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MINIJETS IN ULTRARELATIVISTIC HEAVY ION COLLISIONS AT FUTURE COLLIDERS

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Abstract

The role of minijet production as initial conditions for QGP production at $\tau \sim 0.1$ fm/c in nuclear collisions at the LHC and RHIC energies is discussed.

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The main goal of ultrarelativistic heavy ion collisions (URHIC) is to create strongly interacting condensed elementary particle matter, quark–gluon plasma (QGP), and to study thermodynamics of this new phase of matter. The existence of the QGP phase has been proved by *ab initio* calculations in lattice QCD [1].

High energy particle physics usually aims at producing as few particles as possible in order to create a simple system for the measurements. The URHIC also aim at a simple system but by producing as *many* QCD quanta as possible. In hadronic collisions the produced final state is dilute, further interactions negligible, and the system essentially freely streaming. In URHIC, one would ideally produce a system with a *maximal* amount of final state interactions, *i.e.* a large enough thermal parton system with negligible mean free paths.

From the point of view of QGP formation, as high cms-energies $\sqrt{s}$ and as large nuclei A as possible are preferable. So far, the most energetic nucleus–nucleus collisions have been the Au–Au collisions at $\sqrt{s} = 5$ AGeV at the AGS[2] in the Brookhaven National Laboratory (BNL), and Pb–Pb collisions at $\sqrt{s} = 17.6$ AGeV at the SPS[3] in CERN. A very strong J/Ψ-suppression observed in the central Pb–Pb collisions at the SPS by the NA50 collaboration [2] suggests that the QGP phase may have already been reached at the SPS, and, more importantly, observed.

In future heavy ion collisions, Au–Au at $\sqrt{s} = 200$ AGeV at the BNL RHIC[4], and Pb–Pb at $\sqrt{s} = 5500$ AGeV at the CERN LHC/ALICE[5], initial energy densities far beyond the critical densities of QGP formation will be produced. It is also expected that the system in the central rapidity region of the RHIC and LHC nuclear collisions will stay in the QGP phase for several fm/c, thus giving better possibilities for observing characteristic signals of the QGP like J/Ψ-suppression, thermal production of dileptons and photons, strangeness enhancement, collective flow, disoriented chiral condensates, *etc.* For a review, see Ref. [3].

Particle and transverse energy production in the central rapidity region of URHIC can be treated as a combination of perturbative (hard and semihard) parton production and non-perturbative (soft) particle production. By "hard processes" one usually means clearly perturbative processes with momentum or mass scales of the order of several or tens of GeV, while "semihard" here refers to QCD-processes where partons with transverse momenta of a few GeV, "minijets," are produced. In this article I will discuss the role of perturbative parton production as the early initial conditions for the QGP [4, 5, 6] in URHIC at LHC and RHIC. In particular, some recent results of initial parton production [8, 7] are reviewed in Secs. 2 and 3. I will also briefly discuss other approaches [9, 10] in Sec. 4, and further evolution of the QGP in Sec. 5.

By definition, the semihard processes lie at the border-line of hard and soft physics. Real hadronic jets have been observed in $p\bar{p}$ collisions from $p_{\mathrm{T}} \gtrsim 5$ GeV [11] up to $p_{\mathrm{T}} \sim 440$ GeV [12]. The minijets with $p_{\mathrm{T}} \sim 1...2$ GeV are part of the underlying event rather than distinguishable jets[6]. In nuclear collisions, where thousands (hundreds) of minijets are expected to be produced in the central rapidity unit at the LHC (RHIC) [4, 6, 7], detection

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[2] AGS = Alternating Gradient Synchrotron

[3] SPS = Super Proton Synchrotron

[4] RHIC = Relativistic Heavy Ion Collider

[5] LHC = Large Hadron Collider; ALICE = A Large Ion Collider Experiment

[6] In this sense "minijet" is not a very good name for a semihard parton; it is not a "jet" at all.

of individual semihard partons becomes impossible.

Even though the semihard partons are not observed as jets, their production should fall well within the scope of perturbative QCD (pQCD) since $p_{\rm T} \gg \Lambda_{\rm QCD} \sim 200$ MeV. Ultimately, to how low values of $p_{\rm T}$ one can push the validity of pQCD, is a question of convergence of the QCD perturbation series. The recent results from HERA[7] at DESY [13, 14] indicate that the behaviour of parton densities can be explained within pQCD down to the low scales $Q^2 \sim 1$ GeV^2. This supports applicability of pQCD to semihard parton production as well.

In the division into semihard and soft particle production, the key feature is that one is able to *compute* the semihard parton production from pQCD, given that the parton distributions of colliding hadrons and nuclei are known. On top of this, the non-perturbative particle production can be modelled *e.g.* through strings [15, 16, 17, 18], or in URHIC perhaps also through a decaying strong background colour field [19, 20]. With increasing energies however, the semihard QCD-processes are expected to become increasingly important, particularly in URHIC. This is due to the following reasons:

- With increasing cms-energies, the events tend to become more “jetty” or, rather, more “minijetty”, and in $p\bar{p}$ and pp collisions the rapid rise of the total and inelastic cross sections with the $\sqrt{s}$ can be explained by the copious production of semihard partons with transverse momenta $p_{\rm T} \geq p_0 \sim 1...2$ GeV [21, 22]. Perturbative parton production in AA collisions scales as $\sim A^{4/3}$ [4, 6], while the soft component scales more like $\sim A$, so for large nuclei the importance of semihard partons should be further increased.

- In the deep inelastic ep scatterings (DIS) at HERA it is observed that the structure function $F_2^p(x, Q^2)$ has a steep rise at small values of Bjorken x, at $x \lesssim 0.01$, persisting down to scales $Q \sim 1$ GeV [23, 14, 13]. The quark–antiquark sea is generated by emission from the gluons, so the gluon distributions have this rapid rise as well. In minijet production in the central rapidities, the dominant gluonic processes at $p_{\rm T} \sim 2$ GeV probe the parton distributions typically at fractional momenta $x \sim 2p_{\rm T}/\sqrt{s} \sim 7 \times 10^{-4}$ in the LHC nuclear collisions. For the RHIC, where typically $x \sim 0.01...0.02$, the rise of the parton distributions will not cause such a big effect at the central rapidities.

- Time scale for producing partons and transverse energy into the central rapidity region by semihard collisions is short, typically $\tau_{\rm h} \sim 1/p_0 \sim 0.1$ fm/c, where $p_0 \sim 2$ GeV is the smallest transverse momentum included in the computation. The soft processes are completed at later stages of the collision, at $\tau_{\rm s} \sim 1/\Lambda_{\rm QCD} \sim 1$ fm/c. If the density of partons produced during the hard and semihard stages of the heavy ion collision becomes high enough - there are indications that it will - fusions start to occur, and a saturation in the initial parton production can take place in the perturbative region [5, 24, 25, 8]. As a result, softer particle production will be screened. The fortunate consequence of this is that a larger part of transverse energy production in the central rapidities is computable from pQCD at higher energies and the relative contribution

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[7] HERA = Hadron Electron Ring Anlage

from soft collisions with $p_{\rm T} \lesssim 2$ GeV becomes smaller. Typically, the expectation is that at the SPS the soft component clearly dominates, and at the LHC the semihard component is the dominant one [6, 22, 18]. At the RHIC both components should be taken into account.

The importance of copious semihard parton production in an early formation of the QGP in URHIC was first addressed almost 10 years ago, by Blaizot and Mueller [5], and by Kajantie, Lindfors and Landshoff [4]. In terms of eikonal models for hadronic interactions, minijet production had already been emphasized some years before, in Refs. [21], to explain the rise in the total and inelastic cross sections of $p\bar{p}$ cross sections beyond the CERN ISR energy range. Models including both strings and semihard parton production were introduced around the same time [26]. The work [4] was later improved by including partonic cross sections in lowest order (LO) pQCD [6] and with a better treatment of the rapidity acceptance. Consequences of the HERA results [23] for minijet production in URHIC were studied in [7]. Minijet production in AA collisions has also been studied by Calucci and Treleani from the beginning of the 90's [27], and later by Xiong and Shuryak [28]. In the end of the 80's, systematic efforts began to construct event-generators for URHIC, which would be based on the increasingly important pQCD component. As a result, HIJING by X.-N. Wang and Gyulassy [18], and, Parton Cascade Model by Geiger and Müller [29] were constructed. Also other event generators have options for simulating the URHIC at the RHIC and LHC energies [17, 30, 16].

Treatment of semihard QCD-scatterings is usually based on collinear factorization, where the hard parton–parton scatterings are factorized from the universal parton distributions at a perturbative scale $\sim p_{\rm T} \gg \Lambda_{\rm QCD}$. The parton distributions then contain the non-perturbative experimental input. A novel approach to semihard parton production, not based on the collinear factorization nor independent scatterings, but on a consideration of a classical gluon field, has been suggested by McLerran and Venugopalan in 1994 [10]. Not based on collinear factorization either, and perhaps directly related to the gluon field approach, minijet production in a BFKL approach was studied recently [9]. These topics will be discussed in Sec. 4.

1 Minijet production in AA collisions

The idea of multiple production of semihard gluons and quarks in pp and especially in AA collisions is based on a picture of independent binary parton–parton collisions. The key quantity is the integrated jet cross section:

$$\sigma_{\rm jet}(\sqrt{s}, p_0, \Delta y) = \frac{1}{2}\int_{p_0^2,\Delta y} dp_{\rm T}^2 dy_1 dy_2 \sum_{\substack{ijkl=\\ q,\bar{q},g}} \int dy_2\, x_1 f_{i/N}(x_1, Q)\, x_2 f_{j/N}(x_2, Q) \frac{d\hat{\sigma}}{d\hat{t}}^{ij\to kl}(\hat{s}, \hat{t}, \hat{u}), \quad (1)$$

where $x_{1,2}$ are fractional momenta of the incoming partons i and j. Parton-level quantities are indicated by hats, and $f_{i/N}(x, Q)$ are the parton distributions in N $(= p, A)$ at a factorization scale, chosen as $Q = p_{\rm T}$. The normalization factor 2 comes from the fact that, in the lowest order (LO) pQCD, there are two partons produced in each semihard subcollision. In the eikonal models for pp collisions [21, 22] the ratio $\sigma_{\rm jet}/\sigma_{\rm inelastic}$ can be interpreted as the average number of semihard collisions in one inelastic event. The explicit numbers I will be quoting in the following [8] are obtained with the GRV-LO parton distributions [31] exhibiting a small-x rise similar to that in the HERA data. More detailed formulation can be found in Refs. [4, 8], and a numerical evaluation of Eq. (1) with other parton distributions in Ref. [7].

The above formula is defined in the lowest order, $d\hat{\sigma}/d\hat{t} \sim \alpha_{\rm s}^2$. Often a constant factor $K \sim 2$ is used to simulate the effects of next-to-leading-order (NLO) terms. Studies of the NLO jet cross section $d\sigma/(dp_{\rm T}dy)$ [32] show that (with a scale choice $Q = p_{\rm T}$ and with a jet size $R \sim 1$) this may be a reasonable approximation [33]. Strictly speaking, however, a theoretical K-factor can only be defined for quantities where a well-defined, *infrared-safe* measurement function can be applied [32]. For $E_{\rm T}$-production in nuclear collisions, an acceptance window in the whole central rapidity unit defines such a function, but for this acceptance criterion, and for $p_{\rm T} \sim 2$ GeV, the exact NLO contribution has not been considered yet. For consistency reasons, however, there is no K-factor included in the explicit results I will discuss here.

A first estimate of the average number of produced semihard partons in a rapidity window Δy with $p_{\rm T} \geq p_0$ in an AA collision at a fixed impact parameter $\mathbf{b}$ can be obtained as [4]

$$\bar{N}_{AA}(\mathbf{b}, \sqrt{s}, p_0, \Delta y) = 2T_{AA}(\mathbf{b})\sigma_{\rm jet}(\sqrt{s}, p_0, \Delta y), \qquad (2)$$

and the average transverse energy carried by these partons as [4]

$$\bar{E}_{\rm T}^{AA}(\mathbf{b}, \sqrt{s}, p_0, \Delta y) = T_{AA}(\mathbf{b})\sigma_{\rm jet}(\sqrt{s}, p_0)\langle E_{\rm T}\rangle_{\Delta y}, \qquad (3)$$

where $T_{AA}(\mathbf{b})$ is the nuclear overlap function. The normalization is $\int d^2\mathbf{b}T_{AA}(\mathbf{b}) = A^2$, and since $T_{AA} \sim A^{4/3}$, it describes the typical scaling of hard processes in nuclear collisions. For large nuclei with Woods–Saxon nuclear densities, $T_{AA}(\mathbf{0}) \approx A^2/(\pi R_A^2)$. The acceptance criterion Δy will be $|y| \leq 0.5$, and corresponding cuts will be made for y_1 and y_2 [6]. In Eqs. (2) and (3) above, $T_{AA}(\mathbf{b})\sigma_{\rm jet}$ is the average number of semihard collisions and $\langle E_{\rm T}\rangle_{\Delta y}$ is the average transverse energy carried by the partons produced in each of these collisions into Δy. Parton-flavour decomposition and rapidity distributions can be found in [8].

In Figs. 1, the integrated jet cross sections and the first $E_{\rm T}$-moments for $\sqrt{s} = 5500$ and 200 GeV are shown as functions of the smallest transverse momentum p_0 included in the computation. These quantities naturally depend strongly on the choice of p_0 since the subcross sections diverge as $d\hat{\sigma}/d\hat{t} \sim p_{\rm T}^{-4}$ when $p_{\rm T} \to 0$. Since p_0 is a parameter that decides the division between soft and hard physics, by definition some phenomenology is needed to fix its value. One way to have control over p_0 is to study an eikonal model [22], where the lower limit of p_0 (and simultaneously a possible K-factor) is controlled by the rise of the cross sections. In addition, by fitting measured charged particle spectra in hadronic collisions at high energies, it is possible to extract a value for p_0 in connection with a string model [26]. Also, convoluting the partonic cross sections with fragmentation functions of each parton flavour into charged pions and kaons [35] gives a simultaneous handle (in the LO) on the K-factor at large $p_{\rm T}$ and on p_0 at the small $p_{\rm T}$ part of the charged particle $p_{\rm T}$-spectra. These procedures result in values $p_0 \sim 2$ GeV.

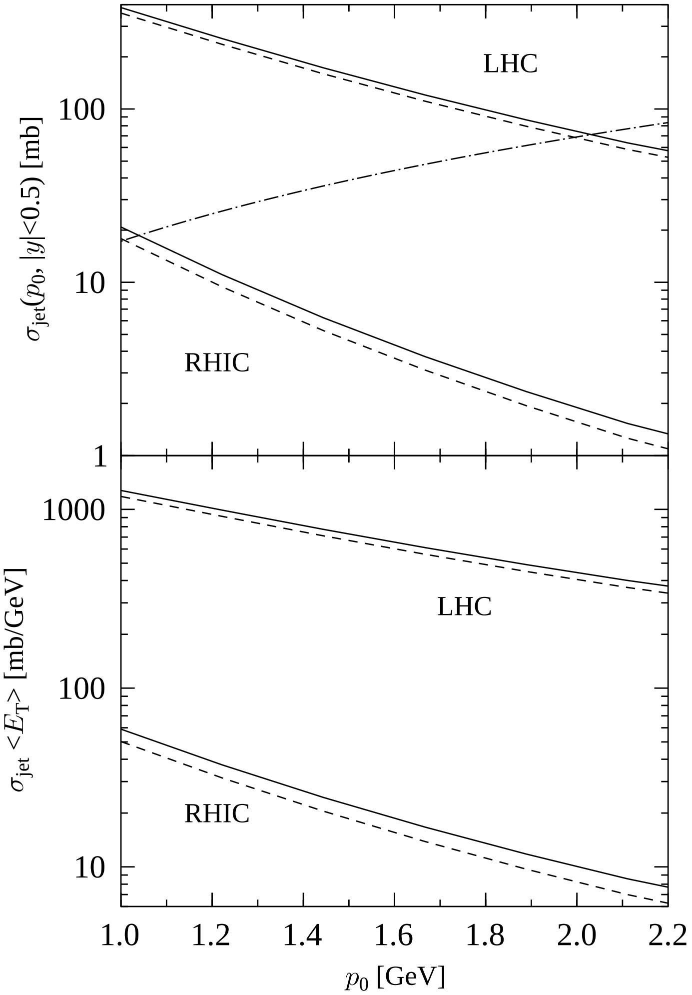

Figure 1: The integrated minijet cross section $\sigma_{\rm jet}(p_0, \sqrt{s}, |y| \leq 0.5)$ and the first $E_{\rm T}$-moment $\sigma_{\rm jet}(\sqrt{s}, p_0)\langle E_{\rm T}\rangle_{\Delta y}$ as functions of p_0 at $|y| \leq 0.5$ at LHC ($\sqrt{s} = 5500$ GeV) and RHIC ($\sqrt{s} = 200$ GeV) from Eqs. (2) and (3). The dashed curves are the gluon contributions, the dot-dashed curve shows the transverse saturation limit for $A = 208$. Shadowing is not included and $K = 1$.

In URHIC then, if sufficiently many partons (mainly gluons) are produced in the very beginning of the collision, the partons (within Δy) start to overpopulate the available nuclear transverse area $\sim \pi R_A^2$, and final-state fusions become important [5, 24]. In this case, further production of partons, especially the transverse energy production, becomes screened. Let us assign an effective transverse area (uncertainty) $\pi/p_{\rm T}^2$ for each parton produced within $|y| \leq 0.5$. Since the partons dominantly have $p_{\rm T} \sim p_0$, we can estimate [8] that a saturation in the semihard parton production in URHIC should happen when $N_{AA}(p_0, \sqrt{s}, |y| < 0.5)\pi/p_0^2 \gtrsim \pi R_A^2$, *i.e.* when

$$\sigma_{\rm jet}(\sqrt{s}, p_0, |y| \leq 0.5) \gtrsim \frac{R_A^2 p_0^2}{2T_{AA}(\mathbf{0})} \sim A^{-2/3} p_0^2, \tag{4}$$

so the larger the nucleus is, the earlier the saturation will occur. The saturation value is plotted in Fig.1 for $A = 208$. The saturation of the minijet production cross section can be expected near $p_\mathrm{T} \sim 2$ GeV for the LHC and near $p_\mathrm{T} \sim 1$ GeV for the RHIC. Therefore, for the LHC, the bulk of transverse energy in the central rapidity unit is expected to come from the semihard processes alone, so $p_0 = 2$ GeV is a reasonable choice for the LHC. The eikonal model and the fragmentation function analysis indicate that a choice $p_0 = 1$ GeV would result in an overestimate of the (inelastic) cross sections and the charged particle p_T-spectra. Instead of trying to fit this value any better for the RHIC, we will consider here the initial conditions for QGP production with the same value $p_0 = 2$ GeV as for the LHC.

Self-consistent screening of initial parton production can also be modelled in terms of a dynamical, medium-induced screening mass [25]. The midrapidity partons are produced at times $\tau \sim 1/p_\mathrm{T}$, so the large-p_T partons are produced first, and partons with smaller p_T are produced later. In a medium of high-p_T partons, a dynamical screening mass (electric, static) m_g [34] is generated, and this mass then screens the production of partons with smaller p_T. If the density of produced partons is high enough, *i.e.* if the $\sqrt{s}$ and A are large enough, the screening mass grows fast enough, causing a saturation of the parton cross section already in the perturbative regime $p_\mathrm{T} \gg \Lambda_\mathrm{QCD}$. In practice, since the transverse part of the screening is not known, we have modelled the screening by simply making the replacement $\hat{t}(\hat{u}) \to \hat{t}(\hat{u}) - m_g^2$ in the partonic cross sections. Saturation in this approach coincides with Eq. (4), and, by computing the first moment of the p_T-distributions, one also concretely observes how the bulk of transverse-energy production is obtained from $p_\mathrm{T} \geq 2$ GeV at the LHC (see [25]).

To conclude this section, I will discuss nuclear parton distributions. In the computation presented above, these are approximated as $f_{i/A}(x, Q^2) = A f_{i/p}(x, Q^2)$. Clearly, this gives a fair first estimate. It is, however, experimentally known that there are nuclear effects to the parton distributions. In the DIS measurements [36, 37, 38], the ratio $F_2^A(x, Q^2)/F_2^D(x, Q^2)$ has been measured, and four regions in x can be distinguished: depletion at $x \lesssim 0.1$ called "nuclear shadowing", enhancement at $0.1 \lesssim x \lesssim 0.3$ called "anti-shadowing", depletion at $0.3 \lesssim x \lesssim 0.7$ called "emc-effect", and cumulative enhancement at $x \to 1$ (and beyond) called "Fermi motion". See Ref. [39] for an extensive review of the experimental data and the various theoretical models.

For the mid-rapidity minijet production, practically only the shadowing region is relevant. It is experimentally observed that the F_2-ratio does not strongly depend on the virtuality Q^2, so a scale-independent ratio may give a first estimate of the nuclear effects to the nuclear quark and antiquark distributions. However, as shown in [41], it is not necessarily so for the gluons, but the QCD scale evolution [44] should be taken into account in more detail. In Fig. 2, I show the evolution of ratios $R_i^A(x, Q^2) = f_{i/A}/A f_{i/p}$ separately for gluon, valence- and sea-quark distributions, and for F_2, from [41]. In this analysis, charge and momentum sum rules are incorporated with the DIS data [38, 37] and the dilepton data [40]. A reanalysis with more modern parton distributions is being prepared [42]. It is also becoming possible to extract the gluon distributions from the logarithmic derivatives of $F_2^{A_1}/F_2^{A_2}$ [43], so further constraints for the badly known nuclear gluon distributions are available. The scale evolution of nuclear parton densities has also been studied by other people, see Refs. [47]. Finally, the role of the GLRMQ correction terms [24, 45] (which were included in [41]) to the DGLAP equations [44] should also be considered in more detail, perhaps along the lines in Ref. [46], but in the light of the most recent HERA-data [13]. To get an idea of the magnitude of

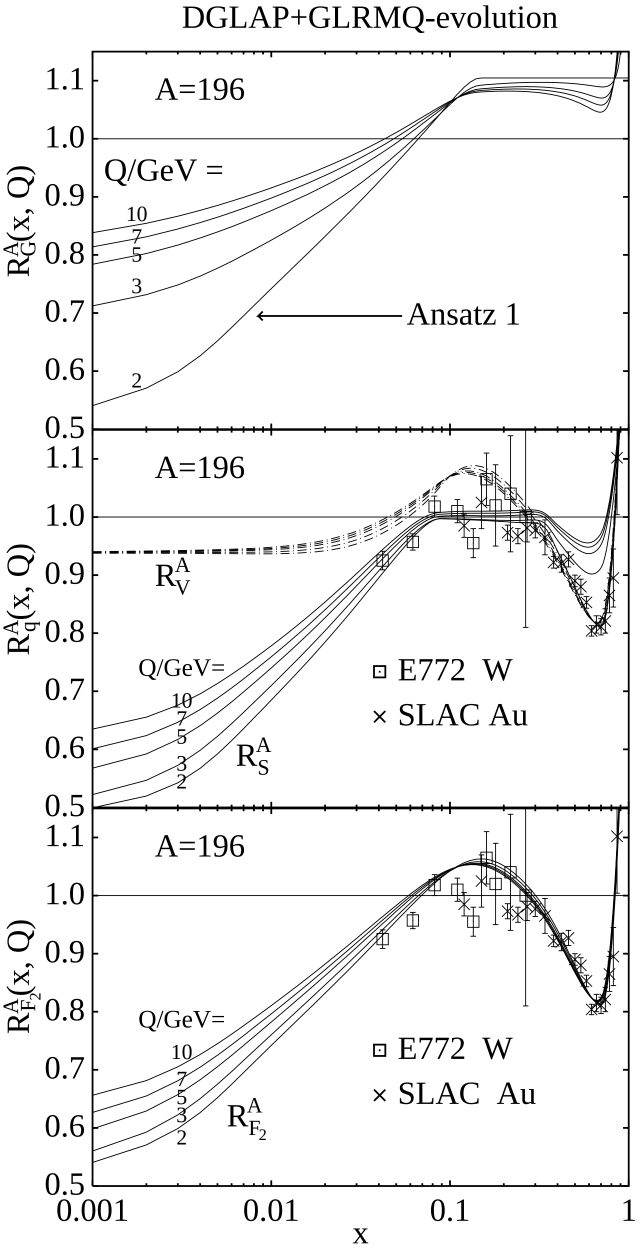

Figure 2: The ratios $R_i^A(x,Q^2) \equiv f_{i/A}(x,Q^2)/Af_{i/p}(x,Q^2)$ of $i = g$, $V(= u_V + d_V)$, $S(= \sum[q_S + \bar{q}_S])$, F_2 for $A = 196$, as functions of x at scales $Q = 2, 3, 5, 7, 10$ GeV [41]. The evolution is lowest order DGLAP, modified with the GLRMQ terms, and the data shown are from [40, 37]

	$\lvert y\rvert < 0.5$	total	g	q	$\bar{q}$
LHC:	$\bar{N}_{\rm PbPb}$	4740	4349	199.9	191.2
	$\bar{E}_{\rm T}^{\rm PbPb}$	14170	12960	620.8	588.8
RHIC:	$\bar{N}_{\rm PbPb}$	120.6	99.58	12.96	8.102
	$\bar{E}_{\rm T}^{\rm PbPb}$	320.7	262.8	36.06	21.87

Table 1: The average numbers and transverse energies of semihard partons at $\tau = 0.1$ fm/c with $|y| \leq 0.5$ and $p_{\rm T} \geq 2$ GeV in central Pb–Pb collisions, as given by Eqs. (2) and (3). No shadowing nor K-factor is included and the GRV-LO [31] parton distributions are used.

the shadowing effects in minijet production at the LHC and RHIC, I refer the reader to the computation in [41].

2 Initial conditions for QGP at $\tau = 0.1$ fm/c from pQCD

As described in the previous section, we obtain a first estimate of the initial conditions of QGP production by fixing the minimum $p_{\rm T}$ as $p_0 = 2$ GeV. In this way, we describe the initial conditions at $\tau \sim 1/p_0 = 0.1$ fm/c. The predictions for the average numbers and transverse energies of partons produced into the central rapidity unit in central Pb–Pb collisions at RHIC and LHC energies are summarized in Table 1 (with even too many decimals). Also individual contributions from gluons, quarks and antiquarks are indicated [7]. There are five quite straightforward but important observations:

- Gluons strongly dominate the perturbative parton and transverse energy production: the initial parton system at $\tau = 0.1$ fm/c is about 90% glue in the LHC and 80% in the RHIC, so that at early times the QGP is actually gluon plasma to the first approximation.
- As discussed in Sec. 2, the parton system at the LHC is transversally saturated at $\tau = 0.1$ fm/c, within the central rapidity unit. This means that production of more (softer) partons increases mainly the rate of final state fusions, not so much the transverse energy production. At the RHIC the same will happen but at a somewhat later stage which may not be entirely controllable by means of pQCD. In any case, it is demonstrated that the parameter p_0 acquires a *dynamical* significance in the URHIC.
- By assigning baryon number 1/3 ($-1/3$) for each quark (antiquark) produced, and by approximating the volume of the parton system by $V = \pi R_{\rm Pb}^2 \Delta y / p_0 = 13.4\,{\rm fm}^3$ for Pb–Pb, the initial net baryon number density at $\tau = 0.1$ fm/c becomes $n_{B-\bar{B}} = 0.21\,{\rm fm}^{-3}$ for the LHC, and, $0.12\,{\rm fm}^{-3}$ for the RHIC. Thus, even at these ultrarelativistic energies the initial net baryon number density is comparable to the nuclear matter density, $0.17\,{\rm fm}^{-3}$, even beyond it at the LHC.[8] Of course, the high initial net baryon density

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[8] Note that by the time $\tau = 0.1$ fm/c, the Lorentz-contracted nuclear disks (the hard parts) are already receding; the transit time of the nuclei is $\tau_{\rm T} \sim 2R_A/\gamma \sim 5 \times 10^{-3}$ fm/c for the LHC and 0.1 fm/c for the RHIC.

will dilute quite fast, but it is interesting that the pQCD computation gives such a high initial density. One would perhaps expect more baryon stopping at RHIC than at LHC. I should emphasize that the number presented here is only the perturbative part of net baryon number and that the increase for the LHC is entirely a gluon distribution effect because the perturbatively produced net quark number in the central rapidity region is mainly due to valence quark–gluon scattering. The typical values of x probed at the LHC are smaller than at the RHIC, so, because of the rapid rise of the gluon densities, there are many more gluons for the valence quarks to scatter with at the LHC than at the RHIC.

- To what extent can the initial system be considered thermalized? One immediately observes that there are far too few quarks and antiquarks as compared to gluons, so that the system cannot be in chemical equilibrium. How about the gluons alone then? In an ideal thermal gas of massless bosons the energy/particle is determined by $\epsilon_g/n_g = 2.7T_{\rm eq}$. From the numbers for the LHC in Table 1 we can determine that

  $$\frac{\bar{E}_{\rm T}^g}{\bar{N}_{\rm PbPb}^g} = \frac{\epsilon_g^{\rm pQCD}}{n_g^{\rm pQCD}} = 2.98\,{\rm GeV}. \tag{5}$$

  In an ideal gas of massless gluons in complete thermal equilibrium, the temperature can be computed from $\epsilon_g^{\rm ideal} = 3\pi^2/90 \cdot 16T_{\rm eq}^4$, and for an ideal gas with an energy density $\epsilon_g^{\rm ideal} = \epsilon_g^{\rm pQCD}$ we find $T_{\rm eq} = 1.10$ GeV. We see that

  $$\frac{\epsilon_g^{\rm pQCD}}{n_g^{\rm pQCD}} \approx \frac{\epsilon_g^{\rm ideal}}{n_g^{\rm ideal}} = 2.7T_{\rm eq}. \tag{6}$$

  So, as far as the energy per particle is concerned, the gluon system is “thermalized” from the beginning at the LHC. At the RHIC, this is likely to happen somewhat later. One should, however, keep in mind that we did not consider isotropization at all here, and, that some uncertainty is connected with the assumption on an isotropization time. In order to estimate this time, a more detailed space-time picture of initial parton production is needed. Such a modelling is presented *e.g.* in Refs. [48, 29].

- Finally, let us consider the initial net baryon-to-entropy ratio of the early QGP. For a thermal boson gas $s = 3.60n$, where n is the number density of thermal gluons, the total initial entropy (glue only) is $S = 15900$ for the LHC; so initially, at $\tau \sim 0.1$ fm/c, the net baryon-to-entropy ratio is $(B - \bar{B})/S \sim 1/5000$. For the RHIC it will be larger, about 2/1000. In the further evolution of the QGP, this number will increase somewhat due to the non-perturbative net baryon production; we estimated the final $(B-\bar{B})/S \sim 8\times10^{-4}(9\times10^{-3})$ for the LHC (RHIC) [8]. Even though we are studying the same phase transition as took place in the early Universe, we are still relatively far away from those extreme conditions regarding $(B-\bar{B})/S$; there, the inverse of the specific entropy is $\sim 10^{-9}$.

3 Beyond the factorized minijet approach

The simple approach of Sec. 2 without shadowing effects in the parton distributions will fail at large rapidities when sufficiently high cms-energies and large nuclei are involved (see [8]). Minijet production at large y is a consequence of a few large-x partons scattering against a large number of small-x partons. Due to the rapid rise of the gluon distributions at small values of x, and without shadowing, the parton luminosity is high and the cross sections at large y are not suppressed enough for the assumption of independent scatterings to hold. Eventually, since $T_{AA} \sim A^{4/3}$, one will run into trouble in conserving energy and baryon number (which scale as $\sim A$) for a large enough A and $\sqrt{s}$. In this case, coherence effects should be considered. However, within the central rapidity unit, where our focus is, the assumption of independent parton scatterings still works quite well: only energy $\sim \mathcal{O}(N_{AA} \times 2p_0) \lll A\sqrt{s}$ is consumed, and only a fraction of the available number of partons will scatter. Naturally, the latter criterion also serves as a further constraint for the value of p_0 in URHIC. I should also emphasize that the approach will work even better once nuclear (gluon) shadowing is included.

The question of the validity of factorization in minijet production in URHIC is, however, an important one, and additional production mechanisms should be studied. During the recent years, quite a different approach to minijet production has been developed, not based on factorization. McLerran and Venugopalan [10] have suggested a model where a large colour charge density of a large nucleus, travelling along the light-cone, generates a gluon field that is effectively classical. The idea then is that the gluon distribution function of the nucleus (perhaps even hadrons) could be computed in the region $\Lambda_{\rm QCD} \ll k_{\rm T} \ll \mu$, where $k_{\rm T}$ is the transverse momentum of gluons, and the scale μ^2 is the area-density of gluons per unit rapidity. Connection of this approach to evolution equations, especially to the BFKL [50], has been considered in [54]. The actual collision of two nuclei has been formulated in [55], and connection of the classical approach to Feynman diagrams has also been recently studied [56]. Also the connection to the BFKL-type minijet formula [52, 9] is under investigation [57]. It remains to be seen what the predictions of the gluon field approach eventually are in actual numbers for URHIC, and how well the gluon distributions and their QCD evolution in nuclei and hadrons are accounted for. In my opinion, it is very important to pursue this work into the direction outlined in [57], where the applicability of the model to URHIC at the LHC and RHIC was studied in more detail. Ultimately, one could hope that while collinearly factorized minijets dominate parton production at $p_{\rm T} \gtrsim p_0 = 2$ GeV, the region of $\Lambda_{\rm QCD} \lesssim p_{\rm T} \lesssim p_0$ (where also non-linear effects will eventually become important) could become better under control in terms of the BFKL and/or gluon field approach.

Minijets can also be emitted from a BFKL ladder [52][9]. By assuming that the small-x increase in F_2 is *entirely* due to the BFKL physics [50], the *maximum* transverse energy deposit in the central rapidity region due to the minijets from a BFKL ladder can be studied. This was done in [9]. Since the increase in F_2 takes place only at $x \lesssim 0.01$, the BFKL mechanism is not expected to be important in the RHIC nuclear collisions.

Minijet production without high-$p_{\rm T}$ tagging jets requires an introduction of unintegrated

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[9] See the useful lecture notes by Del Duca [51] for a derivation of the basic concepts and for original references.

parton densities, which evolve according to the BFKL equation [50] (assumed to be homogeneous [53]), and which can be normalized to the "known" gluon distribution $xg(x, Q)$. Effectively, minijet production from a BFKL ladder can be considered as an $\mathcal{O}(\alpha_s)$, $2 \to 1$ process where two virtual gluons fuse and form the minijet in the mid-rapidity. Technically, this minijet is just one fixed rung of the BFKL ladder (the emitted gluons of which are strongly ordered in rapidity). In [9], we were unable to fix the overall normalization of the process, in the absence of any perturbative Born-level process to compare directly with. By comparing the BFKL computation with the factorized jet-production cross section (in the lowest order) at high $p_{\rm T}$, we were, however, able to argue that the transverse energy production from the BFKL minijets is still subleading at the LHC energies.

Since the HERA results for the increase of F_2 at small x can be explained by the leading $\log(Q^2)$ [44] and/or the leading $\log(Q^2)\log(1/x)$ [49] approximations, the leading $\log(1/x)$ BFKL contribution is obviously *not* the dominant mechanism at the present values of x. Thus, my conclusion at this point is that the BFKL minijets certainly bridge the way towards softer physics at $p_{\rm T} < p_0 \sim 2$ GeV, but the initial conditions relevant for the early QGP formation in the LHC nuclear collisions seem to be dominantly given by the minijets computed in collinear factorization.

4 Further evolution of the minijet plasma

It is very important to understand when and how well the early parton system can be described in terms of hydrodynamics [59]. Not only the thermal signals, but also global variables such as final transverse energy and total multiplicity will strongly depend on the onset of pressure and flow effects. Normally, in hydrodynamical calculations the measured final-state hadron spectra are used for getting an estimate of the initial conditions (see *e.g.* [58]). These then, by definition, depend on the equation of state used. Semihard parton production could now provide the hydro codes with additional and independent information on the early initial conditions. Of course, validity of applying hydrodynamics to the early QGP ultimately depends on how completely and how fast the initial parton system reaches a state of local thermodynamic equilibrium.

I have explicitly shown by using pQCD, how thousands (hundreds) of partons, mainly gluons, will be produced within $\tau \sim 0.1$ fm/c into the central rapidity unit of URHIC at the LHC (RHIC). For the LHC, the perturbative gluon system is shown to be transversally saturated and thermalized in the energy/particle sense. This indicates that already the early evolution of the QGP in the LHC could perhaps be described in a simple hydrodynamical approach [59]. Initially produced perturbative partons do not necessarily, however, have boost-invariant rapidity distributions [8]. By making an extreme assumption of having a locally thermal (gluon) system at $\tau \sim 0.1$ fm/c, and by using the rapidity distributions as computed in [8] for the initial conditions, it is possible to study the deviations from a boost-invariant Bjorken picture. In [60] it is shown that the arising pressure gradients generate somewhat faster cooling of the (Q)GP as in the Bjorken picture.

At the RHIC also the soft component in particle and transverse energy production should be taken into account. A possible modelling for this as a source term in Bjorken hydrodynamics, on top of the minijet initial conditions, was suggested in [20], and also effects of dissipation and colour conductivity were studied. More complicated 3-dimensional systems with minijet initial conditions and density fluctuations have been considered in [61].

Related both to the initial conditions and to the further evolution of the QGP, a more difficult and still open question is thermalization of quarks, *i.e.* how fast, if at all, quarks and antiquarks come into chemical equilibrium with gluons [62]. Phenomenologically, this subject is vital for the thermal electromagnetic signals [63]. Theoretically, the issue is space-time dependent phenomena in gauge theories, a virtually uncharted territory.

5 Conclusions

So far, the diverging minijet cross sections of Sec. 2 can be regulated in URHIC either by a dynamically determined cut-off parameter p_0, or by modelling in a screening mass. These are plausible but phenomenological considerations. Unless more theoretical progress in understanding pQCD parton scattering in the few-GeV range is made, these will remain so. A quantitative study of the NLO terms in the minijet cross sections, especially in transverse energy production, will certainly give us a better handle on the validity of pQCD at these scales. A resummation, as in the Drell-Yan dilepton case [64], will perhaps become possible eventually. As discussed in Sec. 2, the nuclear gluon distributions are also poorly known; ultimately they should be measured better. Coherent scattering and higher-twist effects should be studied in more detail, at large rapidities especially.

The main results given in Secs. 2 and 3 are obtained by using collinear factorization and independent parton–parton scatterings. Minijets from the classical gluon field approach and from the BFKL ladder discussed in Sec. 4 are not based on factorization. By studying the upper limit of minijet production from the BFKL ladder, we were able to argue [9] that the BFKL-mechanism should still be subleading in $E_{\rm T}$-production at the central rapidities, at least up to the LHC energies. Connection of the gluon field and BFKL approaches with the collinearly factorized minijet production should still be understood better [57].

To conclude, it is clear that the analyses of semihard parton production discussed in this article can, and will be, sharpened in various ways. I have, however, no doubt that the semihard partons will play a major role in the formation and evolution of the QGP in central rapidities during the first fractions of fm/c of the LHC and RHIC nuclear collisions. Understanding the primary production mechanisms of partons will be the key to predicting and explaining the signals of the QGP and more global variables measured in the future heavy ion collisions at LHC and RHIC.

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