrated through.

In non-central collisions, the total parton propagation length should depend on the azimuthal direction. It is therefore conceivable that jet quenching would also show up as a specific azimuthal anisotropy of hadron spectra at large p_T, deviating from the low p_T pattern. The suitable quantity to measure azimuthal anisotropy is v_2, the second Fourier coefficient of the azimuthal particle distribution relative to the reaction plane, usually called elliptic flow. Data on v_2 from STAR [32] and PHENIX [33] are shown in Fig. 9. The initial rise is consistent with hydrodynamics [34,35]. The flattening observed by STAR for $p_T > 2$ GeV/c, a clear deviation from hydrodynamics, is due to the onset of hard processes. The calculations contained in Fig. 9 combine a soft hydrodynamic component with a hard pQCD component including jet quenching, i.e., a parton energy loss for different initial gluon densities [35]. The middle curve describes the data reasonably well, the sensitivity of v_2 to the value of the energy loss is remarkable. Ultimately, the two manifestations of jet quenching , a depletion of high p_T particle production and the flattening and decline of v_2, will require a consistent theoretical treatment with the same set of parameters.

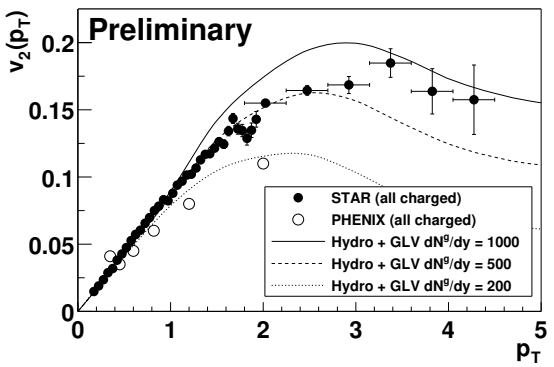

Figure 9. Azimuthal anisotropy v_2 relative to the reaction plane from STAR [32] and PHENIX [33]. The model calculations [35] combine hydrodynamics with hard scattered partons including an energy loss for 3 different initial gluon densities (from [6]).

All in all, jet quenching has given another exciting hint for quark matter formation already after the first round of experiments. Of course, there are and will be doubts as to the normalization procedure, the influence of radial flow, even hadronic scenarios. But there are enormous experimental reserves like a spectral extension up to 10 GeV and direct jet identification. One can only hope that the J/ψ frustration of more than a decade does not repeat itself, and that ultimately numerical and quantitative information on the deconfined stage can be obtained.

2.3. Hadronization

Experimentally, the measurement of hadron yields and low p_T hadron spectra belong to the easier part of the field, and a large amount of data was accumulated over the years. The model description of these data in terms of a statistical language was developed over the last decade by a number of authors, dating back, of course, to Hagedorn [36] almost 35 years ago. Reviews on hadron freeze-out have been given by Rischke [37] and, with special emphasis on strangeness, by Redlich [38] during this conference. I will follow present wisdom and distinguish *chemical* freeze-out, occurring earlier (at *higher* temperature) and determining particle abundances, from thermal-*kinetic freeze-out*, occurring later (at *lower* temperature) and determining particle momentum distributions. The former will be discussed in this section, the latter in section 2.5.

Global Particle Production

The great news of this conference were the first particle yields from RHIC with contributions from all 4 experiments STAR [39-41], PHENIX [42], PHOBOS [43] and BRAHMS [44]; a summary of these data was given by Nu Xu [45]. Compared to AGS and SPS energies, the most dramatic change concerns the central antibaryon/baryon ratios like $\overline{p}/p$, $\overline{\Lambda}/\Lambda$ and $\overline{\Xi}/\Xi$. The $\overline{p}/p$ ratio rises from <0.1 at the SPS to about 0.6 (determined by all 4 experiments), implying that the system created at $\sqrt{s_{NN}}$ = 130 GeV is close to net-baryon free; the net-proton rapidity density for central collisions measured by STAR and BRAHMS is only about 10 [41]. All this was of course anticipated, due to the loss of complete stopping at the much higher energies of RHIC. Conversely, the meson ratios like K^-/π^- or K^-/K^+ are found to be much closer between the SPS and RHIC.

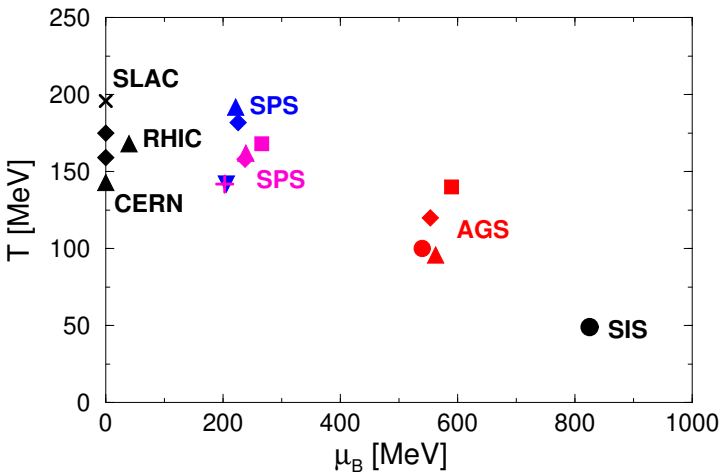

Figure 10. Systematics of the parameters T and μ_B extracted from measured hadron ratios for e^+e^-, $p\overline{p}$ (at μ_B=0) and nuclear collisions at RHIC, SPS, AGS and SIS. The average of the data points corresponds to a systematics for which energy density / total particle density $\sim$ 1 GeV [48]. The 12 references for the individual points are contained in [37] in these proceedings.

The statistical model commonly used to describe particle production at chemical freeze-out for AA collisions is formulated in the *grand canonical* ensemble with global baryon, strangeness and charge conservation. All particle ratios are then a function of only two independent parameters, the temperature T and the baryon chemical potential μ_B. A compilation of the parameters T and μ_B required to describe measured particle production for AA collisions at RHIC, SPS, AGS and SIS energies is shown in Fig. 10 [37]; additional RHIC values can be found in [45,46]. The reasons to choose this particular compilation rather than others [38, 47-49] are several fold: a demonstration of the long list of authors presently contributing, an illustration of the systematical errors of the parameters as

visible by the scatter of the individual points, and a (somewhat incomplete) inclusion of particle production in elementary reactions like $p\overline{p}$ and e^+e^-. Two features are noteworthy. First, the averages of the points can be connected by a common line of constant energy per particle, $<E>/<N>\sim 1$ GeV [48]. This is of great interest in itself, implying the existence of an energy scale below which inelastic collisions stop (see [48] for interpretation), but there is no connection to quark matter formation which is the main issue of this summary. Second, and that *is of* relevance for the issue, the temperature values for the SPS, RHIC and the elementary reactions are essentially identical and numerically, within errors, equal to the critical value T_c for deconfinement from lattice QCD. How close the numbers are can best be illustrated (with smallest systematical errors) by quoting the values (in MeV) from only two groups of authors (which even work together): 168±10 [50], 175±7 [51], 166±6 [52] for the SPS, 175±7 [46] for RHIC, 169±2 for pp at $\sqrt{s} = 27$ GeV [53], 175±15/170±12 for $p\overline{p}$ at $\sqrt{s} = 200/900$ GeV [53] and 169±4 (revised)/167±2 for e^+e^- jet fragmentation at $\sqrt{s} = 29/91$ GeV (PEP-PETRA/LEP).

This surely cannot be fortuitous. To the extent that in e^+e^- hadrons are born from a preceding $q\overline{q}$ pair - could there be any better evidence, that in AA at SPS or RHIC energies hadrons are also born from an ensemble of preceding partons? Is it the basic characteristics of string fragmentation which sets the scale for the universal hadronization parameter "T" $\sim$ 170 MeV? So universal indeed that it also describes the momentum scale of soft particle production in pp or in e^+e^- (orthogonal to the jet axis)? Is the notion of chemical equilibrium among hadrons really appropriate? It is odd for jet fragmentation, and it suffers from the internal inconsistency in AA that the medium effects on hadron masses and decay widths which are *known* to exist at the stage of hadronization, are not incorporated (if they were, T would very much decrease [55]). Is it not more appropriate, as Rischke [37] reminded us, to look at multiparticle production as saturating the available phase space ("born into apparent equilibrium")? And finally - is it some basic feature of QCD which we need to understand, that the scale parameter T in hadronization and the critical temperature T in thermodynamics are numerically close or even identical? And both close to the basic scale Λ_{QCD}?

Strangeness Production

Strangeness enhancement relative to elementary reactions like pp or e^+e^- has been proposed as a signature for quark matter formation almost 20 years ago [56]. Experimental evidence for enhancement has also been with us since long, culminating in the huge factor of 17 for the triple strange hyperon Ω as measured by WA97 and reported again from NA57 during this conference [57]. A compact and elegant way to illustrate the relative level of strangeness production in AA collisions and elementary collisions is provided by the strangeness suppression factor $\lambda_s = 2<s\overline{s}>/(<u\overline{u}>+<d\overline{d}>)$ [58], measuring the multiplicity ratio of newly created valence quark-antiquark pairs (before resonance decays). A recent compilation of the λ_s-systematics is shown in Fig. 11 [52]. The elementary reactions reach a level of 0.2-0.25, rather independent of $\sqrt{s}$. Nuclear collisions, on the other hand, lie higher by a factor of 2, similar for the SPS and the uppermost energy of the AGS. Unfortunately, RHIC points have not yet become available, but it would be a surprise if they would show a huge difference to the SPS.

Despite enormous efforts, the interpretation of the difference in strangeness production between nuclear and elementary reactions has continued to be controversial and incon-

clusive, up to the time of this conference as illustrated by Redlich [38]. It is clear since some years that the statistical hadronization approach describes hadrons with strangeness just as near-perfect as all other hadrons, implying that the term "strangeness suppression" (referred to elementary reactions) as commonly used in particle physics may be more appropriate than "strangeness enhancement". Redlich reminded us that a *canonical* rather than a grand-canonical ensemble with *exact conservation of quantum number locally* is required in the limit of strange particles <1/event, severely reducing the phase space available and thus explaining strangeness suppression in elementary reactions in a natural way (this is actually known since Hagedorn). He also demonstrated the transition

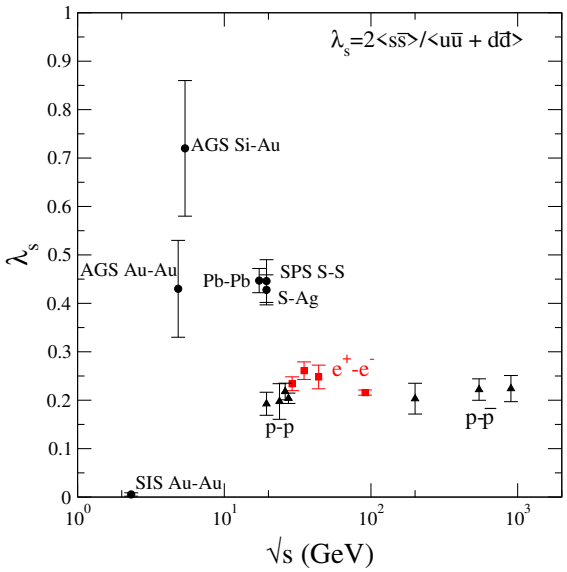

Figure 11. Strangeness suppression factor λ_S as a function of nucleon-nucleon center-of-mass energy $\sqrt{s}$. Values for AA collisions are from [52], values for elementary reactions have been taken from [59] (from [52]).

from one extreme to the other with a calculation of multistrange hyperon production as a function of the number of participants [38,60]. This enhances the crucial importance of precise experimental information on the centrality dependence of hyperon production: NA57 [57] has reported a first point with a decreased yield for $\overline{\Xi}^+$ hyperons in more peripheral collisions, but the error bar and the lack of more complete systematics prohibit firm conclusions at this stage. An experimental proof for a real onset behaviour in the production of strange hyperons (or other strange particles), either in impact parameter or mass number or beam energy dependence, would make a much more convincing case for strangeness production as a memory effect from quark matter formation than the popular model argument (if correct at all) that strangeness equilibration on the time scales available would only work with a preceding partonic scenario.

A final remark concerns pA reactions. As was repeatedly reported during this conference [61,62], pA collisions are also powerful to create additional strangeness relative to pp. As long as this is not very systematically investigated and clarified, including also the suspicious enhancement of strangeness up to the full level seen already at the AGS (see Fig. 11), the issue will remain very much controversial.

2.4. Evidence for the chiral transition

The medium properties around the phase boundary, where hadronization occurs, can experimentally be addressed by the unique tool of low mass dileptons. The instantaneous emission after creation and the absence of any final state interaction conserves the primary

information within the limits imposed by the space-time folding over the emission period. In the low mass region, the thermal radiation is dominated by the decays of the light vector mesons ρ, ω and ϕ. The ρ is of particular interest, due to its direct link to chiral symmetry and its short lifetime of 1.3 fm/c; its in-medium behaviour around T_c should therefore reflect chiral symmetry restoration, as proposed 20 years ago by Pisarski [63].

Experimentally, low mass dileptons are very much the domain of NA45/CERES, an electron pair spectrometer at the SPS which has probably taken more of my personal efforts over the years than any other experiment during my professional life. The results for PbAu at 160 AGeV, last updated at QM 1999, confirmed previous findings for S-Au (seen also by HELIOS 3 in the form of muon pairs). The combined 1995+1996 data show an excess of electron pairs, in the mass region > 0.2 GeV/c^2, of a factor of 2.9 ± 0.3(stat.)±0.6(syst.) above the expectation from hadronic decay sources, setting in around 0.2 Gev/c^2; further findings are an unusually soft p_T-spectrum and a steeper than linear multiplicity dependence. More than 100 theoretical papers have appeared on the issue. There seems to be a general consensus that one observes direct radiation,

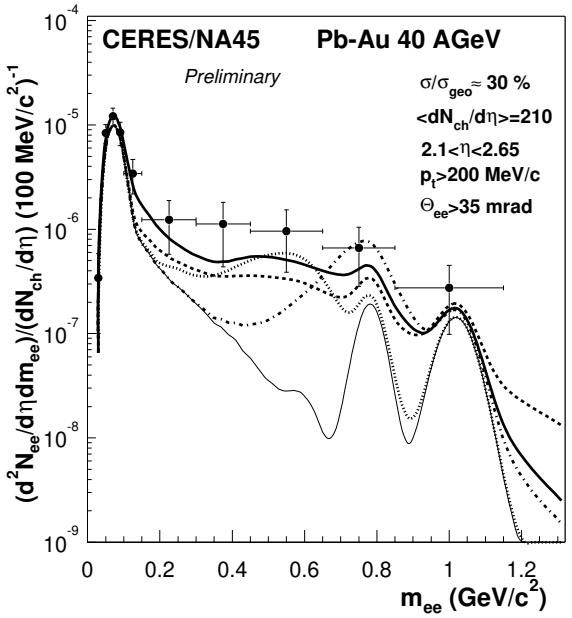

Figure 12. Normalized invariant mass spectrum of e^+e^- pairs at 40 AGeV in comparison to the sum of the known hadronic decay sources (thin solid line, without the ρ). The model calculations also shown [65] are based either on $\pi^+\pi^-$ annihilation with an unmodified ρ (dashed-dotted), an in-medium dropping ρ-mass (dotted) and an in-medium spreaded ρ (thick solid), or on $q\overline{q}$ annihilation (dashed) in the spirit of hadron-parton duality (see text). The figure is updated compared to the version shown at the conference [68,69].

dominated by $\pi^+\pi^-$ annihilation, with a rate corresponding to an average temperature of T $\sim T_c = 170$ MeV [23]. The temperature window contributing is about 120-220 MeV [23], implying that only $\sim$ 10 % of the observed yield is due to $q\overline{q}$ annihilation from the initial (deconfined) part [23,64,65]. The shape of the mass spectrum seems to require a strong medium modification of the intermediate ρ. The main contenders for this are Brown-Rho scaling [66], shifting the mass, and a hadronic many-body calculation of the ρ spectral density, spreading the width [67]. The spread is so large that the whole spectrum can be described, as a parametrization, as if it were due to $q\overline{q}$ annihilation, in the spirit of hadron-parton duality [67,23]. The relation to chiral symmetry restoration is there, but not straightforward [66,67]; insight into the behaviour of the chiral partner a_1 would be highly desirable, as stressed in Gale's review [20].

CERES has now been upgraded with a TPC to obtain a better mass resolution, and this has also very much improved the hadron capabilities of the experiment. As the

CERES report went along [68] with one hadron result after the other, one of my wonderful former CERESian students asked, somewhat shocked, whether CERES made a phase transition from hadron-blind to electron-blind. The proof of the contrary with the preliminary electron pair data at 40 AGeV is shown in Fig. 12 [68,69]. A strong enhancement of 5.0±1.5(stat.) above the hadronic decay sources is again seen; within the limits of statistics and resolution (the experiment was not quite ready), there is consistency with the normalized data at 160 AGeV and with the model calculations for 40 AGeV [65]; the average temperature required is now reduced to 145 MeV [23]. Better statistics than ever before, by a factor of 3-5, was obtained in the 2000 run at 160 AGeV, unfortunately discarding the multiplicity dependence. The mass resolution will be improved down to $\sim$ 2 %. It remains to be seen whether in-medium effects can now be isolated for the ω and ϕ as well, in case of the latter also from comparing the decays into e^+e^- and K^+K^- within the same set-up. Due to the long lifetimes, the chances may be remote [70] (ref. [64] at this conference does not contain the dominating contribution from the decays in vacuum after freeze-out). Further running of CERES lies in the dark. Much improved data at a lower SPS energy and better insight into the multiplicity dependence at any energy seem almost mandatory. Unfortunately, the new experiment NA60, powerful for the ω and ϕ at higher p_T, will not become competitive for m $<$ 0.7 GeV/c^2, due to the low p_T cut inevitably connected with muon pair measurements.

2.5. Expansion and Freeze-Out

The transverse momentum distributions of the produced hadrons, the azimuthal anisotropy v_2, and two particle interferometry are the experimental tools to probe the properties of the fireball in its final stage of thermal kinetic freeze-out, when all strong interactions between the constituents stop. The essential parameters to be discussed in this last chapter are the freeze-out temperature, the asymptotic velocity of the radially expanding fireball and the freeze-out density.

Transverse Momentum Distributions

New data on identified particle transverse momentum distributions have been reported at this conference for all energy regimes, including for the first time 40 AGeV at the SPS (from NA45 [68] and NA49 [71]) and, of course, RHIC (from STAR [72], PHENIX [28] and BRAHMS [73]); a summary of these data and their analysis in terms of the freeze-out parameters was presented by Nu Xu [45]. The inverse slope parameters of the transverse mass distributions as a function of the rest mass of the produced hadrons are shown in Fig. 13 with a direct comparison between full energy SPS and RHIC; the extracted values for the thermal freeze-out temperature T_{fo} and the average collective transverse flow velocity $<\beta_t>$ as a function of the centre-of-mass energy are contained in Fig. 14, including AGS and 40 AGeV SPS data. A number of features are noteworthy. The increase of the inverse slope parameters with mass for the abundant particles π, K, p etc. as visible in Fig. 13 directly reflects a transversely expanding source in the spirit of roughly $T_{slope} = T_{fo} + const\cdot<\beta_t>^2\cdot m$ (const$\sim$0 for pp and e^+e^-). The collective expansion arises from the pressure gradient between the vacuum and the dense equilibrated matter which cools and dilutes until the interactions stop, reaching the asymptotic value of $<\beta_t>$. But what part of the system evolution contributes mostly to $<\beta_t>$? In Fig. 13, the slope parameters seem to fall into two categories: one (II), just discussed, showing the

expansion, the other (I) with the ϕ, Ω and J/ψ (new at this conference) being flat. To the extent that the group (I) particles are all characterized by small interaction cross sections with the other hadrons of the system ("early freeze-out"), this has been taken as evidence that the plateau-like flow with a value of about 0.45 of the velocity of light

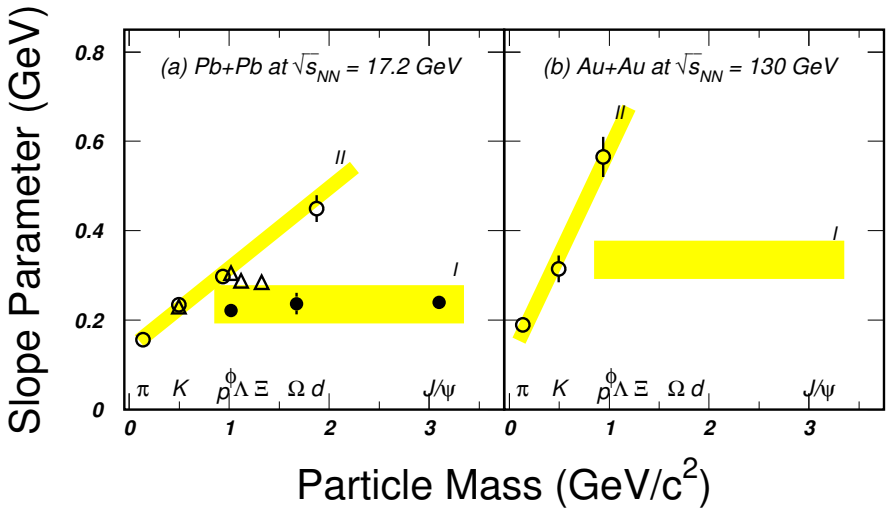

Figure 13. Dependence of the transverse mass inverse slope parameter on the rest mass of the produced hadrons for the SPS ($\sqrt{s_{NN}} = 18$ GeV, left) and for RHIC ($\sqrt{s_{NN}} = 130$ GeV, right). The bands marked by I and II denote weakly resp. strongly interacting particles, see text (from [45]).

in the region $\sqrt{s_{NN}} > 5$ GeV (see Fig. 14) essentially develops in the late hadronic stage of the collision, while the contribution from the primordial part (at the top SPS energy) may be small ("soft" equation of state). The first RHIC point at $<\beta_t> \sim 0.6$, though still

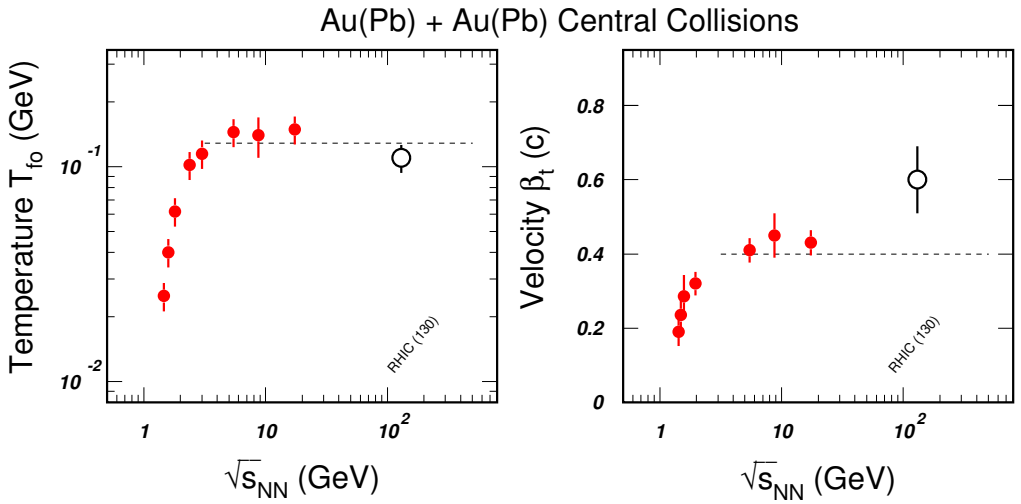

Figure 14. Thermal-kinetic freeze-out temperature T_{fo} and average collective transverse flow velocity $<\beta_t>$ as a function of center-of-mass energy $\sqrt{s_{NN}}$ (from [45]).

with some error (see the steeper slope in Fig. 13 and Fig. 14), is therefore a further most remarkable and important new result from the initial round: is it evidence, like a memory effect, for a strong contribution from a preceding quark matter phase ("stiffer" equation

of state at the higher initial temperature)? Future systematic data with reduced errors and values of the slope parameters for the ϕ, Ω and J/ψ will be crucial to confirm these first hints for a possible primordial flow at RHIC. Two particle interferometry will also be of use here (see below).

The freeze-out temperatures T_{fo}, plotted in the left part of Fig. 14, hardly need discussion. They also saturate at $\sqrt{s_{NN}} > 5$ GeV, reaching a universal value of about 120 MeV, and the first RHIC point does not seem to be very different from that, at least not within the present errors.

Independent information on the degree of rescattering or thermalization with particular weight on the early time of the expansion is contained in the azimuthal anisotropy v_2. Still another most striking result from the first round at RHIC is the large value of 0.06, first found by STAR [74] and then confirmed by the other experiments. A discussion on the systematics of v_2 is contained in Steinberg's review [6] during this conference. The most comprehensive accumulation of data on v_2 was actually shown by Appelshäuser [63]. Fig. 15 reproduces these data, covering the whole beam energy regime from 0.1 AGeV

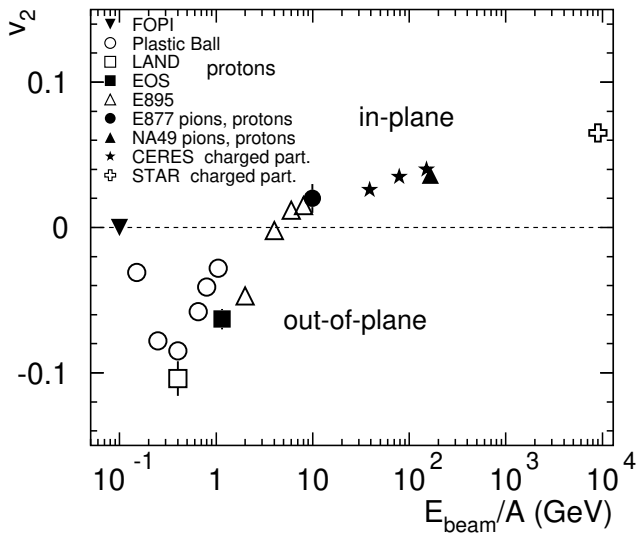

Figure 15. Azimuthal anisotropy v_2 relative to the reaction plane as a function of the beam kinetic energy for semi-central collisions of Pb or Au nuclei (from [68]).

at SIS to RHIC. Three new (still preliminary) points from NA45/CERES [63] seem to suggest a rising trend with $\sqrt{s}$ such that the high point at RHIC is not necessarily jump-like. It remains to be seen whether v_2 is the ultimate quantity to convincingly confirm the existence of a primordial flow at RHIC.

Two Particle Interferometry

Small relative momentum correlations, known as HBT interferometry, have proven extremely useful to study the space-time structure of the fireball evolution in its last stage. New data were reported at this conference for 40 AGeV at the SPS (from NA45/CERES [68] and NA49 [71]) and, again of course, RHIC (from STAR [75]); a review of the present situation was presented by Panitkin [76]. The first results from RHIC can be summarized as follows. (i) Unusually large source sizes, proposed as a signature for quark matter formation [77], have so far not been observed. (ii) The ratio R_o/R_s is, somewhat surprisingly, found to be ≤ 1 and decreasing with k_T. (iii) The spatially averaged 6-dimensional phase-space density <f> of the pions, deduced from the HBT radii and the π^- transverse mass distribution, confirms the hypothesis of a "universal" phase space density at

freeze-out [78]. As shown in Fig. 16, the p_T-dependence of <f> agrees for the data at RHIC and at the SPS (maybe too well), and the model description is clearly inconsistent with a static thermal source, but rather requires a Bose-Einstein distribution modified to include radial flow (with a fit value of $\beta = 0.58$ at RHIC, consistent with the spectral analysis). The new results from NA45/CERES [68] at 40 AGeV and from E895 [79] at their uppermost energy of 8 AGeV at the AGS also roughly agree with the data of Fig. 16 at low p_T, but show increasing deviations towards smaller values of <f> at higher p_T.

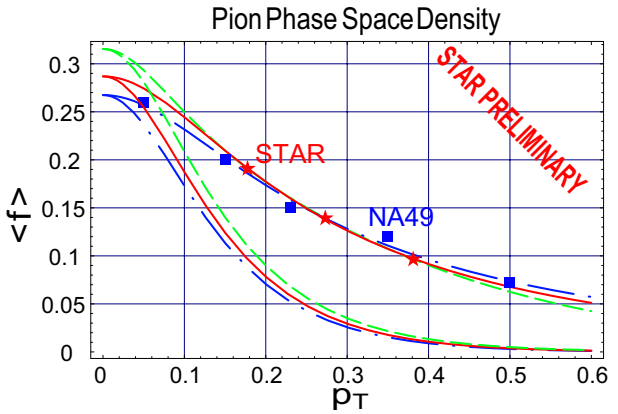

Figure 16. Pion phase-space density at freeze-out for $\sqrt{s_{NN}} = 18$ GeV at the SPS (squares) and for $\sqrt{s_{NN}} = 130$ GeV at RHIC (stars). A model description is also shown; the upper group of lines contains the influence of flow, the lower one does not. The associated freeze-out temperatures are rather low, 100/94/90 MeV for the 3 lines of each group (from [75]).

It appears then, as a joint conclusion of sections 2.3 and 2.5, that the fireball evolution from hadronization onwards until final freeze-out is essentially the same at the SPS and at RHIC, with the possible exception of an increased expansion rate at RHIC.

3. Concluding Remarks

I have written the summary of this conference in the style of an autark mini-review to enhance its usefulness. The physics conclusions are synonymous to the introduction of section 2 and therefore do not need to be repeated. However, I do have some afterthoughts. Twenty years ago we wanted to detect quark matter. We conceivably have seen first glimpses of it at the SPS and already now at RHIC. But we wanted more, namely quantitative physics: the equation of state as a function of temperature, the details of the phase- and the chiral transitions etc. etc. RHIC offers a huge spectrum of exciting new opportunities, and they will doubtlessly be used. But are we altogether on the right track? Have we properly explored the historical opportunities? I have some sympathy with B. Müller's theoretical summary at QM 1999 and C. Lourenco's experimental SPS summary at QM 2001. The SPS has presumably been the ideal machine for the phase *transition* region. Major points have, however, been left open which I touched upon in the respective sections and which concern all four surviving experiments NA45/CERES, NA49, NA57 and NA50 $\rightarrow$ NA60. One can only hope for the wisdom of all of us carrying responsibility, that we will find a proper balance between the needs at the SPS, at RHIC and at LHC to really get the optimum.

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