

## Theoretical summary

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**Abstract.** This is an attempt to summarize the theoretical talks given at the First International Conference “Hard Probes ’05”, dedicated to the study of the properties of quark–gluon matter and its diagnostics with the hard processes. This talk covers the following topics: the structure of quark–gluon matter at finite temperature; the theory of nuclear wave functions at small Bjorken variable  $x$ ; the propagation of jets, heavy quarkonia and heavy quarks through the dense QCD matter.

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### 1 Introduction

The venue of this conference – the small town of Ericeira on the Atlantic coast near Lisbon – is both spectacular and symbolic. We are at the western end of Europe, a place which calls to mind the history of how the New World was discovered. At the end of 15th century, nothing was known yet about the new lands hidden by the extensive ocean. Yet, the discoveries were already anticipated by some, and in 1494 the Pope divided the world to be discovered between Portugal and Spain, in the Treaty of Tordesillas. The sharp, straight boundary extended from North to South and divided what was at the time believed to be an empty ocean; less than 10 years later, South America had been discovered. The subsequent exploration of the New World made the shape of the boundary much more complex, and the subsequent developments eventually made it irrelevant altogether. What lessons can be learned from this story? In my opinion, there are at least three:

- (i) the less we know, the sharper are the boundaries;
- (ii) sharp boundaries do not last long –
- (iii) they disappear with the advance of knowledge.

As Helmut Satz reminded us in his opening talk, this conference grew out of the “Hard Probe café”, which had its first meeting at CERN, in 1994 – five centuries after the Treaty of Tordesillas. The discoveries at the high energy density and small  $x$  frontiers were widely anticipated, and the boundaries on the QCD maps were still very sharp. Regarding the statistical properties of QCD, most of us expected to see the weakly interacting quark–gluon gas just above the deconfinement temperature, although the lattice data already at that time indicated large deviations

from the ideal gas behavior [1]. As for the behavior of QCD at high energies (or small Bjorken variable  $x$ ), it was widely believed that the transition from “soft” to “hard” regimes happens at some typical scale  $Q_0 \sim 1 \div 2$  GeV, which does not depend on the energy, even though the idea of parton saturation [2–4] was already known and the related classical gluon field approach [5] had just been developed.

The experimental heavy ion program at CERN SPS was blooming, and the great potential held by the hard probes had already been made clear by the discovery of  $J/\psi$  suppression [6] predicted by Matsui and Satz [7] (even though the interpretation of the data was a subject of intense discussions). The low-mass dilepton enhancement [8] was observed shortly afterwards and attracted a lot of attention as a potential signature of chiral symmetry restoration, and Drell–Yan pair production proved to be very useful as the baseline. However, high transverse momentum hadrons, let alone jets, were very rare at the SPS energy ( $\sqrt{s} \leq 20$  GeV per nucleon pair).

The new millennium brought RHIC – and with it, the era of hard probes in relativistic heavy ion physics has begun. At this conference, we have heard about the amazing progress made in the experimental study of hard processes in recent years; the excellent overviews of the current situation were made at this conference [9–12].

So what have we learned so far from this wealth of experimental information, and what do we still need to know? In what follows below, I try to address these questions from the theorists’ point of view, based on the talks given at the conference and on some of my own prejudices. The space limits prevent me from describing all of the reported exciting developments, so instead of presenting a catalogue of the given talks I will concentrate on a few selected topics.

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## 2 Quark–gluon matter at high temperature

### 2.1 Strongly coupled quark–gluon plasma: a surprise?

For years, we have been expecting that at “sufficiently high” temperature  $T$  the QCD matter will become an “almost” ideal gas of quarks and gluons. Indeed, a typical inter-particle distance in this matter is  $\sim 1/T$ , and asymptotic freedom tells us that the interactions at short distances are weak. We still hold this expectation, but the data from RHIC tell us that “sufficiently high” temperatures appear beyond the reach of the current, and perhaps future, experiments: at all accessible temperatures the QCD matter behaves quite differently from an ideal gas, as emphasized at this conference by Shuryak [13] and others. The dynamics of the quark–gluon plasma is thus much more rich and interesting, and we have to develop new methods to understand it.

In fact, as discussed at the conference by Karsch [1], there have been numerous indications from lattice QCD that even above the deconfinement transition the interactions among quarks and gluons remain strong. A particularly telling piece of evidence from the lattice calculations is presented in Fig. 1, which shows the behavior of the QCD running constant as a function of distance for different temperatures. At  $T = 0$ , one observes the celebrated property of asymptotic freedom, or anti-screening of the color charge. Above the deconfinement temperature, the strong force gets screened – in agreement with the qualitative picture in which the range of the interaction is reduced because the exchanged gluons can scatter off the heat bath of deconfined thermal quarks and gluons. However, at experimentally accessible temperatures the screening develops at relatively large distances, at which the coupling constant is quite large. We are thus definitely dealing with a deconfined quark–gluon plasma, in which the long-range confining interactions are screened, but the residual non-perturbative effects are still strong.

This property of the observed quark–gluon plasma makes the traditional quasi-particle description of its ex-

citations questionable, as discussed by Blaizot [14] and Rajagopal [15], and one has to re-identify the appropriate degrees of freedom. Blaizot pointed out in particular the experimental implications of this problem for the dilepton production rates. Rajagopal also discussed the corresponding problem in the theory of cold quark matter, described as a color superconductor, and described the applications to the physics of neutron stars. The ways to test the structure of the quark–gluon plasma in lattice simulations and in experiment include the study of fluctuations, as discussed by Gavai [16] and various transport coefficients, including viscosity [13, 19].

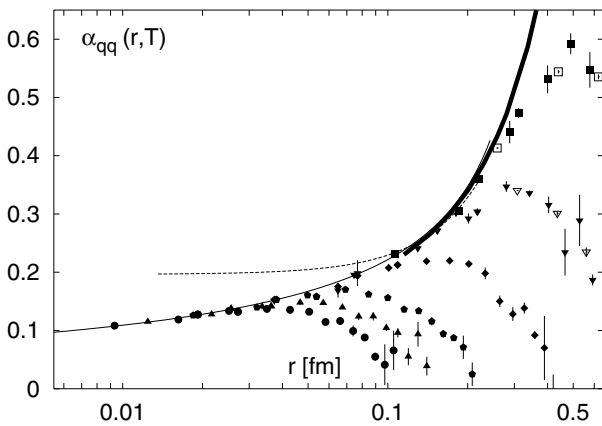
### 2.2 Quarkonium suppression in a strongly coupled quark–gluon plasma

As pointed out a long time ago by Matsui and Satz [7], the study of heavy quarkonia in hot QCD matter allows one to test the persistence of confining interactions. Indeed, this is probably the closest one can get in experiment to measuring the order parameter of the deconfinement – the large distance limit of the correlation function of the Polyakov loops, which measures the interaction energy of the separated heavy quark and antiquark [18]. Therefore, if some residual non-perturbative interactions are present above  $T_c$ , they may manifest themselves in the spectra of heavy quarkonia.

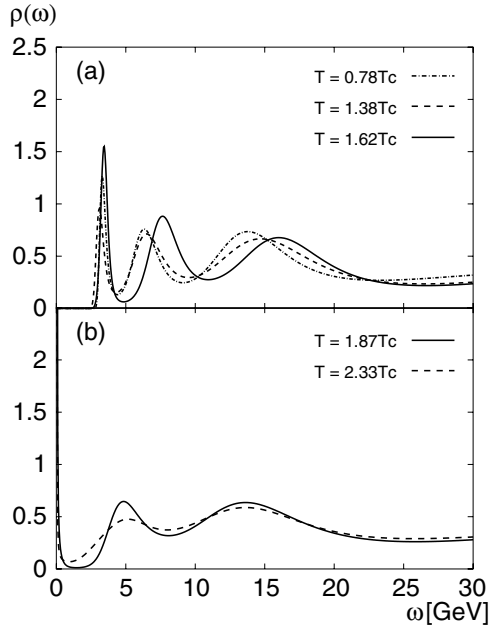
Very interesting lattice results on this issue have been presented at the conference by Hatsuda [19], Petreczky [20], Petrov [21], Digal [22], Kaczmarek and Zantow [23]. All of them point towards the survival of some of the bound charmonium states in the deconfined phase, which is consistent with the large screening radius of Fig. 1. There are two basic ways of accessing the information about charmonia on the lattice: one is to measure the correlation function of the  $\bar{c}c$  current and to reconstruct the corresponding spectral function, another is to compute the effective potential between static sources and to use it in the Schroedinger equation for the bound states.

Each of these methods has advantages and difficulties, so they are complementary to each other: in the spectral function method, one does not have to rely on a potential model, but a reconstruction of the quarkonium spectrum from the data has a limited precision. The effective potential approach provides a precise information on the spectrum, but the validity of the potential model in a heat bath and a treatment of the coupling between the color-singlet and octet components raise some questions.

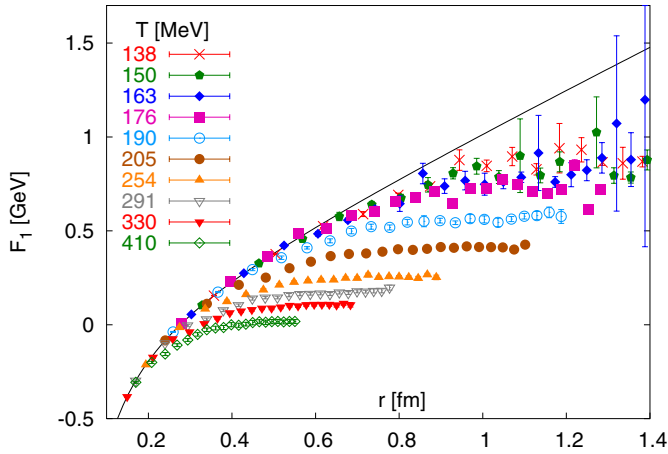
A representative result for the shape of the quarkonium spectral function as extracted from the lattice vector  $\bar{c}c$  correlation functions (the  $J/\psi$  channel) with the help of a MEM (maximal entropy method) approach is shown in Fig. 2. One can clearly see that up to temperatures of about  $T \sim 2T_c$  the peak corresponding to the bound  $J/\psi$  state still survives in the spectrum. Moreover, in this temperature range little, if any, change in the mass of  $J/\psi$  is observed. The effective potential method based on the lattice results shown in Fig. 3 leads to similar conclusions – the remnants of the confining interaction (“short strings”?) still exist



**Fig. 1.** QCD running coupling for temperatures above the deconfinement transition; the sets of points correspond to (going down)  $T/T_c = 1.05; 1.1; 1.2; 1.3; 1.5; 1.6; 3.0; 6.0; 9.0; 12.0$ ; the solid line is for  $T = 0$ . From [1, 17]



**Fig. 2.** Thermal vector  $\bar{c}c$  spectral functions extracted from the maximal entropy method analysis of the quenched lattice QCD calculations; from [19, 25]; see also [1, 26]



**Fig. 3.** The color-singlet free energy in three flavor lattice QCD; the solid line is the  $T = 0$  singlet potential. From [20, 27]

in the vicinity of the deconfinement phase transition and can support bound states. An interesting analysis aimed at linking the spectral function and potential approaches was presented at the conference by Mocsy [24].

Do these lattice results imply that no  $J/\psi$  suppression from quark–gluon plasma should be seen in experiment? In my opinion, the answer to this question is “no”: even if a quarkonium exists as a bound state, it can still be dissociated by the impact of hard deconfined gluons [28], in a process analogous to the photo-effect [29]. The relative importance of the Debye screening and “gluo-effect” processes is governed by the ratio of the quarkonium binding energy  $\Delta E$  to the temperature of the plasma  $T$  [30, 31]:

$$\Gamma(T) = \frac{\Delta E(T)}{T}, \quad (1)$$

where the binding energy depends on the temperature due to Debye screening. In the weakly coupled plasma  $\Gamma \ll 1$ , and the heavy quark bound state simply falls apart with the rate

$$R = \frac{4}{L} \sqrt{\frac{T}{\pi M_Q}}, \quad (2)$$

( $L$  is the size of quarkonium,  $M_Q$  the heavy quark mass) which is the classical high temperature, weak coupling limit of the thermal activation rate. On the other hand, in the strongly coupled case of  $\Gamma \ll 1$ , quarkonium is tightly bound, and the binding energy threshold has to be overcome by the absorption of hard deconfined gluons from the heat bath. In this regime, the heavy quark bound states are quasi-stable, but the dissociation rate is quite large and can lead to a significant quarkonium suppression [32].

At the conference, the fate of heavy quarkonium in the medium was further discussed by Blaschke [33], Rapp [34], and Thews [35]. The latter talks discussed in particular the possibility to create additional quarkonia by recombination of heavy quarks and antiquarks. In particular, it was shown [35] that recombination of heavy quarks leads to a sizable narrowing of the rapidity distribution of  $J/\psi$ 's in Au–Au collisions at RHIC; a high statistics experimental measurement of this distribution can thus help to extract the contribution of this mechanism, or to put an upper bound on it.

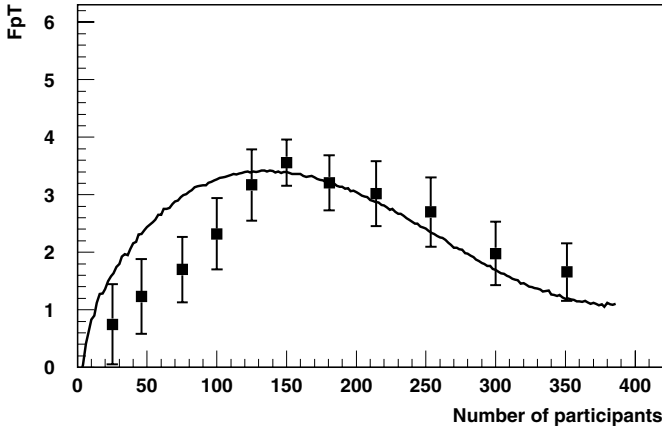
Quarkonium suppression in the percolation approach to deconfinement was discussed by Nardi [36]; the signature of the percolation phase transition in this case is a peculiar centrality and mass number dependencies of the  $J/\psi$  survival probabilities, which are consistent with the existing NA50, NA60 and PHENIX data. The transverse momentum dependence of the  $J/\psi$  suppression in this picture still remains an interesting open problem [37].

Percolation of strings as a description of deconfinement was extensively discussed by Dias de Deus [38] and Pajares [39]. It was pointed out that the percolation approach in particular naturally leads to the observed fluctuations in the transverse momentum (see Fig. 4) and the universal form of the transverse mass distribution of hadrons in nuclear collisions, similar to the one arising from the color glass condensate [41]. This brings us to the next topic which became one of the focal points of the conference – the theory of nuclear wave functions on the light cone, at small Bjorken  $x$ .

### 3 High density gluon matter at small $x$

#### 3.1 “Just a change of the reference frame?”

Recent years have seen an impressive progress in the understanding of nuclear wave functions at small Bjorken  $x$ . What makes this problem interesting? After all, nothing changes if we look at the nucleus in a different reference frame, where it is boosted to high momentum – or so it seems at first glance. But we have to remember that in quantum theory the operator of the number of particles does not commute with the operator of a Lorentz boost,



**Fig. 4.** Fluctuations in the transverse momentum in Au–Au collisions at RHIC at  $\sqrt{s} = 200$  GeV; from [39]. The data from PHENIX [40] are compared to the calculation based on the percolation picture

and so in general a mere change of the reference frame will change the measured number of particles in the system.

This is certainly the situation in QCD, where the boost is accompanied by the evolution of a hadron or nuclear structure function, which leads to a rapid  $\sim 1/x^\lambda$  growth of the number of gluons and quarks at small  $x$ . Because the boost also leads to the Lorentz compression of the nucleus, and because the Froissart bound does not allow the area of the nucleus to grow faster than  $\sim \ln^2(1/x)$ , at sufficiently small  $x$  and/or large mass number of the nucleus  $A$  the density of partons in the transverse plane becomes large and they can recombine [2–4]; when the occupation number becomes  $\sim 1/\alpha_s$ , the system can be described as a semi-classical gluon field [5]. A broad overview of the semi-classical color glass condensate approach to nuclear wave functions and to the heavy ion collisions has been presented by Venugopalan [42].

### 3.2 In search of the ultimate evolution equation

Once the density of partons becomes large, the non-linear effects in the parton evolution become important. The quantum processes of parton splitting and recombination in this regime occur in the background of the strong classical field. The general evolution equation in this case still has to be found, and the progress in this direction has been discussed at the conference by Bartels [43], Iancu [44] and Mueller.

A general introduction into the problem of non-linear evolution equations and the underlying physics was given by Mueller, who also discussed the limits of validity of the existing approaches. Iancu in particular discussed the role of rare fluctuations in hadron wave functions which are not captured by the mean-field equation of Balitsky [45] and Kovchegov [46].

One of the important problems of the perturbative QCD approach to high energy scattering emphasized by Bartels is the following: in the impact parameter  $b$  space, perturbation theory always predicts the amplitudes which fall off as

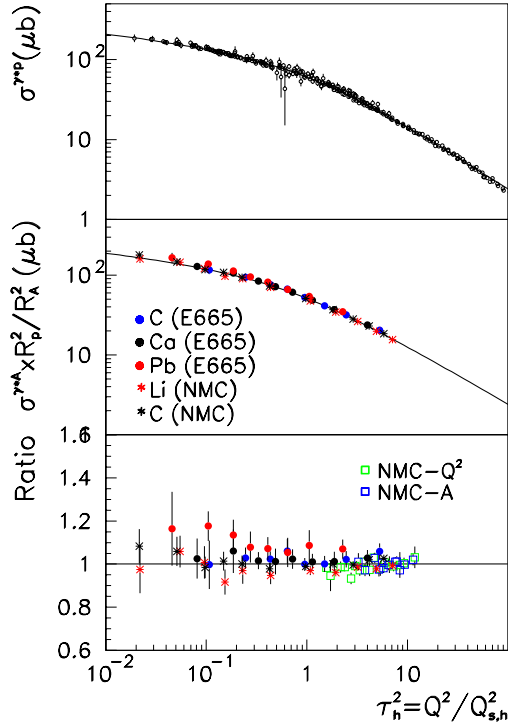
inverse powers  $(1/b)^n$  at large  $b$ . This is because there is no mass gap for the gluon excitations in perturbation theory. On the other hand, in the physical world there are no massless hadronic excitations – pions, as the Goldstone bosons of the spontaneously broken chiral symmetry, are the lightest ones, but their masses  $m_\pi^2 \sim m_q$  do not vanish because of the finite light quark masses  $m_q \neq 0$ . Therefore, high energy hadronic scattering amplitudes must fall off exponentially at large impact parameters, not slower than  $\sim \exp(-2m_\pi b)$  – coupled with the fact that at fixed impact parameter the growth of the amplitude is bounded by a power of energy  $s$ , this leads to the Froissart bound on the total cross sections. Because of the diffusion to large distances in high energy evolution, one is forced to consider the influence of the mass gap on the scattering amplitudes.

### 3.3 Probing the color glass condensate

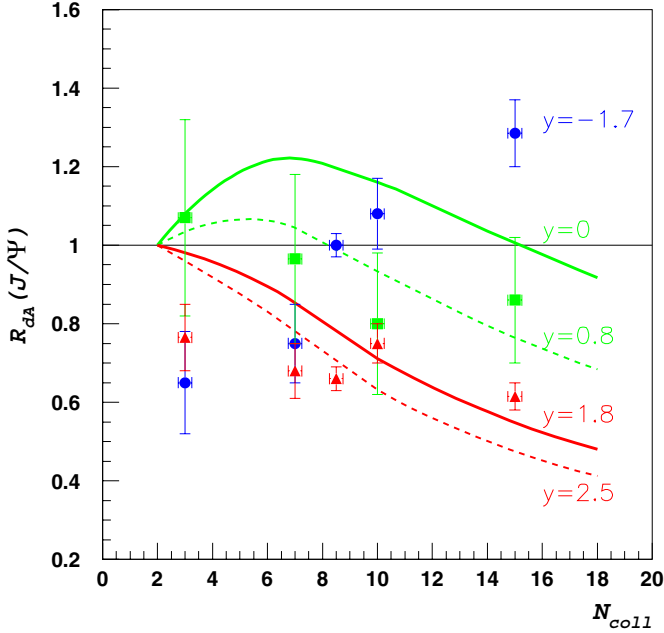
Since the growth of parton distributions in the wave function of a nucleus  $A$  at small  $x$  is tempered by the non-linear effects, the number of partons in a heavy nucleus rescaled by  $A$  is smaller than in a proton. This parton deficit in a heavy nucleus is a quantum effect, which has to manifest itself at sufficiently small  $x$ , when the longitudinal phase space  $\sim \ln(1/x)$  for the emitted gluons is large enough to compensate the smallness of the coupling,  $\alpha_s \ln(1/x) \sim 1$ . Indeed, at the classical level the total number of partons in a nucleus  $A$  is equal to the rescaled number of partons in a nucleons, but they are re-distributed in the transverse momentum which leads to the Cronin effect in nuclear cross sections.

The number of partons in the nuclear wave functions can be measured in hard  $p(d)A$  scattering processes at small  $x$ ; at RHIC this corresponds to the forward rapidity region (the deuteron fragmentation region). Therefore one arrives to the prediction that the cross sections of hard  $dA$  scattering in the forward rapidity region should be suppressed relative to the  $NN$  ones. The physics of this phenomenon has been extensively discussed at the conference by Baier [47], Gay Ducati [48], Jalilian-Marian [49], Milhano and Salgado [50], Triantafyllopoulos [51] and Tuchin [52].

Jalilian-Marian [49] presented a clear introduction to the problem, and discussed the effects of quantum evolution in the color glass condensate on the production of hadrons, dileptons and photons at forward rapidities. Dilepton and photon production at forward rapidities have also been the topics of talks given by Baier [47] and Gay Ducati [48]. Baier in particular has demonstrated the potential of these probes for understanding the nuclear gluon distributions at small  $x$ . Salgado [50] has shown that the saturation picture leads to a consistent description of the small  $x$  data on deep-inelastic scattering off both protons and nuclei; see Fig. 5. He argued that this picture also allows one to describe the data on hadron multiplicities at RHIC. Triantafyllopoulos [51] discussed the transition from the classical to quantum regimes in  $pA$  scattering, and the evolution and disappearance of the Cronin peak with rapidity. Tuchin [52] presented results on the influence of the color glass condensate on the production of charmed quarks



**Fig. 5.** Geometric scaling for  $\gamma^*p$  scattering (upper panel),  $\gamma^*A$  (middle panel), and the ratio of the  $\gamma^*A$  data over the theoretical predictions based on the saturation picture (lower panel); from [50]



**Fig. 6.** The nuclear modification factor in the production of  $J/\psi$  in  $dAu$  collisions at RHIC energy of  $\sqrt{s} = 200$  GeV. Theoretical calculations based on the color glass condensate picture are compared to the preliminary data from PHENIX [53]; from [52]

and charmonia. In the latter case, he found an interesting effect of nuclear  $J/\psi$  enhancement in a certain window in rapidity; see Fig. 6.

Much of the existing theoretical analysis is based on the method of  $k_T$  factorization. The limitations of this approach were examined by Fujii and Gelis [54] using an example of heavy quark and quarkonium production.

Theoretical approaches currently used for the description of  $pA$  collisions were discussed by Qiu [55]; he analyzed the contributions of higher twist effects resulting from coherent multiple scattering, and their influence on hard nuclear processes. The production of hidden and open charm at RHIC and LHC in the more traditional framework of collinear factorization was discussed by Vogt [56]; in particular, she examined the influence of several of the existing approaches to shadowing on the yields of charmed quarks.

## 4 Hard probes of hot and dense QCD matter

### 4.1 Perturbative QCD – the baseline

No-one at present doubts the applicability of perturbative QCD to the description of “sufficiently” hard processes. Perturbative methods therefore provide a crucial baseline for the understanding of the attenuation of high momentum partons in hot and dense matter. Of particular interest to the participants was the long-standing puzzle of the apparent discrepancy between the yields of heavy quarks as measured at collider energies and the perturbative calculations. This problem and possible solutions were discussed by Frixiene [57].

### 4.2 Jets and heavy quarks as a probe

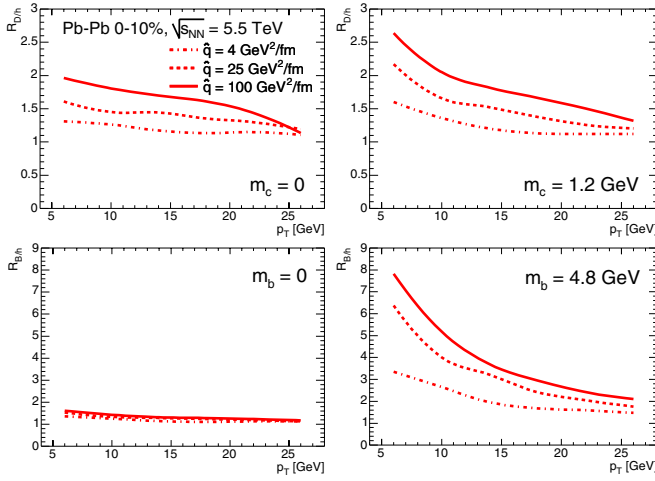
One of the most spectacular successes of the RHIC program is the discovery of the suppression of high transverse momentum particles, predicted as a signature of the quark–gluon plasma. An introduction to the problem, and an overview of the existing and future possibilities with the high momentum probes was given by Wang [58].

The influence of the quark–gluon plasma on jet shapes and on the propagation of heavy quarks was the topic of Wiedemann’s talk [59]. The energy loss of heavy quarks was also discussed by Djordjevic [61]. The results indicate a considerable enhancement in  $D/\pi$  ratios (see Fig. 7) resulting from the interplay between the “dead cone effect” and the coherent multiple scattering, in qualitative agreement with other treatments [62].

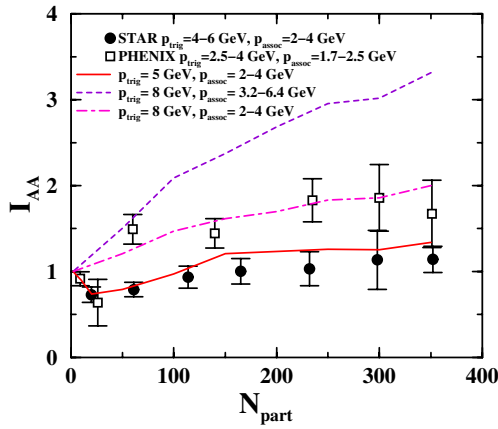
Accardi [63] investigated the relative importance of Cronin effect and jet quenching at different RHIC energies. An interesting analysis of di-hadron correlations in the fragmentation of the jets was presented by Majumder [64], who explored how the dense QCD matter affects the associated hadron distributions (see Fig. 8).

A novel effect of the influence of the hydrodynamical flow on the jet shape was considered by Armesto [68]. He found that the flow can lead to an anisotropic jet shape, as illustrated in Fig. 9.

The influence of the medium on the fragmentation of partons was also the topic of Hwa’s talk [69]. He suggested



**Fig. 7.** The ratio of the nuclear modification factors in the production of heavy and light quarks in heavy ion collisions; from [59, 60]

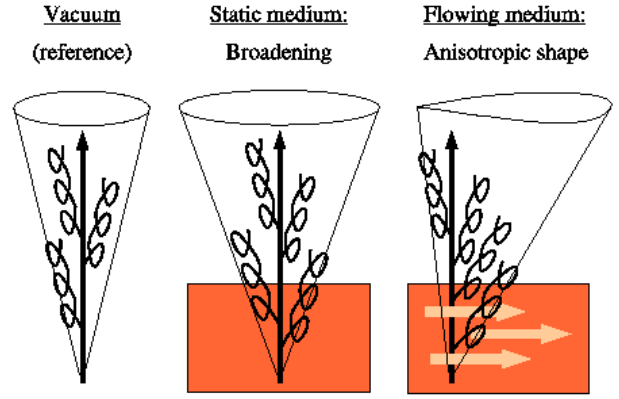


**Fig. 8.** The medium modification of associated hadron distribution from jet fragmentation in Au–Au collisions at  $\sqrt{s} = 200$  GeV for different choices of trigger  $p_T$  and associated  $p_T$ ; theory from is compared to STAR [66] and PHENIX [67] data. From [64, 65]

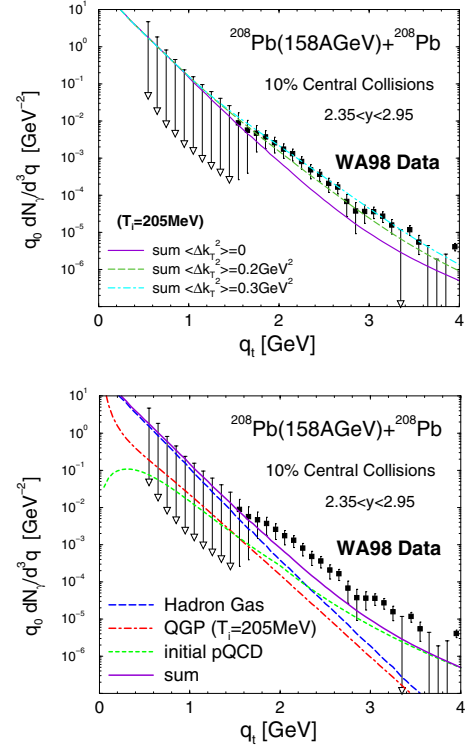
that because of the high density of partons in the quark–gluon plasma, the recombination of partons is a likely mechanism which can affect the composition and the transverse momentum distributions of the produced hadrons. (For a related approach, see also [70].)

### 4.3 Electromagnetic probes

The production of photons and dileptons from a hot quark–gluon matter remains a subject of vigorous theoretical and experimental studies. The state of the theoretical calculations has been reviewed at the conference by Gale [71] and Shuryak. Gale emphasized that a variety of phenomena contribute to the photon and dilepton production, and they have to be carefully evaluated to make the extraction of the quark–gluon plasma component possible; see Fig. 10.



**Fig. 9.** The effect of collective flow on the jet shape; from [68]



**Fig. 10.** The effect of the nuclear transverse momentum broadening on the measured photon spectrum (top panel) and the contributions of prompt and thermal spectra compared to the data on Pb–Pb collisions at SPS from the WA98 Collaboration; from [71]

## 5 Outlook

This summary clearly does not capture the entirety of the theoretical developments presented at the conference – it is impossible to fit the entire week of wonderful talks and exciting discussions in a few pages of written text. Nevertheless, I hope that a more complete picture can be reconstructed by looking at the original talks referenced here. This is the picture of the field which is still at the very beginning – prompted by the huge wave of new high quality data, the theorists are still in search of a coherent framework capable of describing the variety of the observed phenomena.

However, in my opinion, the talks at the conference show that we start to see the essential elements of this unified framework, and enough bright people with enough enthusiasm are working on the problem. Coupled with an impressive progress in experiment, this indicates that the ultimate goal of understanding QCD in the high temperature and strong field regimes may now be within reach.

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