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Domenico Elia · Giuseppe E. Bruno ·
Pietro Colangelo · Leonardo Cosmai
Editors

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Editors
Domenico Elia
Dipartimento Interateneo di Fisica
Istituto Nazionale di Fisica
Nucleare (INFN)—Sezione di Bari
Bari, Italy

Giuseppe E. Bruno
Dipartimento Interateneo di Fisica
Istituto Nazionale di Fisica
Nucleare (INFN) and Politecnico di Bari
Bari, Italy

Pietro Colangelo
Dipartimento Interateneo di Fisica
Istituto Nazionale di Fisica
Nucleare (INFN)—Sezione di Bari
Bari, Italy

Leonardo Cosmai
Dipartimento Interateneo di Fisica
Istituto Nazionale di Fisica
Nucleare (INFN)—Sezione di Bari
Bari, Italy

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More than 270 participants attended the SQM 2019 conference at Villa Romanazzi, Bari (Image credit: Domenico Elia)

Members of the SQM 2019 Organizing Committee at the conference social evening (Image credit: Domenico Elia)

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Preface

The XVIII International Conference on Strangeness in Quark Matter (SQM 2019) was held from 10 to 15 June 2019 in Bari, Italy. Hosted by the INFN (the Italian National Institute for Nuclear and Particle Physics), in collaboration with the Physics Department of the Bari “Aldo Moro” University and Polytechnic University, the conference attracted more than 270 participants from 32 countries, including a large number of graduate students and young scientists. The SQM series focuses on new experimental and theoretical developments on the role of strange and heavy-flavour quarks in high-energy heavy-ion collisions and in astrophysical phenomena. The main scientific topics addressed at SQM 2019 were the following: strangeness and heavy-quark production in nuclear collisions and hadronic interactions, hadron resonances in the strongly coupled partonic and hadronic medium, bulk matter phenomena associated with strange and heavy quarks, QCD phase structure, collectivity in small systems, strangeness in astrophysics, open questions and new developments.

The scientific programme consisted of 50 invited plenary talks, 76 contributed parallel talks and a quite rich poster session with more than 60 contributions. A state-of-the-art session opened the conference, with a tribute to the late Roy Glauber entitled “The Glauber model in high-energy nucleus-nucleus collisions” by Reinhard Stock (Goethe University Frankfurt), followed by two overview talks to set the scene on the theory and experiment sides, respectively. The first 2-day plenary sessions were dedicated to highlights from theory and experiments: they included reports on results from low- and high-energy collisions, as well as on hyperon interaction in lattice QCD and thermal model. Representatives from all major collaborations at CERN’s LHC and SPS, Brookhaven’s RHIC, the Heavy Ion Synchrotron SIS at the GSI Darmstadt and the NICA project at the JINR Dubna made special efforts to release new results at SQM 2019: thanks to the excellent performance of these accelerator facilities, a wealth of new data on the production of strangeness and heavy-flavour quarks in nuclear collisions have become available. The conference was organized in further plenary sessions dedicated to the main scientific topics, two half-day parallel session afternoons, a poster session evening and a final session on “Future experiments and physics perspectives” on the last morning before the “Summary and closing”.

Among the highlights presented at the conference, identified particle yield measurements were shown to be progressing towards determining where phenomena such as strangeness enhancement are localised in phase space. This is currently addressed using complementary methods such as transverse multiplicity estimators and two-particle correlations: such new approaches promise to constrain theoretical models in unprecedented ways. Collective behaviour in small systems was also a highlighted and much discussed topic, with new results from PHENIX showing that p-Au, d-Au and 3He-Au exhibit elliptic flow coefficients consistent with expectations regarding their initial collision geometry. This remarkable finding indicates that even in these systems the observed v2 coefficient is not due to jet-like phenomena but is rather a true manifestation of initial conditions translating into momentum anisotropies, a hallmark feature of the classic flow paradigm. Further results from ALICE, CMS and STAR complete the picture and consistently corroborate the presence of elliptic flow in small systems. An increasing interest in transverse-momentum differential baryon-to-meson ratios in the heavy-flavour sector was also evident. Recent results from pp and Pb-Pb collisions from both ALICE and CMS suggest that the same dynamics observed in the ratio Λ/K^0_S may be present in the Λc/D despite the fact that strange and charm quarks are thought to be created in different stages of system evolution. Further studies and potential future measurements may still be needed to fully conclude on the similarities in these baryon-to-meson ratios.

A promising new perspective at the LHC is to use high-energy pp and p-Pb collisions as factories of identified hadrons created by a source of finite radius and then measure the ensuing interactions between these hadrons using femtoscopy. This technique has allowed the ALICE Collaboration to study interactions that were so far not measured at all and probe, for instance, the p-Ξ and p-Ω interaction potentials. These results provide fundamental constraints to the QCD community and are significant in the context of the astrophysics: such potentials indeed serve as input when modelling neutron stars under the hypothesis that hyperons are present in this extreme state of matter. New results on the onset of deconfinement were shown by the NA61/SHINE Collaboration, in particular, with the measurement of a charged kaon-to-pion ratio in Ar-Sc intermediate compared to results in pp/Be-Be and Pb-Pb, possibly suggestive of a change in the production mechanism that can involve a phase transition. Recent results on strangeness production at low energy from HADES and BM@N were also very welcome and enriched the discussion at SQM 2019.

Presentations at the final session on Saturday morning showed good prospects in the field for future measurements with FAIR at GSI Darmstadt, NICA at JINR Dubna, Heavy Ions at J-PARC Tokai and at CERN with the currently ongoing upgrades, opportunities for HL-LHC and next-generation experiments (HL/HE-LHC and FCC). Perspectives for QCD measurements at future Electron Ion Collider facilities were also presented. On the theory side, new developments and strong research efforts are currently taking place towards a better understanding of strangeness production and open heavy-flavour dynamics in heavy-ion collisions. Small system scan with more information about heavy flavour, crosstalk on the Equation of state (EOS) between lattice QCD, Heavy ion collisions (HIC), neutron stars, and global polarization in HIC are also topics of currently large interest.

Two young scientist prizes, sponsored by the NuPECC, were awarded to the best experimental and theory posters, respectively, Bong-Hwi Lim (Pusan National University, Korea) and Olga Soloveva (Goethe University Frankfurt, Germany). A special award dedicated to the memory of a friend and colleague has been established for this conference series: the inaugural "Andre Mischke Award" for the young scientist with the best experimental parallel talk at SQM 2019 was assigned to Erin Frances Gauger (University of Texas at Austin, United States).

The scientific and organizational success of SQM 2019 was the result of the work of many people. We would like to thank the colleagues of the International Advisory Committee for their valuable help and guidance in shaping the scientific programme of the conference. We are also warmly grateful to the members of the Local Organizing Committee, the team of secretaries, the technical and administrative support staff and the student helpers: with them we've been sharing a fantastic human and professional adventure over a year or so, in a common effort to make sure that all aspects of the meeting were handled smoothly and efficiently. Last but not least, we express our gratitude to the Italian and international organizations that provided financial contributions to the conference, allowing us to support the participation of more than 50 young scientists to SQM 2019.

More information about the conference, including all oral and poster presentations, is available on the conference website at https://sqm2019.ba.infn.it/. The next International Conference on Strangeness in Quark Matter (SQM 2021) will take place in Busan, Korea, in May 2021.

Bari, Italy

Domenico Elia
Giuseppe Eugenio Bruno
Pietro Colangelo
Leonardo Cosmai
Editors

Contents

Part I
Opening

Chapter 1
ROY GLAUBER: In Memoriam the Glauber Model in High Energy Nucleus-Nucleus Collisions

Reinhard Stock

Abstract This article is devoted to the memory of Roy Glauber. His multi-diffractive model of nucleus-nucleus collisions has served a wide variety of applications in our field. After a sketch of the model we illustrate a number of physics observables where, in particular, the construction of the initialization phase of a A+A collision rests on Monte Carlo simulations of the participant-spectator geometry of the incident configuration. This results, chiefly, in the determination of the nucleon participant , and the binary collision number, as well as in a specification of the spatial expansion modes of the source that lead to the observables of directed flow. Finally, one can attempt to pin down the colour glass initial state, in comparison to Glauber initialization.

At the opening of this Conference let us commemorate Roy Glauber who passed away last December. From among the many themes of his theoretical life-work it is the "Glauber-Model" of multiple hadronic scattering phenomena which has become basic to the understanding of nucleus-nucleus collisions at high energy. From Bevalac time until today we employ the model to define observables of increasing complexity: initially it served, in particular, to quantify the concept of "central" collisions and centrality classes but it then provided for the geometrical basis of the family of flow-observables from which we have concluded on the bulk properties of the QGP liquid. And, finally, it helps to quantify the basics of analysis of individual events, thus opening up the wide field of observables related to event-by-event fluctuations of the initial geometry. Thus, Roy Glaubers work has become a "household article" in essentially all bulk QCD matter questions where we talk about Glauber-initialization vs. colour glass condensate initialization, to give just one example. A few of these aspects will be recollected below. Let us begin, however, with a short look at Roy Glaubers trajectory, in life and science.

Roy Glauber was born Sept. 1, 1925 in New York. He attended the famous Bronx High School of Science, as a kind of *Wunderkind* with exceptional science talent,

R. Stock (✉)
FIAS and Institut für Kernphysik, Johann Wolfgang Goethe-Universität, Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany
e-mail: stock@ikf.uni-frankfurt.de

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much reminding of Richard Feynmans famous performance in his “teenage years”. At age 16 he entered undergraduate study at Harvard, and in 1943 he was drafted into the Manhattan Project, the youngest scientist there, involved in critcal mass computations. Returning to Harvard he got his Ph.D. in 1949 with Julian Schwinger (Nobel laureate for the formulation of QED, later on). A period of *Wanderjahre* then sees him at Princeton, Zuerich (with W.Pauli) and Caltech (where he substituted for Feynman for a year). In 1976 Harvard again, he became Full Professor there, from now on his permanent academic home but interspersed with many foreign visiting positions including CERN. His principle research topic was Quantum Electrodynamics in the interaction of light with matter, addressed to Quantum Optics. He also first tackled the problems of multiple hadronic collisions at high energy, where he developed the foundations of the so-called Optical Model for diffractive forward scattering. The application to high energy proton-deuteron scattering then resulted in the formulation of the Glauber Model to which we shall turn below because it became extraordinarily useful later on, in the environment of nucleus-nucleus collision at relativistic energy where the concept of participant and spectator nucleons, seen along a straight trajectory in an *optical eikonal* approximation, proved highly useful. Figure 1.1 shows a photo of Roy Glauber as we all remember him, taken at

Fig. 1.1 Roy Glauber at the Nobel Prize ceremony 2005

the occasion of his Nobel Prize ceremony in 2005. What a remarkable picture! A deep, and passionate academic and research life trajectory culminates, at age 80, in this radiant and encouraging image of one of the Noblemen of science. We sadly commemorate, today, to his passing away on December 26, 2018. His ideas live onward in our research.

1.1 The Glauber Model

This is not the place for a detailed review of the Glauber Model of diffractive multi-hadronic scattering [1] but let us briefly sketch the main points of the optical *eikonal* approximation, the basis of the model. At very high energy the nucleon scattering from a nucleus will stay essentially undeflected because of the far excess of longitudinal over transverse momentum. Thus one might approximate its trajectory by a light ray, the nucleon summing up all the successive phase shifts received at the scattering centers inside the target. What emerges is a diffractive shadow image in the transverse plane: the target is *X-rayed*. Thus the name eikonal approximation, from greek eikona = image. This model neglects the fact that the participating nucleons are, in reality, quantum mechanical objects, but it allows to implement all the geometric aspects of the multiple scattering process, i.e. impact parameter of the projectile, and participant density distributions. We show in Fig. 1.2 the result by Franco and Glauber [2] for proton-deuteron scattering at 1 and 2 GeV incident energy. It illustrates the concept of participant and spectator nucleons, invented in this context. The steep forward peak reflects single nucleon-nucleon scattering which is by far the most frequent sub-process owing to the very dilute nucleon density distribution of the deuteron.

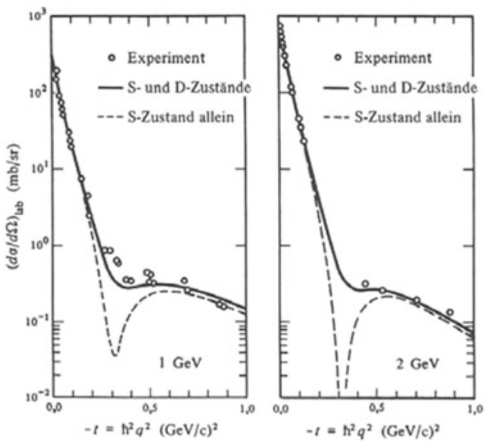

Fig. 1.2 Elastic proton-deuteron scattering with Glauber Model fits. From [2]

1.2 Participant, Spectator and Collision Number

The assumption of independent straight line trajectories of the constituent nucleons of target and projectile nuclei in a nucleus-nucleus collision makes it possible to simply count the number of participating nucleons from target and projectile and, moreover, the number of binary collisions occurring at the microscopic level, during interpenetration. In a Monte Carlo realization one has to dial an instantaneous, *frozen* position map of the nucleons of target and projectile, based e.g. on a Woods-Saxon density distribution. The nucleon trajectories are given finite transverse extension according to the know (or assumed) nucleon-nucleon cross section. The entire geometrical calculation takes place at a chosen impact parameter (see [3] for a comprehensive review). We illustrate this process in Fig. 1.3 where a snapshot of a Au+Au collision is shown. At an impact parameter 6 fm the instantaneous nucleon density distributions are seen approaching each other along the beam axis [3]. One can now read off the distributions of to-be participants (deep colours), and count the number of binary encounters of each participant, thus the total binary collision number. At first sight this picture, and procedure, looks utterly unrealistic. If the microscopic nature of the overall collision process is seen as independent and *successive* N-N scatterings there is hardly a justification to consider a participant nucleon to be still intact exerting its initial cross section, after, say, 6 successive encounters. The misconception is in the word successive. At the ultra-relativistic energies considered here the Lorentz factor exceeds thousand, and thus all aspects of both longitudinal and transverse motion of extended objects, such as nucleon form factors, must occur essentially simultaneously. There are no sequential instances of time resolvable. This point would clearly deserve more discussion! However, the most elementary aspects of the picture, the number of to-be involved or not involved nucleons, as a function of target/projectile nuclear size, and of impact parameter, remain well defined. And, please note, that this is all we need in the analysis of $A + B$ collisions, as the following examples will illustrate. We do not perform a full Glauber model analysis of the collisions

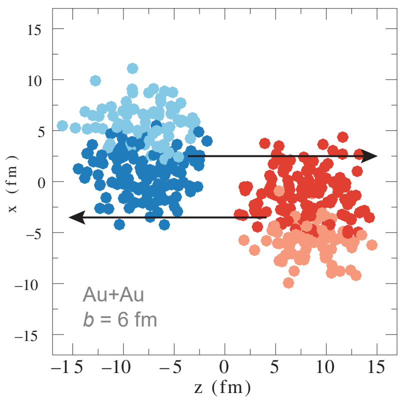

Fig. 1.3 Initial state of a simulated Au+Au collision at impact parameter 6fm, specifying participants (dark colour) and spectators (light colour). From [3]

but need to pin down all geometrical influences, including, more recently, also the event-by-event fluctuations in the geometrical positions of the impinging nucleons. Now to a bit of history.

1.3 Bevalac Physics: Carved—Out Fireballs, Rows on Rows

In the mid-70ties the Berkeley LBL Bevatron provided beams of ^{20}Ne at energies up to 2.1 GeV per projectile nucleon. The Fireball Model [4] was addressed to the proton p_t distributions of minimum bias Ne+U collisions. It combined the Glauber-type geometrical abrasion model [5] of Swiatecki and collaborators, employed to fix the interaction volume and the effective participant center of mass velocity, with a Hagedorn-inspired statistical thermal emission model. Note that this approach came to stay until today, where we initialize the A+B collision with a Glauber calculation and then interpolate the resulting momentum space distribution by the energy-momentum tensor from which a hydrodynamic evolution originates. Figure 1.4 shows a sketch of the abrasion ("clean cut") model applied to the Ne+U collision at a peripheral impact parameter [4].

The assumption of thermal equilibrium met with serious critique (not for the first time: Hagedorns entire life was accompanied by remarks like Feynmans about the "nonsense to smash delicate swiss watches against the wall and study the debris"). This motivated Huefner and Knoll [6] for their *rows on rows* model, a strict and complete Glauber model calculation of Ne on U collisions that we illustrate in Fig. 1.4. In fact they showed that the equilibrium assumption was a good approximation in collisions of heavy nuclei, as a consequence of multiple scattering at the microscopic level.

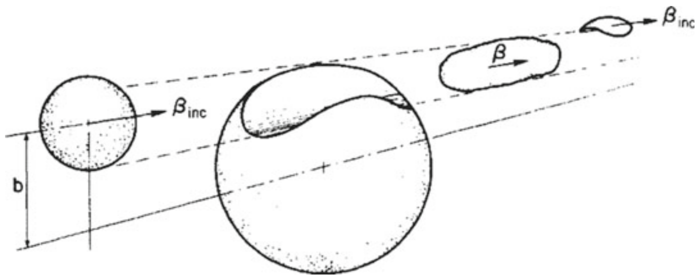

Fig. 1.4 Sketch of the Fireball Model geometry for a Ne+U collision. From [4]

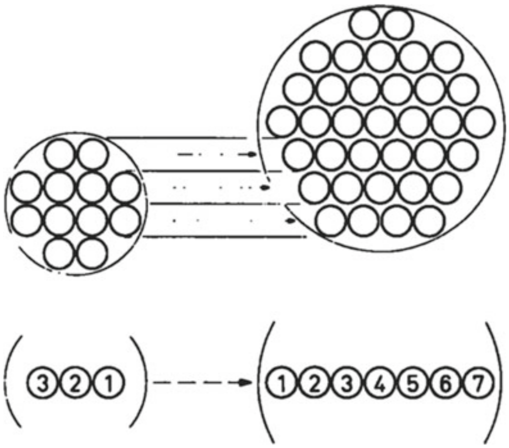

Fig. 1.5 Rows of nucleons along straight line Glauber trajectories for the combination of a light projectile and heavy target. From [6]

1.4 Asymmetric Collision Systems

Figure 1.5 illustrates a notorious difficulty in dealing with asymmetric collision systems, such as the Bevalac Ne+U collision. The effective center of mass varies drastically with impact parameter! In Fig. 1.5 a typical central Glauber-row of nucleons is shown, a 3 on 7 collision. Toward surface reactions one finally approaches a 1 on 1 case! The shifting effective center of mass is beautifully illustrated in Fig. 1.6 by the d+Au data from PHOBOS [7], the only RHIC experiment with a wide rapidity acceptance. One sees a systematic shift of the charged particle rapidity distribution with centrality (impact parameter), from symmetry about mid-rapidity for surface reactions (the 1 on 1 case), to a downward peak shift of about 2.5 units for the most central selection. This has important consequences [8], most often overlooked, for the analysis of p+A and d+A data from experiments with a narrow rapidity acceptance such as STAR, PHENIX and ALICE. Note that the center of mass for hard collisions (jet production) will always stay fixed at mid-rapidity: parton-parton scattering. Thus in central collisions the bulk soft production medium—oftentimes called the co-traveling plasma—moves with considerable longitudinal velocity opposed to the leading parton. Moreover, if the acceptance is placed symmetric to the N-N center of mass rapidity, i.e. $y = 0$ in collider experiments, the effective center of mass rapidity of the soft bulk production falls far outside the acceptance. This explains the high priority placed from Bevalac time onward on equal mass target and projectile collisions.

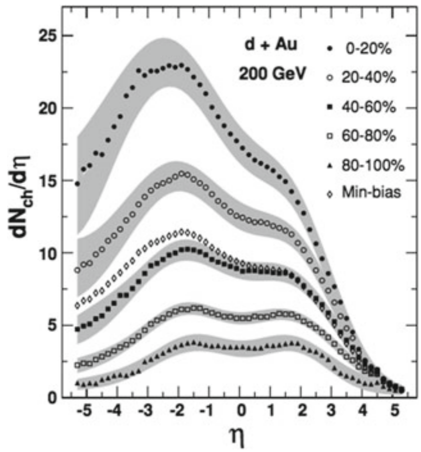

Fig. 1.6 The shift with centrality of the charged particle pseudorapidity distribution in d+Au collisions at 200 GeV, measured by PHOBOS at RHIC [7]

1.5 The Glauber - Relation Between $\langle N_{charge} \rangle$, $\langle N_{part} \rangle$ and Impact Parameter $\langle b \rangle$

From a minimum bias experiment with sufficient event statistics one obtains the distribution of the charged particle multiplicity cross section, or of some related quantity. This is sketched in Fig. 1.7 which illustrates the further steps in the Glauber-type analysis [3]. Integrating the cross section downward from maximum multiplicity one defines the successive multiplicity classes 0−5%, 5%−10% etc. A Glauber calculation then establishes the connection between impact parameter b and average corresponding participant number $\langle N_{part} \rangle$. Note that the latter varies from event to event due to nucleon position fluctuations in the impinging nuclei, so even a sharp b yields a broad Npart distribution, with mean $\langle N_{part} \rangle$. The converse is equally true. Finally, one integrates the resulting $\langle N_{part} \rangle$ distribution downward from its maximum into corresponding percentile classes, and associates this with the N_{ch} percentile classes. A typical final statement arises: in the 5%−10% class the average N_{ch} is about 1200, $\langle N_{part} \rangle$ is about 300 and the mean corresponding impact parameter is about 4 fm. This then sets the stage for a representation of other experimental results, such as e.g. strangeness per participant pair versus centrality. Furthermore, it provides the geometrical input for all model calculations, devoted to soft and hard production. The Nuclear Modification Factor R_{AA} makes further use of this calculation because a mean number of binary collisions is also associated with each of the percentile bins in Fig. 1.7. One can then consider R_{AA}, the ratio of a certain hard production cross section (photons, high p_t hadrons) observed in an $A + A$ collision, to the corresponding elementary proton-proton minimum bias collision cross section as multiplied by the appropriate number of collisions. The case $R_{AA} = 1$ stands for *nothing but trivial collision number scaling*. Figure 1.8 illustrates the modification factors for central Au+Au collisions at top RHIC energy obtained by PHENIX [9]. The photons stay close to unity, they do not significantly interact with the medium,

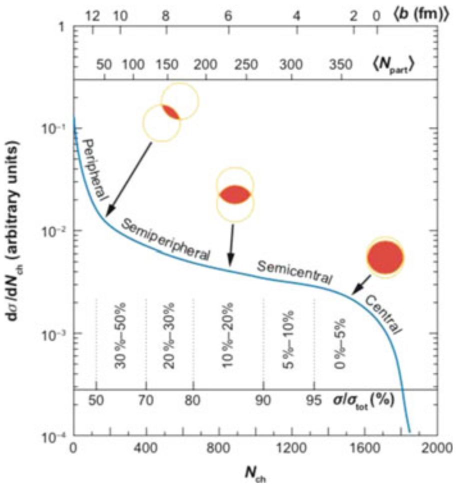

Fig. 1.7 Definition of centrality windows in the charged particle multiplicity distribution in Au+Au collisions, exhibiting the correspondence of impact parameter, participant nucleon number and charged particle multiplicity. From [3]

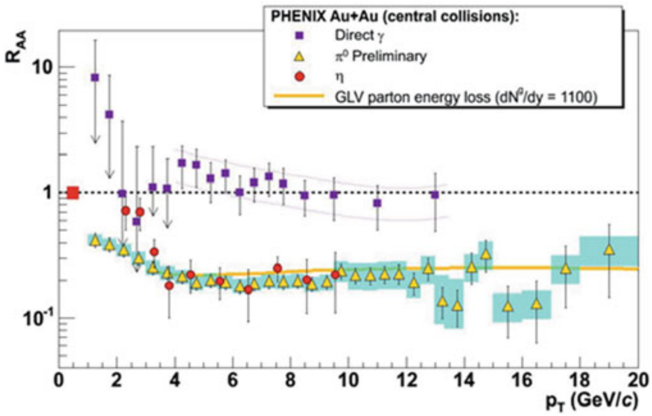

Fig. 1.8 The nuclear modification factor dependence on p_t for pions, η and direct photons, measured by PHENIX [9], compared with the parton energy loss model [10]

whereas the pions and η suffer a drastic suppression, they lose momentum in the "cotraveling" QCD plasma. Diagnosis of its properties thus becomes possible, as illustrated here by comparison to the GLV parton energy loss model [10]. Other models feature the QCD transport coefficient $\hat{q} = \langle q_t^2 \rangle / \lambda$ as the fit variable.