QCD BASED SPACE-TIME DESCRIPTION OF HEAVY ION PHYSICS ¹

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ABSTRACT

The current understanding of the early stage of heavy ion collisions at collider energies on the basis of the improved parton model and kinetic theory is presented. The space-time evolution of these reactions is investigated in terms of the dissipative dynamics of (semi)hard quark and gluon interactions within perturbative QCD. The partons' phase-space distributions are evolved in real time according to a transport equation through multiple collisions, emission and absorption processes. The resulting parton cascade picture is applied to study the issues of thermalisation, chemical equilibration, and particle production in AA collisions at RHIC and LHC.

1. NUCLEAR REACTIONS AT COLLIDER ENERGIES

After a head-on collision between two heavy nuclei of at many GeV/nucleon several hundred or even thousand charged particles are emitted. No one would care to study such events, unless there existed a challenging reason. The current interest in nuclear collisions at very high energies (far above 1 GeV/nucleon in the center-of-mass system) [1] is fueled by the expectation that a *quark gluon plasma* may be created temporarily in these events [2]. Moreover, such ultra-relativistic heavy ion collisions are expected to exhibit new phenomena associated with the microscopic dynamics of quarks and gluons in the hot, ultra-dense environment that may be created in the central collision region of these reactions. The experimental programs at the future heavy ion (AA) colliders, the BNL Relativistic Heavy Ion Collider (RHIC) with maximum available beam energy $\sqrt{s} = 200$ A GeV (gold on gold) and the CERN Large Hadron Collider (LHC) with $\sqrt{s} = 6000$ A GeV (lead on lead), will provide for the first time the opportunity to study nuclear matter under extreme density compression and very high temperatures. With the advent of these accelerators it is an exciting challenge to recreate and explore aspects of the early universe when the hadron matter to quark gluon plasma transition occurred.

Let me briefly recall the general features of the dynamics of ultra-relativistic nucleus-nucleus collisions, particularly those involving very heavy nuclei [3]. At suffi-

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ciently large beam energies ($\sqrt{s}/\text{nucleon} \gtrsim 100$ GeV), it is expected that in the center-of-mass frame two highly Lorentz contracted nuclei pass through each other and deposit their kinetic energy gradually behind them. The commonly accepted qualitative space-time evolution of these reactions is schematically illustrated in Fig. 1: Immediately after the *first instant of nuclear contact*, in the region between the two fast receding discs, the partons of the colliding nuclei begin to interact frequently with each other, resulting in a vehement materialization of excited quanta. The excited partons can rescatter and emit new particles and thereby evolve through a *pre-equilibrium* stage towards a thermalized *quark gluon plasma* state, from which the system evolves further according to the laws of relativistic hydrodynamics. The plasma expands and cools, and eventually a phase transition - perhaps via a mixed parton-hadron phase - into a purely *hadronic gas* occurs. The *freeze-out* of the hadron matter subsequently produces the final hadron yield escaping from the collision region to the detectors.

Fig. 1: Space-time diagram of the (longitudinal) evolution of a relativistic nucleus-nucleus collision.

Of central interest is the very early stage in these reactions, namely from initial parton materialization via pre-equilibrium to plasma formation, since it is expected that most of the entropy and transverse energy are produced already here [4]. Moreover, the parton dynamics during the first 1–2 fm determine the initial and boundary conditions for a hydrodynamic expansion of the plasma phase, so that any characteristic signal for this stage must be seeded here. To study these issues systematically, a comprehensive description of the dissipative processes occurring during very early stage of high energy nuclear collisions is necessary. A kinetic space-time description based on non-equilibrium kinetic theory is needed: starting from the measured parton structure of the colliding nuclei, a dynamical calculation must evolve the initial partons smoothly from their first hard scattering, through a pre-equilibrium stage, into a thermalized plasma. This requires a realistic framework that links together concepts of *relativistic transport theory* on the one hand and *renormalization group improved perturbative QCD* on the other hand.

Within QCD phenomenology there exist basically two kinds of approaches to describe the evolution of high energy nuclear collisions both of which have been ex-

tensively investigated in the last years, namely, a) the *string picture* [5] and b) the *parton approach* [6].

a) *String picture*: Based on phenomenological models of soft hadron-hadron interactions, the collision of two nuclei is viewed as their interpenetration with only small rapidity loss (of the order of one unit). The wounded nucleons draw color flux tubes (strings) between each other, and these strings subsequently fragment by $q\bar{q}$ production within a typical proper time of ~ 1 fm. The production of entropy and transverse energy is thus associated with non-perturbative, phenomenological string dynamics.

b) *Parton approach*: The description is founded on the improved parton picture of hadronic interactions and on the firmly established framework perturbative QCD. The colliding nuclei are visualized as clouds of quasireal quarks and gluons which penetrate through each other, leading to rapid materialization. Multiple short range scatterings between partons (minijet production) together with associated QCD radiation (gluon bremsstrahlung) produce the major part of the total entropy and transverse energy.

Both approaches have their conceptual problems and limitations. The *string picture* becomes questionable at very high energies, when the string density becomes large and the strings begin to overlap, so that they cannot be treated as individual entities that fragment independently. Concerning the issue of quark gluon plasma formation, it appears inconsistent to assume that the establishment of a truly perturbative QCD phase should proceed via non-perturbative dynamics. The *parton approach* on the other hand becomes invalid at lower beam energies, where most partonic scatterings involve momentum transfers too small to be described by perturbation theory. Long range color forces are neglected, so that non-perturbative collective effects and color correlations are (at this point) beyond the scope of this description. One might therefore view the string picture and the parton approach as complementary to each other.

2. THE PARTON PICTURE OF HADRONIC INTERACTIONS AT HIGH ENERGIES

In what follows, I will be concerned with the parton approach to high energy nuclear collisions [7]. The viewpoint advocated here is that perturbative QCD provides a firm basis for the description of the nuclear dynamics in terms of the evolution of the parton distributions in phase-space. I hope this talk helps overcoming the still widespread illusion that perturbative QCD processes are only rare fluctuations that have hardly anything to do with the global reaction dynamics. In fact, as I will argue, most of the entropy and transverse energy is expected to be produced already within the first fm after nuclear contact by very frequent so-called *semihard* parton interactions with only a few GeV momentum transfer [4]. Therefore I believe that the space-time evolution of nuclear collisions at collider energies *must* be investigated in terms of the dissipative parton dynamics within perturbative QCD.

The description of hadronic interactions in terms of parton cascades is based on the improved parton model within perturbative QCD [6]. A fast nucleon may

be considered as a coherent cloud of quasireal partons with life times much larger than the typical interaction times (the time needed for the interaction with another particle). Each parton is characterized by the fraction x of the initial nucleon energy which it carries, and by its transverse momentum $q_{\perp}$. At each instant an individual parton can initiate a space-like virtual cascade by branching into a number of partons with smaller x . The global probability for a branching of a parton can be rather large, because the phase-space available is very large at small x and the smallness of the coupling constant α_s at the branching vertex is compensated by the logarithmically large integration over the momentum of the daughter partons. Such a cascade can be described in terms of a tree-like structure, composed of many branchings. First the partons in a cascade multiply, then they assemble back due to their coherence (since they do not have enough energy to exist as free particles) [Fig. 2a]. Thus, such a space-like cascade lives for a finite time, but new cascades are born to replace the former ones. However, if a parton in a cascade collides on its way with some other particle, then this interaction destroys the coherence of the cascade. The *virtual* parton is struck out of the cascade and becomes a *real* excitation. As a result the other partons in the cascade branch cannot reassemble, but continue to live [Fig. 2b]. The additional emission of new partons increases the parton density and in turn the interaction probability of parton scatterings and rescatterings.

Fig. 2: a) Coherent space-like cascade of partons as part of the wavefunction of a fast moving nucleon. b) The interaction with another particle destroys the coherence of the cascade and 'freezes' the partons of the struck branch of the cascade.

In this picture, the major part of the total entropy and transverse energy production arises from the very frequent *semihard* parton interaction processes. Such processes involve the production of quark and gluon minijets with comparably large transverse momenta $q_{\perp} \gg 1/R_N$, but with a small fraction $x \ll 1$ of the initial energy per nucleon. The global cross-section proves to be rather large: $\sigma(\text{semihard}) \sim R_N^2$ [6]. Since these semihard processes occur at distances $r(\text{semihard}) \sim 1/\sqrt{q_{\perp}^2} \ll R_N^2$, they can be calculated in perturbative QCD. Therefore it is possible to study rather typical hadronic interactions ($\sigma \sim R_N^2$) by perturbative methods.

The approach of semihard physics within perturbative QCD has been very successful in describing the dynamics of high energy hadron-hadron collisions. It predicts the correct behaviour of the strong increase with energy (s) of the total and inelastic cross-sections, mean transverse momentum and multiplicities, as well as the inclusive spectra of hadrons with $(q_\perp) \gtrsim 400$ MeV with good accuracy [6]. These predictions result essentially from the fact that the average total multiplicity of partons in a cascade increases with beam energy, $\bar{n} \sim \exp(\text{const.} \cdot \alpha_s \ln s)$, most of them carrying small energy fractions z . Therefore, at high energies the interaction probability approaches unity and a nucleon appears to be increasingly "black". This property gives rise to the experimentally observed *BEF* effect [8]: at high energies a nucleon appears to become *blacker*, *edgier*, and *larger*. Asymptotically, a nucleon looks like a black disc with a energy dependent radius $R \propto \ln s$.

3. SPACE-TIME DESCRIPTION - QCD TRANSPORT THEORY

So far I have only talked about the general implications of the partons' perturbative QCD interactions for hadronic reactions. No reference to the space-time development was made. In contrast to hadronic collisions, however, in nuclear collisions the microscopic dynamics is very complex and space-time structure of the dynamics has to be taken into account. In order to investigate the space-time evolution of the parton distributions, one needs to extend the momentum space description to full six dimensional phase-space and time. Efforts to formulate a rigorous quantum kinetic theory for QCD have been made [9], but due to the non-abelian character of the theory, a number of unresolved conceptual and technical problems prevent yet a practical application to realistic problems. An alternative approach is realized in the parton cascade model (PCM) [10, 11] within semi-classical kinetic theory: the partons are considered as "extended" quanta dressed with a specific QCD formfactor, that propagate on classical trajectories in *between* their interaction vertices, but the interactions at the vertices are described quantum theoretically according to QCD and quantum statistics.

In order to quantitatively describe the dynamics of a statistical many-parton system in complete phase-space and time, the basic idea is to embody the perturbative parton cascade picture into a relativistic version of the semiclassical kinetic theory. Consider the partons as *off-shell* particles characterized by their species $a = q, \bar{q}, g$, virtuality Q^2 , momentum $\vec{p}$ and position $\vec{r}$. The energy is determined by $E^2 = \vec{p}^2 + m_a^2 + Q^2$ where m_a is the rest mass of parton a and Q^2 denotes a possible space-like ($Q^2 = -q^2$; $q^2 < 0$) or time-like ($Q^2 = m^2$; $m^2 > 0$) virtual mass ($Q^2 = 0$ for partons on mass shell). Thus, energy and momentum are independent variables, because of the continuous dynamical mass spectrum of the partons. One can define the *Lorentz invariant single particle distribution function* for the time-dependent phase space density of partons of species a , $F_a(p, r) d^4p d^3r$, which is the expected number - at time t - of partons of type a in d^3r around $\vec{r}$ with momentum in d^3p around $\vec{p}$ and virtuality $Q^2 = E^2 - \vec{p}^2 - m_a^2$. This function contains all the information is required for the statistical description of the time-evolution of a many-parton system

in six-dimensional phase-space. The time evolution of the many-parton system can be described on the basis of a relativistic transport equation for the parton distribution functions $F_a(p, r)$,

$$p^\mu \partial_\mu F_a(p, r) = \sum_{\text{processes } h} I_a^{(h)}(p, r). \quad (1)$$

To solve this equation, one needs to specify the form of the collision kernel and the initial parton distribution. The collision kernel $\sum_h I_a^{(h)} \equiv \sum_h I_a^{(h)\text{gain}} - I_a^{(h)\text{loss}}$ balances the various processes h by which a parton of type a with four-momentum p at space-time point r may be gained or lost in a phase-space volume $d^3p d^3r$ centered at $\vec{p}$ and $\vec{r}$ at time t . It is a sum over Lorentz invariant collision integrals that involve the matrix elements for the different kinds of interaction processes in which at least one parton of type a is involved [12]. The initial phase-space distribution of partons in the incoming nuclei at time $t = t_0$ (the moment of nuclear contact), $F_a(p, r)|_{t=t_0} \equiv F_a^{(0)}(p, r, Q_0^2)$, must be constructed phenomenologically from the measured nuclear structure functions [10, 11].

Starting from the initial parton distributions at $t = t_0$, the time evolution of the phase-space densities $F_a(r, p)$ reflects the state of the system around $\vec{r}$ and $\vec{p}$ at any time $t > t_0$. Therefore, by extracting the functions $F_a(r, p)$ from eq. (1), one can calculate in a Lorentz invariant way the time dependent local density of partons $n(r)$, the entropy density, energy density, and local pressure, $s(r)$, $\epsilon(r)$, and $p(r)$, respectively, [12, 13]. It is important to realize that these quantities are well defined in terms of phase-space integrals for any distribution $F_a(r, p)$ within the statistical description. Also, one can always define an "effective temperature", e.g. as $T = (\epsilon + p)/s$, even for a non-thermal system, but which coincides in the case of thermalization with the expression for the true temperature of an ideal plasma.

4. THE PARTON CASCADE MODEL FOR ULTRA-RELATIVISTIC NUCLEAR COLLISIONS

The PCM [10, 11] is a relativistic kinetic model for high energy nuclear collisions which is inspired by the parton picture of hadronic interactions outlined in Sec 2. It provides a comprehensive description of hadron-hadron, hadron-nucleus and nucleus-nucleus collisions in terms of the space-time evolution of parton cascades, i.e. the nuclear dynamics is traced back to the microscopic level of quark and gluon interactions in the framework of perturbative QCD. Embedded in the above semiclassical kinetic formulation, this approach allows to study the time evolution of the nuclear collisions in complete phase-space from the instant of nuclear contact, through the perturbative QCD evolution of parton distributions, up to the formation of final hadronic states. The model as a whole consists of three major building blocks:

1. *Initial state*: Phenomenological construction of the initial state in terms of the partons' phase-space distributions in the incoming nuclei (or hadrons) on the basis of the experimentally measured nucleon structure functions and elastic nucleon form-factors, as well as nuclear shadowing corrections.

2. *Parton cascade development*: Time development of parton cascades in complete six-dimensional phase-space according to a semiclassical, relativistic transport equation with a collision kernel that contains the asymptotically dominant perturbative QCD interaction processes among the partons. The time variation of the parton distributions, the number and type of interactions is determined by the dynamics itself.

3. *Hadronization*: Formation of color neutral clusters from the ensemble of final partons at the end of the perturbative QCD phase. Independent hadronization of each cluster through isotropic two-body decay yielding primary hadron resonances which subsequently decay into final hadrons according to the particle data tables.

Fig. 3: a) Typical cascade development in the PCM as an interrelated combination of $2 \rightarrow 2$ scattering, $1 \rightarrow 2$ branchings, and $2 \rightarrow 1$ fusions. b) Corresponding representation in terms of 'effective' matrix-elements that generate the evolution of partons according to the transport equation (1).

To give an idea how the space-time evolution of the parton distributions in a nuclear collision according to the transport equation (1) is described in terms of parton cascades, in Fig. 3a a typical parton cascade development is illustrated. I emphasize that there are many such cascades, which are interrelated and simultaneously evolving. Each cascade can be subdivided into elementary $2 \rightarrow 2$ scatterings, $1 \rightarrow 2$ branchings (emissions), and $2 \rightarrow 1$ fusions (absorptions). For example, a primary parton a that originates from one of the incident nuclei, collides with another parton b with some momentum transfer $Q_{ab}^2 = p_{\perp}^2$. The parton a has evolved from the initial scale Q_0^2 at which it was resolved in its parent nucleus, up to Q_{ab}^2 by successive space-like branchings. From the scattering of a and b the partons c and d emerge, both of which can initiate sequences of time-like branchings. These newly produced partons can themselves radiate, rescatter, and/or absorb (be absorbed by) other partons. Formally this cascade development can be cast in terms of effective matrix-elements, in which each of the particles coming in and going out of an elementary vertex, is dressed with a specific formfactor that takes into account the higher order corrections to the elementary Born terms. This is illustrated in Fig. 3b. These effective matrix-elements enter the collision integrals in the transport equation (1) and generate the

evolution of the parton system in terms of multiple parton scatterings and associated emission/absorption processes.

5. PARTICLE PRODUCTION AT COLLIDERS: FROM $p\bar{p}$ TO AA

Before applying the parton cascade approach to nuclear collisions, both the perturbative QCD cross-sections and the amplitudes for parton emissions, have to be regularized, because of the well known infrared divergences associated with non-perturbative color forces and confinement mechanisms. In the PCM this is done by requiring a minimum momentum transfer $p_{\perp, \text{min}}$ for semihard and hard parton collisions and a minimum virtuality μ_0 for parton emissions [4]. These parameters of the model are fixed by experimental data for the $p\bar{p}$ ($p\bar{p}$) cross-sections [14] and e^+e^- annihilation [11], respectively. With the model parameters $p_{\perp, \text{min}}$ and μ_0 assumed to be universally fixed, it is useful to test the applicability of the PCM in $p\bar{p}$ collisions which have been studied experimentally as well as theoretically in great detail. Generally the model results agree well [11] with the measured data for particle multiplicities, momentum spectra, and the rise of the total cross-section. It is satisfactory that other models based on perturbative QCD, e.g. HIJING [15] and DTUJET [16], produce almost identical results.

Fig. 4: $p\bar{p}$ collisions: calculated transverse momentum (left) and (pseudo)rapidity spectra (right) of the final partons before hadronization and b) of the resulting hadrons.

Fig. 4 shows the exemplarily the inclusive transverse momentum spectra and the (pseudo)rapidity distributions at various beam energies, both for the final state parton configuration just before hadronization and for the resulting hadrons. The most important aspects are: (i) The shapes of the final hadron spectra are essentially predetermined by the corresponding distributions at the parton level. (ii) The p_T -spectra exhibit a characteristic QCD power law tail, reflecting contribution of comparably hard parton collisions and branchings. (iii) The increase of the central rapidity density around $y = \eta = 0$ is totally due to the growing number of parton-parton collisions

and the multiplicity increase of partons produced in the associated cascades.

Proceeding to AA collisions, the above mentioned different models based on the perturbative QCD parton approach also give the same qualitative predictions for the particle spectra and the multiplicity increase with collider energy. However, there is a significant uncertainty in global observables, e.g. the absolute number of produced particles, which is mainly due to the different regularization procedures, i.e. the interpretation of the cut-off parameters $p_{T,cut}$ and μ_0 . Further discrepancies arise from the different (and partly absent) treatment of nuclear and dense medium effects that are not present in pp collisions. As an example, Fig. 5 compares the results of HIJING and PCM for the p_T - and η -spectra of charged hadrons produced in heavy ion collisions at RHIC and LHC. The similarity of the spectra is obvious and is a direct consequence of the perturbative QCD description common to both models, but note the difference in the absolute magnitude of the particle production. I emphasize that the parameters of the models are kept the same as for pp collisions at the same energy. However, one would expect that nuclear and dense medium effects modify the values of $p_{T,cut}$ and μ_0 , depending on the local, time-dependent phase-space density. This issue remains to be investigated quantitatively.

Fig. 5: Comparison between the predictions of HIJING and the PCM for the transverse momentum and (pseudo)rapidity spectra of charged hadrons produced in central heavy ion collisions at RHIC and LHC energies.

The new physics associated with the nuclear and medium effects on the parton level that determine the dynamics of AA collisions drastically evident in Fig. 6, where the various curves a)-e) exhibit the characteristics of different evolution scenarios [11], namely, a) 'naive evolution', b) plus nuclear shadowing, c) plus parton fusion and absorption, d) plus Landau-Pomeranchuk-Migdal effect, e) plus soft gluon interference. Fig. 6a displays the average cumulative number of secondary partons per nucleon a function of time measured in the total CM frame for $Au + Au$ ($A=197$) collisions. The

dotted and full lines correspond to the evolution scenarios (a) and (e), respectively (except for nuclear shadowing). Comparing the curves (a) and (e) one sees that in the latter case the multiplicity of secondary partons is significantly lower and the evolution of the system is dilated. Furthermore, in scenario (e) a suppression of parton production following the explosive increase at $t \approx 0.6$ fm is caused by saturation of the parton densities due to dense phase-space occupations and increasing absorption probability. Fig. 6b displays the charged particle distributions in pseudorapidity (η), calculated for central $Au + Au$ collisions with $\sqrt{s} = 200$ A GeV and $\sqrt{s} = 6300$ A GeV. The particle density in the central rapidity region is reduced successively from the 'naive' calculation (case a) to the default result (case e) by more than a factor of 3. From RHIC to LHC energies, i.e. increasing in $\sqrt{s}$ by a factor of 30, the central rapidity density roughly doubles (from ≈ 1200 to ≈ 2500 in case e).

Fig. 6: Impact of nuclear and dense matter effects on (i) the parton evolution and (ii) the resulting charged particle spectra in $Au + Au$ collisions at RHIC and LHC energies. The different evolution scenarios are explained in the text.

6. SPACE-TIME EVOLUTION OF AA COLLISIONS AT RHIC AND LHC: FROM PRE-EQUILIBRIUM TO PLASMA FORMATION

Let me now come to the space-time evolution of ultra-relativistic heavy ion collisions during the first 2-3 fm. The time evolution of the parton distributions is described in terms of the proper time τ , taken to be $\tau = \text{sign}(t - t_0(s)) \sqrt{(t - t_0(s))^2 - z^2}$, where t is the center-of-mass time and $t_0(s)$ is its value at the moment of maximum overlap of the colliding nuclei (e.g. $t_0 \approx 0.8$ fm for $\sqrt{s} = 200$ A GeV) and z is the beam axis with the center-of-mass at $z = 0$. Furthermore, I define the central collision region, for $\tau \geq 0$, as a cylindrical expanding volume bounded by $|\eta| \leq 1$ and $|\vec{r}_\perp| \leq 5$ fm, where η is the ordinary space-time rapidity and $\vec{r}_\perp$ the transverse coordinate perpendicular to the beam axis.

In Refs. [12, 13] detailed investigations of the characteristics of the partons' space-time evolution have been presented. It was found that the time development of the

partons' momentum distributions in the central collision region of Au + Au collisions indeed rapidly approach kinetic equilibrium, as reflected by the increasingly thermal shape. The highly non-thermal initial momentum distribution of the partons in the incoming nuclei first develops a power-law shape characteristic for the harder primary parton collisions and the associated (mini)jet production. With progressing time this QCD power-law tail flattens out and the exponential slope at lower momentum ($p \lesssim 3$ GeV), which is already visible at $\tau = 0.2$ fm, becomes steeper, indicating the decrease in the effective temperature of the system. Fig. 7a summarizes the corresponding thermodynamic properties of the system of partons, for the case of central Au + Au collisions at $\sqrt{s} = 200$ A GeV, implied by the time evolution of the phase-space distributions [13]. Shown are the pressure p , the number density n , energy density ϵ and entropy density s , as well as the associated temperature $T \equiv 4/3(\epsilon/s)$ as functions of the proper time τ in the local rest frame of the matter. The time dependence of the quantities n , p , ϵ , s and T may be parametrized in terms of negative powers of τ/τ_0 with the parameter $\tau_0 = 0.05$ fm, which results in the solid curves in Fig. 7a. This time evolution remarkably resembles [13] the one of an ideal plasma of non-interacting partons [3]. Consistent with that is also the result found in [12] that the deviation of the entropy produced per particle in the realistic model calculation from the one of an ideal gas amounts only to a few percent. Although the model includes massive quarks and accounts for interactions among the partons, the system of partons looks also from this point of view effectively like an almost ideal gas.

Fig. 7: a) Pressure p , the number density n , energy density ϵ and entropy density s , and associated temperature $T \equiv 4/3(\epsilon/s)$ as functions of the proper time τ in the local rest frame of the matter in the central collision region of Au + Au collisions at $\sqrt{s} = 200$ A GeV (the curves are interpolations of the data points to guide the eye). b) Time evolution of the ratio $\rho_q = n_q/n^{(q)}$ for the individual parton species in Au + Au at RHIC energy. Dashed lines for u and d represent valence quark contributions, full lines are total quarks plus antiquarks.

As an objective measure to estimate the degree of chemical equilibration among the partons one may compare for example the actual parton number densities n_q with the equilibrium densities $n^{(q)}$ for a perfectly equilibrated gas of non-interacting, massless partons at the same temperature. Fig. 7b displays, as a function of time τ , the ratio in the central region $\rho_q^{(c)} = n_q/n^{(q)}$. An indication for the establishment of a perfect chemical mixture would be that $\rho_q^{(c)}$ tends to unity for gluons and each quark flavor individually. It is obvious that the system of partons can not establish perfect chemical equilibrium with proper admixtures of gluons and quarks, although, as argued above, it exhibits the thermodynamic behaviour of an ideal parton gas. The gluon density n_g , which rapidly increases and reaches its maximum around $\tau = 0.5$ fm, approaches to within 10% of its equilibrium value at about $\tau = 1.2$ fm. The densities of light quarks plus antiquarks, $n_q + n_{\bar{q}}$, build up only to about 80% of their equilibrium densities. The heavier quarks s and c achieve even less.

7. CHARACTERISTICS OF THE PARTON PLASMA - OBSERVABLES

There have been various other independent investigations of the parton evolution during the early stage of nuclear collisions, which qualitatively agree in the understanding of the first few fm after the nuclear contact [17, 18, 19]. The emerging current picture may be summarized as follows:

- (i) $\tau_c \leq \tau \lesssim 0.2$ fm: The vehement materialization of initial virtual partons plus associated gluon emission produces most of the entropy and results in a large number of 'few GeV' excitations, which are mostly gluons.
- (ii) $0 \lesssim \tau \lesssim 0.3$ fm: Both the gluons and quarks rapidly reach a local kinetic equilibrium in the central collision region with approximately isotropic momentum distributions in the local restframe of the matter.
- (iii) $0.3 \lesssim \tau \lesssim 2$ fm: The gluons approach complete equilibration - the saturation of the phase-space density towards its chemical equilibrium value. The phase-space population of quarks evolves significantly slower, mostly by gluon induced processes, and yields at most $1/2$ to $2/3$ of the quarks' chemical equilibrium densities.
- (iv) $\tau \gtrsim 2$ fm: The gluon dominated plasma expands and cools without further significant change of its chemical composition.

Thus, the early evolution of these nuclear collisions is governed by the dominant role of gluons, due to their large interaction probability and the large gluonic component in the initial nuclear wavefunctions. This leads to a 'hot glue scenario' [17], in which the large number of initially produced energetic partons create a high temperature, high density plasma of predominantly hot gluons and a considerably smaller number of quarks. If such extreme conditions indeed would be established in the central collision region of ultra-relativistic heavy ion collisions, then this would significantly modify previous expectations for the initial conditions for a parton plasma evolution [12, 17], enhance the standard QGP signals (production of dileptons, strange,

and charm particles), suppress the central rapidity density and the production of high p_T particles due to dense medium effects, and, the dependence on A and $\sqrt{s}$ of hadronic multiparticle production.

As two examples of the possible implications of a hot glue scenario, let me briefly discuss first, dilepton emission and second, strangeness and charm production by cascading partons in this environment.

Fig. 8: Probes of the early stage of heavy ion collisions: calculated yield of (i) dileptons, and (ii) strange, charm, bottom quarks, which are produced during the first 2-3 fm in the central region of Au + Au collisions in the energy range between RHIC and LHC.

Dilepton emission: Lepton pairs are considered to be good probes of the early, highly excited pre-equilibrium and plasma phases of a nucleus-nucleus collision (see e.g. review [20]). Most high energy lepton pairs and photons should be created by parton interactions early in the collision when the energy density, and the energy available in parton scatterings, is the greatest. Moreover, these particles escape from the system without rescattering and carry information about the high density matter unscathed to the detectors. In Ref. [21] dilepton production in central Au + Au collisions at RHIC energy was investigated within the PCM. Fig. 8a compares the PCM results for the dilepton yield with standard hydrodynamic and free-streaming curves that correspond to an initial temperature $T_0 = 550$ MeV and formation time $\tau_0 = 0.12$ fm [20]. The PCM results show a smooth evolution of the l^+l^- mass distribution from pre-equilibrium towards quark-gluon plasma that at low masses is similar to hydrodynamic and free-streaming evolution, but at large masses is dominated by the Drell-Yan yield.

Strangeness and charm production: The properties of strangeness and charm production in high energy heavy ion reactions are similar as dilepton and photon emission, commonly believed to provide characteristic signatures for the formation of a deconfined parton plasma during the early stage of these reactions. Originally this

idea was proposed many years ago by Shuryak [3]. In Ref. [22] the flavor production in heavy ion collisions was investigated within the PCM. Fig. 8b shows the central rapidity density $dN_{Q+q}/dy|_{y=0}$ versus the normalized beam energy $\sqrt{s}/A$ of produced strange, charm and bottom quarks plus antiquarks ($Q = s, c, b$) in central Au + Au collisions. The calculated energy dependence of dN_{Q+q}/dy with plasma formation is shown in the left panel, whereas the right panel shows the purely hadronic production, without plasma formation, which was mimicked by simulating pp collisions, and simply scaling the calculated multiplicities to Au + Au. Comparing the two scenarios with and without plasma formation, one observes a substantial enhancement of more than one order of magnitude of the quark production for all three flavors s, c and b .

8. CONCLUSIONS AND OPEN PROBLEMS

Much more experimental and theoretical study is required before robust conclusions for experimental observables and fundamental theoretical problems can be drawn. Nevertheless, I believe, already at this point an understanding of the fundamental problems on the basis of perturbative QCD and transport theory has been reached. Instead of a summary, and as a balance to the optimistic viewpoint advocated here, I list below some of the main problems and open questions connected with the parton cascade approach to heavy ion collisions:

- (i) *Initial state:* the still very uncertain small x -behaviour of gluon structure functions (gluon shadowing).
- (ii) *Perturbative QCD evolution:* the interpretation of the infrared cut-offs p_{T0}, μ_0 which in pp are constrained by data but not unique, and in AA are related to infrared behaviour in a QCD plasma (screening).
- (iii) *Semiclassical approximation of parton transport:* the shortcomings and approximations of the Boltzmann equation, the use of single particle distributions and the neglect of long-range color forces and color correlations.
- (iv) *Hadronization:* the question of how to describe the confinement mechanisms in AA (parton recombination, or hydrodynamics with QCD phase transition, or dynamical nucleation, ...).
- (v) *Other problems:* conceptual questions associated with averaging over color degrees of freedom, the off-mass-shell behaviour of partons, the Landau-Pomeranchuk-Migdal effect in QCD,

If in the near future these problems can be partly overcome or at least better understood, quantitative ab-initio calculations of ultrarelativistic heavy ion collisions may become feasible by the time when RHIC starts operation.

1. References

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