PROSPECTS OF ULTRA-RELATIVISTIC
HEAVY ION COLLISIONS

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ABSTRACT

A review of theoretical models and experimental features of Quark-Gluon Plasma (QGP) phenomenology has been given in this article. String models for incoherent particle production in nucleus-nucleus collisions have been discussed with a comparison of their main features. Experimental results in relation to the model calculation and QGP signatures are analysed. Suggestions have been put forward for the new experiments.

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1 Introduction

Of the many phase transitions that are studied in particle physics and cosmology, the confinement transition of quantum chromodynamics (QCD) is one of the least understood theoretically. Though the non-perturbed features of QCD such as confinement have not yet been rigorously established, it is widely believed on the basis of Lattice Monte Carlo that at either high temperature or high densities normal hadronic matter undergoes a phase transition to a new confined state of matter, the Quark Gluon Plasma (QGP) formed by the basic constituents of the hadrons i.e., the quark and gluons [1]. Estimates of the critical temperature and density are \( T_c \approx 200 \text{ MeV}, \rho_c \approx 2 - 3 \text{ GeV/fm}^3 \) [2]. Now the physical environments in which these conditions on the temperature and density can be achieved are known to be: the early universe [3], the cores of neutron stars [3] and the heavy ion collisions [4]. It can immediately be understood that the best chance for actually studying the properties of QGP is in the laboratory by colliding the heavy ions [4]. This phase transition has not only an intrinsic importance, but also its finding in laboratory, particularly in heavy ion collisions at very high energies, could enlighten the development of the collision process in space time. Phenomenological estimates of various kind also suggest that ultra-relativistic heavy ion collisions (URHIC) provide the best way to produce such extreme conditions in the laboratory for QGP formation [26]. It is the prospect of simulating such process in the laboratory of creating quark matter, and watching it freeze into hadrons, that make the URHIC a subject of such fundamental importance.

In recent years, one of the more active fields in particle physics has been that of identifying reliable signatures of the QGP formation in URHIC. But, there is no theory available to describe the background in heavy ion collisions necessary to amplify the phase transition signals, because we do not know how to apply the QCD to soft processes (small momentum transfer), which are the bulk of the events taking place in heavy ion collisions. QCD based phenomenology has, therefore, been introduced by extrapolating the ideas developed for the hadron-hadron and hadron-nucleus interactions, correctly describing the soft nucleus-nucleus collisions the best way to analyse these questions.

The Quark-Parton Model [5], the Quark Model [6], the Additive Quark Model [7, 8], the Constituent Quark Model [6], the Multichain Model [9], and the Wounded Nucleon Model [10] are a few examples to quote that look at the dynamics of quark matter. The later and the more popular, however, are the Lund Model [11] and the Dual Parton Model.
There are several Monte Carlo programs based on Dual Parton Model (DPM) for incoherent nucleus-nucleus collisions. They are IRIS [14], VENUS [15], QGSM [16] and Dual Multichain Monte Carlo [17]. Closer to DPM are PYTHIA [18] and HIJING [19]. These DPM Monte Carlo use different codes for fragmentation functions, but are all applicable to nucleus-nucleus collisions. Other Monte Carlo codes for Lund Model are FRITIOF [20], ATTILA [21], SMP [22], COJET [23], EUROJET [24] and ARC [25]. One of the main motivations of writing these programs has been to reliably compute what we are expected to get in nucleus-nucleus collisions.

A first generation of experiments has been done during the last few years; such as E802, E810 and E814 at Brookhaven with Si$^+$ and S$^{32}$ ions at 14.5A GeV, and NA34, NA35, NA36, NA38, WA80 and WA85 at CERN, in addition to the emulsion experiments EMU01 to EMU10, with O$^{16}$ and S$^{32}$ ions accelerated to 60A GeV and 200A GeV energies. The experimental work at the CERN energies was almost completed by 1991 [26]. Except for some latest results to quote from the experiments [27-32], and model calculations of the data from the experiments completed at CERN [33, 34], nothing striking has been reported during the last couple of years to understand the QGP phase transition. However, from the available data it is easy to conclude that of the QCD based phenomenological string models the Additive Quark Model [7], Lund Model [11] and the DPM [12, 13] explain certain important features of the reaction dynamics reliably. Moreover, the temperature of about 200 MeV and energy density of about 2 GeV/fm$^3$ are already known to have been reached in S$^{32}$ collisions at the incident energy of 200A GeV [26]. The proposed signals like strangeness enhancement, multiplicity fluctuations, $p_T$ enhancement, $J/$ suppression and dilepton emission etc., have also been achieved, but explanations other than QGP have been given [35]. Thus at the moment it can only be conceived that we do seem to produce very dense matter. But to decide whether it is "still" hadronic matter or "already" a Quark Gluon Plasma (QGP), we need some more experimental information.

From the foregoing discussion it becomes evident that we still lack a real understanding of the quark structure of matter and of the phenomena in high energy physics, and hence need to know more about the QCD phase transition. In some models doubts were cast on the QGP formation in URHIC [36, 37], but the latest calculations [38-40] still support the idea. The string models inspite of their fairness cannot fully explain features of URHIC in their entirety. Several are the signatures of the QGP formation which have not been completely rejected. Thus it is still an interesting subject to study whether the QGP phase transition does take place and if so what is the order of transition.

At present new experiments are being planned because URHIC are still believed to provide a way of producing the QGP related conditions in the laboratory [41], and the facility for larger ions is expected at CERN during 1994-95 [42]. The first aim of the new experiments should be to survey the general properties of URHIC by model calculations. Any deviation would signal the onset of a new physics. The second aim should be to explore specific probes of QGP once the general features of the reaction dynamics are understood. It is worth considering, therefore, to review the whole situation with respect to the reaction dynamics, suitability of models, and QGP formation signatures.

In this review we present our understanding of the QGP phenomenology with reference to the above stated features of URHIC. We present a comparison of the string models, discuss the experimental outcome in respect of the reaction dynamics and signatures for QGP formation, analyse the latest theoretical predictions, and finally make suggestions for the future experiments.

This article has been arranged in the following manner. In Section 2 we briefly discuss the string models giving a comparison between them. In Section 3 we consider some experimental results regarding the reaction dynamics to see which of the models could reproduce them successfully. Section 4 is devoted to the experimental status of QGP signals. In Section 5 we review the latest developments in the field. Section 6 deals with the future experiments and suggestions thereon.

2 The String Models

In the search of quark-gluon plasma, it is necessary to have some models which describe reasonably well the dynamics of nucleus-nucleus collisions in order to identify the possible signatures of quark-gluon plasma formation from the "classical background". Many models have been proposed to understand some observables or some phenomena of this classical background, but only a few of them have been extensively applied to understand the nucleus-nucleus collisions and the variety of observables measured related with such interactions. Here we concentrate on some of the successful models, the Dual Parton Model [12, 13], Fritiof [11, 20] and the Additive Quark Model [7], making a comparison between them, with some other models and with the experimental data, for any attempt to apply them in the future experimental investigations. It would be interesting to know what kind of modifications occur in different observables if some unorthodoxal pieces are added to these models in order to see true signatures of QGP.
In contrast to the hydrodynamical/thermodynamical models which are based on coherent nuclear collisions: each nucleus interacts as a whole, the models under discussion take into account the incoherent mechanism: there is no collective effect and the collision is a succession of independent nucleon-nucleon collisions. Following in the footsteps of Bialas [43] we start by illustrating some data from proton-proton and proton-Xe collisions [44] shown in Fig. 1, which exhibit characteristic features. The maximum in target fragmentation region exceeds several times the value of \( \nu \) the average number of inelastic collisions of the projectile inside the nucleus. Thus the fast secondaries do not interact in nuclear matter, as they are formed outside of the nucleus, the reason being very long formation time needed for creation of a fast hadron. A hadron takes on the average a certain time \( \tau \) in its rest frame for formation. In other frame the required time is, \( \tau = \gamma \tau_0 \), where \( \gamma \) is the Lorentz factor (for time dilation) of the produced hadron. For a high energy hadron the Lorentz factor and formation time \( \tau \) might be very large. Different models propose different detailed mechanisms leading to this effect. One important consequence of this effect is that, at high energies, the particle production process (hadronization) is not directly related to the collision process, as they are separated by a large time interval. When applied to hadron-nucleus collisions, this statement implies that the description of particle production need not be a simple reflection of multiple scattering of the projectile inside the nucleus. Needless to say, the existing models take advantage of this possibility.

Having accepted and explained the absence of cascading in the central region of rapidity, we nevertheless have to account for a moderate increase of the multiplicity in this region. The very presence of this increase indicates that there must be more than just one collision of the projectile in target nucleus. On the other hand, the data are clearly below the value of \( \nu \) and thus they cannot be explained trivially by multiple collisions in one collision of the projectile in target nucleus. On the other hand, the data are clearly below the value of \( \nu \) and thus they cannot be explained trivially by multiple collisions in the nuclear matter. The explanation of data in this region is the major goal for all the models.

For nucleus-nucleus collisions, these general observations have one extremely important consequence: Since the nuclei seem rather transparent to high energy hadrons, we expect similar transparency in collisions between high energy nuclei. Thus, even in a head-on collision we do not expect the nuclei to stop in the centre of mass system, but rather to pass through each other relatively unperturbed. The complicated process of production of energetic particles and of consequent slowing down of the projectile takes place later – with relevant Lorentz factors determining this “formation time”. Thus the emerging picture seems quite different from that of low-energy nuclear collisions.

The general picture of an inelastic hadronic interaction is thus a multistep process: first we have one or several low momentum transfer collisions between the scattering objects. This phase takes a rather short time – approximately the time needed for the scattering objects to pass through each other. As a result of this first step an intermediate state is created. This intermediate state lives a fairly long time (depending on the energy of the system) before it hadronizes in the third and final step. Such a complicated situation has led, naturally, to several different ideas on possible mechanisms of this process, on the nature of the intermediate state and on its possible time evolution. Several models were proposed based on these convictions but we shall consider only those which try to incorporate, in different ways, the current ideas of strong interactions as derived from hadron-hadron scattering as well as from theoretical concepts of QCD.

### 2.1 Additive Quark Model

In the additive quark model the non-diffractive nucleon-nucleon interaction starts by exchanging a coloured object (gluon or a system of gluons) between one (constituent) quark from the projectile and one (constituent) quark from the target. In the next step an intermediate state is formed: a coloured string develops between the two “wounded” quarks. Afterwards, the string fragments into hadrons, giving rise to particle production in the central region. Fragmentation of the forward and backward moving spectator quarks populate mostly the fragmentation regions. This is illustrated schematically in Fig. 2. It should perhaps be pointed out here that the fragmentation of the string is a complicated process which itself is (at least) two-step. Presumably, string decays into quarks and gluons which subsequently rearrange and form hadrons. The time at which a given piece of the string fragments depends on relevant Lorentz factor and therefore on reference frame used for the description of the process. In the extensions of this model to nucleon-nucleus collisions one takes into account the possibility that more than one quark from the projectile interacts (i.e. exchange of colour) inside the target nucleus. The model considers wounded quarks, spectator quarks in the projectile, spectator quarks in the target, and coloured strings between the projectile and the target. The phenomenological assumption here is that there is only one string attached to one wounded quark in the projectile (as is seen in Fig. 3). This assumption is usually justified by the observation that the colour content of the coloured system exchanged between one quark (colour triplet) and the nucleus must be that of an octet, independently of how complicated this system is. Since it is likely that the fragmentation of the coloured system is determined primarily
by its colour content, we identify every object extended between one quark and the target with just one string.

Generalization of this picture to nucleus–nucleus collision goes along the same line, and the only problem is to determine the number of wounded and spectator quarks in projectile and target, as well as number of coloured strings extended between them. The average number of strings is calculated as the ratio of the number of quarks attached to one string divided by number of quarks attached to a nucleus. The last number can be determined as the average number of quarks in nucleus with just one string.

In the fragmentation regions which are dominated by spectators, particle production is expected to be determined by number of spectators (i.e. interact inelastically), with a total number of 'n' inelastic collisions taking place. Let $n_{A,B}$, $n_{A,n}$ be the corresponding cross section. Since each inelastic collision produces two chains of hadrons, 2n chains will be produced. The valence fragments available are: $n_A$ valence quarks and diquarks in nucleus $A$, $n_B$ valence quarks and diquarks in nucleus $B$. In the case $n_A < n_B$ the only chain one can form involving these valence constituents are $n_A$ chains of type $(qq)_A - q^B_1$. $n_A$ chains of type $q^A_1 - (qq)_B$. $n_A$ chains of type $q^A_2 - q^B_1$ and $n_B - n_A$ chains of type $q^A_2 - (qq)_B$, i.e. the valence constituents are contained in $2n_B$ chains. The rapidity density in a nucleus $A$–nucleus $B$ collision is then given by

$$N_{AB}(y) = \frac{1}{\sigma_{AB}} \sum_{n_A,n_B} \left( \sigma_{n_A,n_B} \left( \delta(n_B - n_A) \left[ n_A \left( N^{(qq)_A - q^B_1}(y) + N^{q^B_1 - (qq)_B}(y) \right) + (n_B - n_A) \left( N^{q^A_1 - (qq)_B}(y) + N^{q^A_2 - (qq)_B}(y) \right) \right) + (n - n_B) \left( N^{q^A_1 - q^B_1}(y) + N^{q^A_2 - q^B_1}(y) \right) \right) \right)$$

(2)

For $A \ll B$ a good approximation to Eq. (1) is obviously to take

$$N_{AB}(y) = \langle n_A \rangle \left( N^{(qq)_A - q^B_1}(y) + N^{q^B_1 - (qq)_B}(y) \right)$$

(1)

For $A \ll B$ a good approximation to Eq. (1) is obviously to take

$$N_{AB}(y) = \langle n_A \rangle \left( N^{(qq)_A - q^B_1}(y) + N^{q^B_1 - (qq)_B}(y) \right)$$

(1)

In fact this formula gives results remarkably close to those obtained from the exact expression (1) for $A \ll B$. In this way we can compute the double inclusive cross section.
For simplicity we use Eq (2). Squaring this equation and assuming that particles produced in different chains are uncorrelated, we obtain in a straightforward way

\[ \langle N_{\text{AB}}^2 \rangle = \langle n_A \rangle (2D_{w}^2 + D_{w}^2_{v} - D_{w}^2_{v} - D_{w}^2_{v}) \\
+ (\langle n_B \rangle (2D_{w}^2_{v} + D_{w}^2_{v} - 2D_{w}^2_{v}) \\
+ 2(\langle n_B \rangle D_{w}^2 - 4(\langle n_A \rangle^2 \langle n_B \rangle)^2 \\
+ (\langle n_B \rangle^2 (N_{w_{v}w_{v}} + N_{w_{v}v_{v}} - 2N_{v_{v}v_{v}})^2 \\
+ (\langle n_A \rangle^2 (2N_{w_{v}v} - N_{v_{v}v} - N_{w_{v}v})^2 \\
+ 4(\langle n_B \rangle) N_{w_{v}v} (N_{w_{v}v} + N_{v_{v}v} - 2N_{v_{v}v}) \\
+ 4(\langle n_B \rangle) N_{w_{v}v} (2N_{w_{v}v} - N_{v_{v}v} - N_{w_{v}v}) \\
+ 2(\langle n_A \rangle n_B) (2N_{w_{v}v} - N_{v_{v}v} - N_{w_{v}v}) (N_{w_{v}v} + N_{v_{v}v} - 2N_{v_{v}v}) \]

(3)

where \( D_{\text{chain}} = \sqrt{\langle N_{\text{chain}}^2 \rangle - \langle N_{\text{chain}} \rangle^2} \) are the dispersions of the individual chains.

Let us consider next the case of a central nucleus A–nucleus B collision. In the literature, there are many definitions of a central collision. Usually it refers to a collision at zero impact parameter. However, this definition is not suitable to compare with experimental data. We adopt here an experimental definition: central collision is the collision in which there is no fragment of the projectile inside a small veto angle. This definition corresponds to the cross section of having \( A \) wounded nucleons in the projectile and all of them giving rise to a baryon in the final state which is slow enough not to be seen in the veto angle.

According to this definition we have to replace in Eqs (1) to (3), \( n_A \) b A (all nucleons in the projectile are wounded) and \( \sigma_{\text{AA}}, \sigma_{\text{AB}}, \sigma_{\text{BB}}, \sigma_{\text{BB}^*}, \sigma_{\text{BB}^*}^* \), \( \langle n_A \rangle, \langle n_B \rangle \) and \( \langle n_B \rangle^* \) by \( \sigma_{\text{AA}}, \sigma_{\text{AB}}, \sigma_{\text{BB}}, \sigma_{\text{BB}^*}, \sigma_{\text{BB}^*}^* \), \( \langle n_A \rangle^* \) and \( \langle n_B \rangle^* \) respectively. All these quantities are computed using an extension of the method developed by A. Capella et al. [45]. Results have been compared for the reactions \( B + Ag(Br), Ca + Pb, Si + Ag(Ag) \) and \( Ca + C \) reactions in Figs.5 and 6 [46].

Let us make now a comparison of these results with some other model calculations to understand their differences and similarities.

### 2.2.1 Additive Quark Model (AQM)

Many of the predictions of this model are very similar to those of the dual parton model, but differences appear when an extension is made to nucleus-nucleus collision. In Fig.7 the rapidity densities obtained in AQM [47] are compared with the results of the dual parton model. For collisions of heavy nuclei the AQM density is much lower than the one in dual parton model. For \( U – U \) collisions the difference is as large as 50%. One should, therefore, expect larger differences at higher energies. The dual parton model thus has a substantially stronger predictive power than AQM.

#### 2.2.2 Wounded Nucleon Model

In this model [10] the rapidity density for nucleus–nucleus collisions is given by

\[ \frac{dN_{\text{AB}}}{dy} = \frac{dN_{\text{NN}}}{dy} \left( \langle n_A \rangle + \langle n_B \rangle - \langle n_{\text{chain}} \rangle \right) \beta(y) \]  

(4)

where \( \beta(y) \) is a function extracted from particle–nucleus interactions. Eq. (2) of the dual parton model can be written as

\[ \frac{dN_{\text{AB}}}{dy} = \frac{dN_{\text{NN}}}{dy} \left( \langle n_A \rangle + \langle n_B \rangle - \langle n_{\text{chain}} \rangle \right) \left( \frac{N_{\text{NN}} \epsilon_{\text{NN}} (y) + N_{\text{NN}} \epsilon_{\text{NN}} (y)}{N_{\text{NN}} \epsilon_{\text{NN}} (y) + N_{\text{NN}} \epsilon_{\text{NN}} (y)} \right) \]

(5)

The difference between Eqs. (4) and (5) resides in the additional term appearing in Eq. (5). The difference \( \langle n \rangle - \langle n_B \rangle \) is only significant for \( A > 64 \) and \( B > 108 \), where \( A \) and \( B \) stand for nuclei (see Table 1), and the quark–antiquark sea densities are quite negligible outside the central rapidity region, and even there they are practically negligible up to energies around \( \sqrt{s} = 40 \text{ GeV} \). Thus only for collisions between heavy nuclei at very high energies (of the order of \( 2 \text{ T\nu V} \)), the difference between Eqs. (4) and (5) can be significant near \( y = 0 \). For central collisions the difference \( \langle n \rangle - \langle n_B \rangle \) is larger and will be more important.

#### 2.2.3 Multichain Model (MCM)

This model [9] is based on the multiple scattering model of Capella and Krzywicki [48] and is therefore very similar to the multichain dual parton model. The difference comes mainly from the different energy partition among the various inelastic collisions. The treatment of nucleus–nucleus collisions require in this model very drastic approximations. The computation of the observables in central collisions is done at fixed impact parameter 'b' and afterwards an integration over low values of 'b' is performed. Therefore the definition of central collisions is not the one used in the dual parton model.
The results of the model are given in Table 2, and it may be seen that the obtained multiplicities are larger than in the dual parton model. This fact arises mainly from the large value of $\langle n \rangle^2$.

Table 1 Calculated values of wounded nucleons in Wounded Nucleon model for various projectile and target mass combinations

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>$\langle n \rangle$</th>
<th>$\langle n^2 \rangle$</th>
<th>$\langle n_a \rangle$</th>
<th>$\langle n_p \rangle$</th>
<th>$\langle n_c \rangle$</th>
<th>$\langle n_b \rangle$</th>
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<td>64</td>
<td>5.23</td>
<td>10.23</td>
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<td>10.23</td>
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<td>6.46</td>
<td>12.16</td>
<td>11.62</td>
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Table 2 Calculated values of multiplicities in Multichain and Dual Parton models as a function of energy for varying projectile and target mass combinations

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>$E$(TeV/N)</th>
<th>$N^{AC}_{\text{tev}} \times 2$</th>
<th>$N^{90\text{degree}}_{\text{lab}}$</th>
<th>$N$ (MCM)</th>
<th>$N$ (DPM)</th>
<th>$\frac{\sum N_{\text{lab}}}{N_{\text{MCM}}} = 0$</th>
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<td>600</td>
<td>760</td>
<td>-</td>
<td>29.4</td>
</tr>
</tbody>
</table>

In Fig.5(a, b) we show the rapidity densities (broken line), compared with the dual parton model data and with the experimental data. It may be noticed that the rapidity densities in the MCM are symmetric with respect to $y = 0$ while the experimental data are not. From the definition of central collisions used in the DMP there is no reason for symmetry and in fact the DMP results are not symmetric.

Another large difference appears in the dispersions. For Al – Ag or Si – Ag at 0.3 TeV the value of $D$ obtained in the MCM is around 100. In the DPM this value is much smaller, around 20. Again the difference must come mainly from the different definition of central collisions used in the two models, although it may also be due to the drastic approximation in the MCM referred to above.

2.3 Lund Model Fritiof

Both the Lund model and Fritiof originate from the old multiperipheral models and hence in these models the production of particles in hadron-hadron collisions is a two-step process:

(a) the two hadrons are excited

(b) constituents of the two excited hadrons exchange a string as shown in Fig.8.

Now we compare the similarities and also the differences in these two more successful models. In the DPM the string is formed between the constituents of two colliding hadrons. Therefore, there is a colour exchange between the two hadrons which are broken in coloured fragments. The strings are formed between fragments of different hadrons (Fig.8a). In Fritiof the strings are formed between the constituents of the same hadron and hence there is no colour exchange. The interaction produces an exchange of momentum between the incoming hadrons. The strings are formed between fragments of the same hadron (Fig.8b).

In DPM the slow quarks of the leading diagram, which are valence quarks, have a $1/\sqrt{s}$ momentum distribution. In Fritiof the slow quarks behave like $1/x$. (In DPM there are other slow quarks, the sea quarks, which appear in subsequent collision behaving like $1/x$.) Subsequent contributions in DPM come from $4,6,\ldots 2n$ chains ($n$ is the number of inelastic collisions) due to unitarity. Unitarity controls such corrections and it is fundamental in DPM. In Fritiof the corrections to the leading diagram come from the inclusion of soft gluon emission which results in a bent string and from the inclusion of hard parton-parton scattering infrared stability is guaranteed and it is fundamental in Fritiof.

In nucleus-nucleus collisions [49], if we have $n$ inelastic collisions and $n_A$ and $n_B$ are respectively the number of interacting nucleons of nucleus $A$ and nucleus $B$, $n_A + n_B$ chains
of type $qq$ (diquark–quark) are formed in both models. These $n_A + n_B$ chains in DPM are $2n_A$ of type $qq$ and $n_B - n_A$ chains of type $q - q$. In addition to these $n_A + n_B$ chains, in DPM, $2n - n_A - n_B$ chains of type $q - q$ are formed. These $2n - n_A - n_B$ are $(2n - n_B)$ of type $q_B - q_B$ and $n_B - n_A$ of type $q_A - q_A$.

The main difference between the two models comes from the $2n - n_A - n_B (q - q)$ chains contributing to the central rapidity region. It is in this region and for central collisions where $2n - n_A - n_B$ is large and therefore where differences should be seen. In the fragmentation regions, where there are no $q - q$ chains, both models give similar predictions. Also some differences appear in the leading baryon spectrum [12, 50] (nuclear stopping power) due to the different momentum carried by the valence quarks and by the diquarks as in Figs.9 and 10.

3 The Experimental Status

We now present some experimental results at CERN energies and discuss their comparison with the model calculations.

3.1 CERN Experiments

In Fig. 11 we show the rapidity distribution for central, medium and peripheral collisions [51], compared with Fritiof and DPM results. The results of DPM were obtained by Pansart with the M-C event generator without including cascade [14]. Also Fritiof does not include it. It is seen that a large difference exists for central collisions in the central rapidity region. Fritiof is below the experimental data. Notice that precision is in these conditions where the additional $2n - n_A - n_B (q - q)$ chains of DPM contribute. In the target fragmentation region both models are below data. The reason is the existence of cascading in that rapidity region. In DPM cascade has been incorporated by Ranft [17] introducing a parameter, the formation time $\tau_c$. Its value turns out to be around 2-3 fm (Figs.12 and 13). With this value, the $y$-distribution for nucleus-nucleus collisions is reproduced [52], including the target fragmentation region.

The effect of cascading is also important in the $P_T$ distributions in the target fragmentation regions. In Fig.14 the comparison of the results of Pansart [14] without cascading and the experimental data [52] shows discrepancies. Notice that the difference is larger for O-W than for S-W as it should be. In fact there is less cascade in the latter case because there are less spectator nucleons of the target. With cascading the discrepancies disappear as is shown in Fig.15 where we compare the data with the Ranft results [17].

It may be noticed that for a large variety of beams and target nuclei, and for different energies, all the data [46, 53, 54] lie on a KNO curve as is shown in Fig.16 illustrating a distribution of $n_P$, as a function of $n/(n)$ for O-Pb according to DPM and Fritiof. A different set of experimental data lies on the DPM curve for O-Pb. Only some of JACEE events and collisions between very light nuclei are clearly outside. This surprising scaling is nothing but the fact that the dispersion is proportional to the multiplicity with almost the same proportion as it was pointed out earlier [55]; see Fig.17. Only for very light or very heavy nuclei or for very high energy some departure of such behaviour occurs. These facts can be explained by geometrical arguments. We shall discuss this scaling in detail in Section 4.4.

Let us now consider the single and double $P_T$ distributions and their correlations. NA35 experimental data on single $P_T$ distribution for O–Au and p–Au for high and low multiplicities have confirmed the effect that the ratio between high and low multiplicity events is larger than one for low $P_T (P_T < 0.25 \text{ GeV/c})$ and for high $P_T (P_T > 0.8 \text{ GeV/c})$ [47]. The trend of the data at 1.8 TeV goes in the same direction. This behaviour indicates that low and high multiplicities $P_T$ distributions would be like Fig.18 [56].

Fritiof and DPM, which are able to explain the known correlation between $P_T$ and $dn/dy$, fail to explain this effect. In Fig.19 is shown the NA35 data [53] and the Fritiof results. In DPM the $P_T$ of the produced particles is obtained by giving a primordial transverse momentum to the end of the chains. This primordial momentum is transmitted along the chain to all the particles. For long chains the degradation of the primordial momentum can be larger than for short chains due to having more particles. Therefore, the probability of obtaining particles with very small $P_T$ is larger for long chains than for short chains. As for low multiplicities the weight of long chains relative to short chains is larger than for high multiplicities, an effect opposite to the experimental one should be expected at low $P_T$.

We may say something now about the coherence. Fritiof and DPM, and many other models like the multichain model [9], can be seen as an incoherent superposition of chains or collisions. In connection with the quark–gluon plasma search, it would be interesting to know how the phase transition takes place in these models and how can it be simulated. In these models, it could be assumed that above a determined density of particles, the strings which produce these particles collapse. When the energy of each string is known, then known is the total energy density available for the initial state of the subsequent
observables. One way is to look at the effects in the multiplicity distribution of adding to the MCM a coherence signal. The multiplicity distribution is written as:

\[ P_{AB}(n) = (1 - r) P_{AB}^{MCM}(n) + r P_{AB}^{FTM}(n) \]

where \( P_{AB}^{MCM}(n) \) is the multiplicity distribution in MCM which is taken as background, and \( P_{AB}^{FTM}(n) \) is the multiplicity distribution of the colour flux tube model which is taken as coherence signal. By comparing with the experimental data on \( O - Au \) at 200 GeV for central collisions an upper bound for coherence signal was found \((r < 0.3)\). These kinds of studies should be applied to other observables as they can be very useful.

It should be emphasized that both DPM and Fritiof were made for soft processes, i.e. for small momentum transfer between two successive components of the string. But this is not always the case in URHIC.

From all this discussion it may be understood that both DPM and Fritiof are successful but the DPM has an edge over the Fritiof. This model has been able to describe [49] with considerable success multiparticle production in hadron-hadron interaction (shape of the plateau, multiplicity distribution, inclusive cross section, and correlation including the detailed structure of the long-range forward-backward rapidity correlation). It may, therefore, be extended in a straightforward way to nucleus-nucleus [49] interactions at high energies with high expectation to yield reliable results.

### 3.2 The Emulsion Data

We now examine the situation with the latest results on the reaction dynamics at CERN energies confining to the emulsion experiments because the latest results have come from these experiments, and also they account well for the intranuclear cascade. Moreover, nuclear emulsions very well describe the pseudo-rapidity distributions.

Barbier et al. [57] have compared the central \( O^{16} - Ag, Br(Emul) \) collisions results at 14.5, 60 and 200 GeV (Fig.20) with proton-emulsion data at the equivalent energies. They have shown that produced charged secondaries are consistent with the picture of a nucleon-nucleon collision as a superposition of elementary interactions, providing an allowance for cascading within the nucleus. This recent picture has further confirmed the existence of intranuclear cascade which should be taken into account when explaining the nucleus-nucleus collisions. In a relatively recent experiment [58], with \( O^{16} \) as well as \( S^{32} \) ions at exactly the same energies, it is calculated that as comparison to Fritiof model, which does not reproduce fully the experimental data, the VENUS version of DPM well reproduce the results for shower particles \((n_s)\) as well as the grey particles \((N_g)\). But the multiplicity distributions for black prongs \((N_b)\) for the four beams \( 14.5A GeV^{28}Si, 60A GeV^{16}O, 200A GeV^{16}O, 200A GeV^{S^{32}} \) (Fig.21) show significant departure from VENUS for the same set of \( n_0 \) used in the context of the \( N_b \) distributions. The failure of VENUS to describe the multiplicity distributions of black prongs (target protons) is a natural consequence of the simple geometry described by the Monte Carlo code. The model reproduces the shapes of angular distributions of grey particles from all beams quite well, and the best results are obtained at BNL energies (14.5A GeV). The multiplicity and angular distributions of shower \((n_s)\) and grey \((N_g)\) particles are successfully reproduced by VENUS at CERN and BNL energies. However, the simple rescattering mechanism included in VENUS is inadequate for explaining the distribution of black particle tracks. The model thus needs full intranuclear cascade which include all subsequent collisions of hadrons created in the secondary collisions. The same conclusion has been drawn in another experiment [59] about the validity of multistring model VENUS which includes the rescattering of string fragment of resonances among themselves and with target spectators. It may thus be concluded that the DPM VENUS well describe the reinteractions among the produced secondaries (enhanced baryon production in the target fragmentation region). This model also determines the rescattering parameter \( r_0 \) which plays a vital role in the energy density and hence is important in the QGP studies [60]. In Helios emulsion collaboration [61] the interaction of \( O^{16} \) and \( S^{32} \) at 200A GeV have been studied in emulsion and in emulsion-tungsten chamber targets at CERN. Some global parameters have been compared with the expectations of dual parton model. The correlation between transverse energy, multiplicity and rapidity density in different rapidity intervals have been investigated for \( O^{16} \)-emulsion, \( S^{32} \)-emulsion as well as for \( W \) (emulsion plus a thin tungsten foil) interactions at the same energy of 200A GeV. The distribution shown in Fig.22(a, b) for emulsion target have broad peak close to \( \eta \)-values expected for \( A_{eff}(Ag) \) where,

\[ A_{eff} = (3/2) \; A_p^{1/3} \cdot A_t^{1/3} \]

in a simple geometrical picture at zero impact parameter for \( O^{16} \) and \( S^{32} \) projectile on heavier targets, while \( A_p, A_t \) stand for atomic mass of projectile and target nucleus respectively. In the case of \( W, \) Fig.22(c), a peak at \( \eta(A_{eff} - A_t) \) shows up at the highest \( E_t \). This result could signal violent reinteraction processes, following a central collision
on a large target by the former spectators producing hundreds of secondaries in the target fragmentation region. Results of interactions have been described in prescription of dual parton model. Charged particle rapidity distributions are superimposed in Fig.22(d, e, f) corresponding to the same selection used for emulsion. Fitting of the data show that model tends to underestimates the dependence of rapidity density distribution $dN/d\eta$ on the atomic mass of the target, whereas the dependence on the atomic mass of the projectile, as well as the charged particle multiplicity are somewhat overestimated. Thus globally the results agree but difference arises due to rescattering phenomena which should be incorporated well in DPM.

On the other hand the Fritiof model has been found to reproduce [62] the data with some accuracy for the overall pseudo-rapidity ($\eta$) distributions of the produced particles for $O^{16}$ and $S^{32}$ interactions at 200A GeV. The results of EMU91 collaboration [63, 64] confirm further these features of the Fritiof model. But the Fritiof model as well as Ranft fail to reproduce the general angular shape of the multiplicity distributions [65] in 200A GeV $O^{16}$ collisions. The Lund model, however, also gives a good estimate of the shower particle multiplicities [66] and forward-backward correlation of multiplicities [67]. These correlations provide information regarding the reaction dynamics according to the standard information theory [68].

The WA80 collaboration tried to apply the Multichain Fragmentation Model [69] to their results from $O^{16}$ beam at 60 and 200A GeV, but the model was found not to reproduce the yield and the transverse energy of baryons in the target fragmentation region.

To conclude this discussion it may be said that even in the URHIC although both Fritiof and VENUS compete; the DPM seems to have an edge over the Fritiof model.

It was pointed out in a preceding paragraph that geometry plays a vital role in URHIC. It has been shown [70] that since inelastic part of proton-proton cross section varies only with a few percent in the 1 GeV to 1 TeV range, the geometry in ultra-relativistic heavy ion collisions is basically independent of the incident energy. It has actually been found that both the slow target associated particles [71], the projectile fragments [72] as well as the particles produced in the fragmentation region [73] show energy independent features. Thus nuclear geometry is said to be energy independent over a large range of energy, and a clean cut participant-spectator picture may well be used as a guiding hypothesis for ultra-relativistic heavy ion collisions as assumed in most of the models [74]. Projectile mass independence has also been shown in the emulsion experiments [59]. The WA80 collaboration [74-76], using a simple geometrical approach, calculated average transverse momentum ($p_T$) per participating nucleon in different type of interactions. The results from these analyses clearly indicate that, for a given geometry, the number comes out essentially the same independent of the target mass, projectile mass, and centrality.

4 Signals for QGP

Now we review the experimental status of the proposed signatures for the Quark-Gluon Plasma (QGP) to draw some conclusion for their validity in future.

4.1 Transverse Momentum

Van Hove [77] and Shuryak and Zhirov [78] have suggested that perhaps a rapid increase of $\langle p_T \rangle$ should be due to the formation of QGP. One should measure the average $\langle p_T \rangle$ as a function of the energy density, or some other quantity which should be proportional to the energy density, and see whether the trend sketched in Fig.23 is obtained; a small increase in $\langle p_T \rangle$ for small $t$, corresponding to normal hadronic matter, a transition region in a sort of plateau and a rapid increase which should be due to the formation of the QGP.

Three experiments have results on $\langle p_T \rangle$: WA80, NA34 and NA38.

The WA80 collaboration measured the $p_T$ distribution of $\pi^0$'s produced in proton $+Au$, $O + C$ and $O + Au$ interactions, in three cases at 60 and 200A GeV [79]. From the first analysis resulted the invariant differential cross section $E \frac{d^2\sigma}{dp_T^2}$ as a function of $p_T$ which is shown in Fig.24(a) for 200A GeV and 60A GeV. The $p_T$ distribution of Fig.24(a) show a change in slope for $p_T \leq 0.8$ GeV/$c$, which is more reproduced for the heavy systems, being weakly indicated in the proton $+Au$ data. This change in slope is consistent with the results of the NA34 collaboration. In the second analysis two comparisons of invariant differential cross section were made, both at 200A GeV as shown in Fig.24(b). A second comparison at 200A GeV was of central with peripheral collisions in $O + Au$ events. This is shown in Fig.24(c). The NA34 collaboration studied the $p_T$ distribution of negative particles (mainly pions) produced in proton $+W$, $O + W$ and $S + W$ at 200A GeV and the results were compared in different ways [80], which are given in Fig.25 and Fig.26. No abnormal effects were detected in the $p_T$ spectra or in their ratios, as well as no dependence on the transverse energy of the interaction.
The NA38 collaboration studied the $J/\psi$ production in $O + U$, $O + Cu$ and $S + U$ interactions at 200A GeV, as given in Fig. 27 [81] without correction for acceptance. There is a slight enhancement of the average $(p_T)$ as $E_T$ increases, as is usually seen in hadron production, corresponding to the first part of the curve as shown in Fig. 23. The conclusion from this study of the NA38 collaboration on the average transverse momentum of $J/\psi$ is that nothing unusual was detected.

General conclusion on $p_T$ distribution is that WA80 experiment found for $\pi^0$'s produced in $O + Au$ collisions at 200A GeV a slope parameter larger for central than for peripheral collisions, and an increase in the slope parameter for peripheral collisions for $p_T \gtrsim 1.8$ GeV/c. The NA34 experiment detected no unusual features in the $p_T$ distributions of negative particles. The NA38 experiment found nothing special in the $(p_T)$ of the $J/\psi$. Hence concerning a possible signature of QGP nothing strikingly unusual was found.

### 4.2 Photon Emission

Electromagnetic production of leptons and photons from the hadronic matter was first considered by Feinberg [82]. Shuryak proposed its application in the diagnosis [83] of hot QGP.

If a photon is produced in a QGP it leaves the hot plasma with a small probability of interacting in the outer freeze-out region (see Fig. 28). In order to see whether there are directly produced photons in the QGP we must study inclusive photon production and find out whether there are some kinematical differences between the sample of the selected inclusive photons and the photons which are known to originate from normal hadron decays. Direct photons as a signature of the QGP have been investigated by Raha and Sinha [84].

The NA34 collaboration studied inclusive photon production in proton $+ W$, $O + W$, $S + W$ and $S + Pt$ interactions at 200A GeV [85]. The results are given in Fig.29, from which it is to be concluded that:

- The shape of the $p_T$ distributions agree well with that expected for photons coming from known meson decays.
- There is no difference between the spectra of inclusive photons produced in those three interactions.
- The ratio of number of $\gamma$'s to the number of $\pi^0$'s does not vary with $E_T$.

The WA80 collaboration studied inclusive photons produced in proton $+ Au$, $O + C$ and $O + Cu$ central interactions at 60 and 200A GeV [79]. Fig.30 shows the inclusive photon $p_T$ spectrum, $1/N_{event} dN/dp_T$. The main results from the WA80 collaboration indicate that:

- $(p_T)_{1.8}$ increases by $\sim 15\%$ from peripheral to central collisions, showing the trend observed in other experiments, like UA1 or the $(p_T)$ of the $J/\psi$ measured by NA38 (Fig.27).
- $(p_T)_{1.8}$ also increases with the entropy, levelling off at some value of the entropy.

Both NA34 and WA80 made a very important search for direct photon production and provide fundamental information on inclusive proton production. However, concerning the QGP neither of the two experiments detected any strong effect which could be an evidence for direct photon production in the nucleus-nucleus interaction studied.

### 4.3 The $J/\psi$ Suppression

The suppression of $J/\psi$ production was originally proposed as a QGP signal by Matsui and Satz [86]. The NA38 experiment studied the $J/\psi$ production in proton $- U$, $O + U$, $O + Cu$ and $S + U$ interactions at 200A GeV [87, 88]. Results are given in Fig.31(a, b, c). Conclusions which can be drawn are:

- The ratio $'S'$ of the number of $J/\psi$'s upon number of events in the continuum mass spectrum in the $J/\psi$ mass region decreases as the energy density of the interaction increases.
- The ratio $'R'$ of the value of $'S'$ at the highest $E_T$ band to the value of $'S'$ at the lowest $E_T$ band was found to be $0.52 \pm 0.11$, $0.50 \pm 0.10$ and $0.73 \pm 0.10$ for $O + U, S + U$ and $O + Cu$ interactions respectively.
- The suppression of $J/\psi$ production is stronger at low $p_T$ as shown by the ratio $'R'$ in Fig.31(c).

The ratio $R \approx 0.5$, which show that there is about 50% of the $J/\psi$ suppression in central collisions relative to peripheral collisions in $O + U$ and $S + U$ interactions, at the first sight might seem small. If we assume the existence of the QGP these ratios are in fact rather large. Because, under this assumption, the experiment measures the product of two probabilities: the probability to produce the QGP and the probability of $J/\psi$ suppression.
due to the QGP. Each of these two probabilities would be larger than 50% and would be on the average about 70%, which is very high. This means that on the one hand the trigger on muons used in the experiment has the remarkable property of selecting central collisions associated with \( J/\psi \) such that in more than half of them the QGP is produced; and on the other hand, once the QGP is produced, more than half of the \( J/\psi \)'s are suppressed. These are the remarks one may give regarding the NA38 experiments. Secondly, the energy density in \( S + U \) collisions is little larger than in \( O + U \) collisions, certainly not smaller. Therefore we should expect about the same percentage of \( J/\psi \) suppression in both collisions, as it seems in fact to be indicated by the values of \( 'R' \), which are nearly equal. However, the comparison of \( R(p_T) \) values versus \( p_T \) for \( O + U \) events with \( S + U \) events shown in Fig.31(c) is rather disturbing because the dependence of \( R(p_T) \) on \( p_T \) for \( S + U \) collisions is much less pronounced that for \( O + U \) collisions. This is queer and is in contradiction to what we should expect. Taking the NA38 experimental data as they are, this point is difficult to be understood and should be clarified in the future.

Matsui and Satz's prediction [86] that, if a Quark Gluon Plasma is created, the production of the \( J/\psi \) should be suppressed was independent of, and prior to the results of NA38 experiment at CERN. After these experimental results became known, several models were proposed to explain the \( J/\psi \) suppression. There are two classes of models: one class assumes that the QGP is formed; the other assumes that there is no QGP formation and the \( J/\psi \) suppression takes place as \( J/\psi \) interacts inelastically with some dense hadronic matter created in the collision. A rather detailed account of the different models and their comparison with NA38 results can be found in Ref.[89], which should be consulted in the future experimental efforts.

In inclusive reactions of the type: hadron + hadron \( \rightarrow J/\psi + \) anything, the \( J/\psi \) is not always promptly produced; in many cases it originates from the decay of \( x \)-states and in some cases from the decay of \( \psi' \). The only data on this question come from an experiment on \( \pi^- \)-Berilyum interaction at 185 GeV/c [90] in which \( \sim 40\% \) of the \( J/\psi \)'s originate from the radiative decay of \( x \)-states, \( x \rightarrow J/\psi + \gamma \), and \( \sim 5\% \) from the decay of the \( \psi' \) (about 50% of the \( \psi' \) decay into \( J/\psi \)). The \( x \)-states involved are mainly the \( x_{0}(3510) \) and the \( x_{0}(3555) \). The NA38 detector was not adopted to measure such decays. However, due to the similarity of kinematical conditions at 200A GeV, it is plausible to assume that also in the NA38 experiment \( \sim 40\% \) of the \( J/\psi \)'s originate from radiative \( x \)-decays and \( \sim 5\% \) from \( \psi' \) decays. Many charmonium states are produced in 200 GeV hadronic interactions. If we call \( N_0, N_x \) and \( N_{\psi'} \) the numbers of produced \( \pi^- \), \( x \) and \( J/\psi \) respectively, Ref.[90] gives the ratio

\[
\rho = \frac{N_0 + N_x}{N_{\psi'}} = 3 - 4
\]

As we have discussed, in the NA38 experiment presumably nearly 40% of the \( J/\psi \)'s come from the decay of \( x \)-states. Those 40% are more affected by the presence of the QGP than the 60% of \( J/\psi \)'s which are promptly produced. These simple considerations show clearly that in order to compute the rate of suppression of a resonance formation due to QGP, we must know:

- the formation time and size of the resonance,
- the plasma lifetime,
- the longitudinal and transverse dimensions of the plasma and their evolution with time,
- the exact relationship between the Debye colour screening radius \( r_D \) and the plasma temperature \( T \). Uncertainties which exist at present on this relationship should be eliminated [86].

Different models are based on different assumptions about these points. But these models have some common characteristics which are given below:

- They all assume that the \( J/\psi \) is produced locally inside the nucleus.
- They all use for the \( J/\psi + \) nucleon cross section the value of 1 to 3mb, obtained in \( J/\psi \) photoproduction experiments.
- They assume that the \( J/\psi \) has only transverse momentum \( p_T \) and that its \( p_L \) in the CMS of a nucleon-nucleon collision is zero.
- They all use for the probability that the \( J/\psi \) does not interact (survival probability) to the classical expression:

\[
\text{Prob.} = \exp(-\lambda)
\]

where

\[
\lambda = \int_{t_0}^{t_f} v(p_T, t) dt,
\]

\( t_0 \) is the initial time when the \( J/\psi \) enters the hot matter, \( t_f \) is the final time when absorption stops, \( v \) is the number of collisions per unit time, \( p_T \) is the \( J/\psi \) transverse
There is a great difficulty with the J/ψ absorption models. One has to understand how a
remembered that the pion volume is \( \approx 0.8 \, \text{fm}^3 \) nucleon density in normal nuclear matter and still stay as normal hadrons. It should be
remembered that the pion volume is \( \approx 0.8 \, \text{fm}^3 \).

In addition to models assuming the formation of the QGP there is another class of
models assuming inelastic scattering of the J/ψ in some dense hadronic matter. The
theoretical \( R(\nu T) \) differs from the experimental data in both cases by a factor of 2 to 4.
Taking into account on the one hand the uncertainties due to our ignorance on the plasma
and resonances characteristics in the first class of models, and on the composition of the
hadronic matter and on J/ψ-hadron cross section in the second class, and on the other
hand the rather large NA38 experimental errors, there are no objective criteria to prefer
one of these class of models to the other. Both are acceptable. However, if the QGP is
not formed we have to understand the high hadron density per unit volume in the central
region of the collisions, which is obtained from a combination of the Bjorken model with
the NA35 results.

It seems that within these two classes of models whatever explanation we choose for
the J/ψ suppression, we need the q̅q pair going through a medium of high density, either
of QGP or of hadronic matter. Finally, due to the success of QCD as a theory of strong
interactions we should expect that the ultimate explanation for J/ψ suppression should
come from QCD.

4.4 Multiplicity Distributions

One of the earliest probes suggested for QGP formation requires a study of the global
parameters of the events, e.g. the energy deposition, multiplicity and the momentum
spectra of the emitted pions, as a function of beam energy \( E \) and mass number \( A \) [91, 92]. Multiparticle production in hadronic and nuclear collisions is so far very poorly un-
derstood because the role of perturbative QCD in such soft collisions is less clear. Several
theoretical models have been developed to explain the experimental results but there is
certainly considerable overlap among these approaches. Many attempts are based on searching
for certain systematics or scaling relations which are universal to all types of reactions. Any
distinct deviation from these relations observed in ultra-relativistic nuclear collisions will
be the indicator of a new phenomenon taking place.

One such phenomenon which is universal to all types of reactions is the scaling properties
of multiplicity fluctuations which are now called intermittency. Koba, Nielsen and
Olesen (KNO) proposed in 1972 one scaling property for the total particle multiplicity [93].
The probability \( F_n(s) \) to find \( n \) particles in one event depends on the total centre-of-mass
energy \( \sqrt{s} \) only through the scaling variable \( z = n/\bar{n} \),

\[
F_n(s) = \psi(z),
\]
in the high energy limit, where \( \psi(z) \) is an energy-independent function and \( \bar{n} \) is the
average multiplicity. KNO scaling is found to be valid up to ISR energies \( (\sqrt{s} = 60 \, \text{GeV}) \).
It also implies that the scaled factorial and normalized moments defined as

\[
F_K = \langle (n(n-1)\ldots(n-K+1))/\langle n \rangle^K \rangle, \quad C = (\langle n^K \rangle)/\langle n \rangle^K,
\]
are energy-independent. With the advent of very high energy accelerators, these phe-
nomenological laws reached their limits of validity. At higher energies of the CERN-SPS
collider, the UA5 collaboration observed quite dramatic KNO violation [94].

At very high energies \( (\sqrt{s} > 50 \, \text{GeV}) \), a universal power-law behaviour of multiplicity
moments as a function of rapidity interval was observed [95]. Such a behaviour follows
from a self-similar or a fractal pattern of multihadron production. Whether the self-
similar behaviour is relevant to QG is not obvious at this moment. However, the subject
is highly pertinent to relativistic heavy ion collisions where the signatures of collective
behaviour based on the correlations among the produced hadrons can be obtained [96].

4.4.1 Fluctuations and Intermittency

The experimental distribution of a variable has fluctuations. There is always a statistical
fluctuation due to the finite number of events. However, fluctuations in a distribution
might be due to some physical process. For instance, just as a conceptual consideration,
let us assume that the QGP is created in some collision and that in some events many
pions coming from the plasma are concentrated in a particular solid angle, the rapidity
distribution of such pions will have a fluctuation in that solid angle. It is important to
know whether a fluctuation is in fact statistical or is due to some physical process. We
usually consider that a fluctuation is not just due to statistics when it is larger than 5
or 6 standard deviations. Large, non-statistical fluctuations, e.g. of rapidity or energy density, have been proposed as a possible signature of the QGP phase transition [97].

Based on these lines a new method of analysis of fluctuations has been proposed by Bialas and Peschanski [98], in terms of the scaled factorial moments, \( F_i \). The method allows the detection of large non-statistical fluctuations as well as investigation of the pattern of the fluctuation (eventually leading to their physical origin). They call intermittency the physical fluctuation, in analogy with the phenomenon of intermittency in fluid turbulence.

For an intermittent pattern, the values of \( F_i \) obey a power law

\[
(F_i) = \left( \frac{\Delta y_i}{\delta y} \right)^{\phi_i} = M^{\phi_i}
\]

(1)

From this expression we have

\[
\ln (F_i) = \phi_i \ln \Delta y - \phi_i \ln \delta y
\]

(2)

By making \( \phi_i \ln \Delta y = a_i \), we have,

\[
\ln (F_i) = a_i - \phi_i \ln \delta y
\]

(3)

Three experiments on intermittency have been performed with heavy ion beams; two of them with nuclear emulsions, EMU07 or KLM collaboration and EMU01 collaboration, the third one performed by the WA80 collaboration. The KLM collaboration [99] studied intermittency in the following interactions: proton-emulsion at 200 and 800 GeV/c, with emulsions exposed at FERILAB; \( O^{16} \)-emulsions at 60 and 200A GeV with emulsions exposed at CERN.

Fig.32 gives the slope \( \phi_i \) of Eq.(3) as a function of the order \( i \). The conclusions from KLM experiment are:

- the pseudorapidity distributions of particles produced in proton-emulsion and the 0-emulsion collision show an intermittent pattern.
- Monte-Carlo generated events do not show intermittent patter.
- the slopes \( \phi_i \) increase with the order \( i \): \( \phi_i > \phi_4 > \phi_2 \).
- for the same order \( i \) there is no correlation between \( \phi_i \) at 200 GeV/c and \( \phi_i \) at 800 GeV/c for protons.

For the \( O^{16} \) events Fig.32(b) shows that:

- Again \( \phi_6 > \phi_5 > \phi_4 > \phi_3 > \phi_2 \)
- for the same order of \( i \) there is a correlation, \( \phi_i \) at 200A GeV is larger than \( \phi_i \) at 60A GeV; this seems to show that for the heavy ion interactions the slope is larger for larger interacting systems.

The WA80 collaboration looked for intermittency in \( O^{16}+C \) and \( O^{16}+A u \) interactions at 200A GeV [100]. Conclusions from these experiments are:

- The pseudorapidity distributions of particles produced in \( O+Au \) and \( O+C \) collisions at 200A GeV show intermittent patter.
- Fig.33 shows that both for \( O+C \) and \( O+Au \) collisions the slopes \( \phi_i \) are larger in medium than in central collisions, and for each type of collision they are larger for \( O+C \) than for \( O+Au \).
- Fritiof generated events do not show intermittent pattern.
- The second conclusion seems to show that the slopes \( \phi_i \) are smaller for larger interacting system. This is in contradiction to the conclusion drawn from the KLM collaboration.

Conclusions from these experiments are that intermittent pattern has been observed in the rapidity distribution of secondary particles produced in nucleon-nucleus and nucleus-nucleus interactions. However, it has also been observed in the experiments with other beams [101, 102]. As far as a search for QGP is concerned, nothing strikingly different was found in nucleus-nucleus collisions at high energy. It is very difficult to draw a physical conclusion from an intermittency pattern. The cause of the intermittency might be different in different reactions.

Study of fluctuations in rapidity density as a possible signal for QGP has gained much importance during the last couple of years. The results have mainly come from the emulsion experiments with \( O^{16} \) and \( S^{32} \) ions at 60 and 200A GeV. Analysis of the scaled factorial moments have been carried out with these ions and energies extensively. The EMU01 collaboration has found [103] that the moments rise (in the log-log plot) with decreasing pseudorapidity bin size \( \delta \eta \) (Fig.34) but slopes roll off to approximately zero for \( \delta \eta < 0.1 \). Results are comparable with the alpha model of Bialas and Peschanski.
In another emulsion experiment [104], the function \( f_\eta(\phi) \) which characterize the multiplicity fluctuations has been found to depend (see Fig.35) upon the projectile mass, energy and impact parameter. In another similar investigation [105] the scaled factorial moments were calculated for the multiplicity distributions in one \((\eta \phi)\) and two dimensional \((\eta \phi)\) phase space. The data revealed that a cascade mechanism was responsible for the observation of intermittency. This effect was found to be more pronounced in two-dimensional analysis as compared to one dimensional (Fig.36).

In the recent emulsion experiments [106, 107], which include results on 14.5A GeV \( S_{15} \) interactions, it has been concluded that (Fig.37) the interaction for \( S_{15} \) beam fulfill the prediction of self-similar cascade model in observing the intermittency, where its strength increases with the order of the factorial moment in \( \eta, \phi \) and \( \eta \phi \) phase space. When compared with data from other beams at higher energies, the data point in case of \( \eta \) overlap exhibiting the same trend for all \( q \)-values. The value of \( \lambda(\phi) \) and \( \lambda(\eta \phi) \) become more flat for \( q > 3 \) in case of \( O_{16} \) and \( S_{22} \) beams. The data of all the beams within their statistical errors do not exhibit any definite indication of the presence of the phase co-existence with any of the variables. One of these experiments [107] confirm an intermittency power-law in the observed central collisions of \( O_{16} \) and \( S_{22} \) at respectively 200A GeV, 16A GeV, and \( S_{15} \) at 14.5A GeV.

### 4.5 Strange Particle Production

It has been suggested that one of the possible signatures of the QGP would be an enhancement in the production of strange particles relative to the production observed in nucleon-nucleon collisions. Rafelski, who proposed this signal a decade ago, has given a detailed review [108], but we confine to some important results only.

Results on strange particle production in heavy ion collisions have been obtained by the E802, NA34, NA35, NA38 and WA85 collaborations. The E802 collaboration showed [109, 110] a net enhancement of \( K^+/\pi^+ \) in \( S + A \) relative to proton-proton. The most interesting results are those ratios measured as a function of \( p_T \). This is displayed in Fig.38, where those ratios are plotted with ratios obtained in proton-proton and proton-Pb interactions at comparable energies. The enhancement is more pronounced in \( K^+/\pi^+ \) and in \( K^-/\pi^- \) and increases with \( p_T \). The results are compared with the ones obtained with Fritiof Monte Carlo and shown in Fig.39 displaying the "double ratio" \( K_3/\pi \) i.e. the ratio \( (K_3/\pi) \) experimental/(\( K_3/\pi \)) Fritiof. Since Fritiof results agree with \( \pi^- \)-production, it is concluded that the enhancement in the \( K/\pi \) ratio is due to an enhancement in \( K^- \)-production.

The NA34 collaboration measured the \( K^+ \) and \( \pi^+ \) transverse momentum and transverse mass spectra in \( S + W \) collisions at 22A GeV in the rapidity range 1-1.3 and \( p_T \) range 0.15 - 0.45 GeV/c [111]. Fig.40 shows the \( K^+/\pi^+ \) and \( K^-/\pi^- \) ratios. The dashed and solid lines show the \( K/\pi \) ratios observed in proton-proton interactions at the CERN ISR for \( \sqrt{s} = 23 \) GeV for positive and negative particles, respectively, normalized to the rapidity interval 1 - 1.3. Only the \( K^+/\pi^+ \) point at 450 MeV/c is higher than the proton curves, but other points for \( K^+/\pi^+ \) and \( K^-/\pi^- \) are not.

The NA38 collaboration studied the single muons from the like-sign pairs produced in \( O + U \), \( S + U \) and proton +U collisions at 200A GeV in order to obtain, indirectly, information about the \( p_T \) distribution and the strangeness content of the sample of the parent pions and kaons [81, 112]. In spite of the large statistic nothing striking was found.

The NA35 collaboration has interesting results on production of \( K^- \)'s and \( \Lambda \) in \( S + S \) interactions at 200A GeV [113, 114] Fig.41(a,b) shows \( \langle N_\Lambda \rangle \) and \( \langle N_{K^-} \rangle \) as a function of \( \langle N_{\pi^-} \rangle \) for the three categories of events. The dashed lines are prediction from the Fritiof and the dotted lines are the predictions from a model, called NN model, introduced in the investigation. From this experiment the observed enhancement of \( \Lambda \) and \( K^- \)'s in central \( S + S \) collisions relative to the Fritiof and the NN model could be related to QGP but could also be due to final state interactions of protons in a parton gas.

The WA85 experiment has presented preliminary results on the production rates of negative particle, \( \Lambda \) and \( \bar{\Lambda} \) as a function of the multiplicity of charged particles, as well as on the ratios of \( \bar{\Lambda} \) to \( \Lambda \) and of \( \Xi^- \) to \( \Xi^- \) production, in \( S + W \) central collisions at 200A GeV [115, 116]. Fig.42 gives the average numbers, per event, of negative hadrons, \( \langle n_- \rangle \), of \( \Lambda \)'s, \( \langle n_\Lambda \rangle \) and of \( \bar{\Lambda} \)'s, \( \langle n_{\bar{\Lambda}} \rangle \), respectively as a function of multiplicity. We see that the three average numbers increase very approximately linearly with the multiplicity, except perhaps \( \langle n_\Lambda \rangle \) for multiplicities less than \( \sim 40 \). This is confirmed by Fig.43, which shows the ratios of \( \langle n_- \rangle \), \( \langle n_\Lambda \rangle \) and \( \langle n_{\bar{\Lambda}} \rangle \) to the multiplicities. The ratio of \( \Lambda \) to \( \bar{\Lambda} \) was found: \( \Lambda/\bar{\Lambda} = 0.24 \pm 0.02 \). Similarly the ratio found for \( \Xi^- \) and \( \Xi^- \) was: \( \Xi^-/\Xi^- = 0.44 \pm 0.10 \).

All collaborations gave useful results but no collective effect could be detected. It should, however, be stressed that the results from E802 on the ratio \( K/\pi \) are very important and even more so because they are given as a function of \( p_T \) in a rather wide range of \( p_T \) for the beam energy involved. The absence of an enhancement of \( K^- \)'s, \( \Lambda \) and \( \bar{\Lambda} \) found by the NA35 collaboration in \( O + A \) collisions is based on rather small statistics. The
different behaviour of $\Lambda$ production in $S + S$ collisions relative to $O + Au$ collisions may become interesting and should be followed. The ratios of $\Lambda/A$ and $p^{-}/p^{+}$ obtained by the WA85 collaboration are important and it will be rather interesting to see the evolution of this, especially if one can measure these ratios as a function of $p_T$.

5 The Latest Scenario

It will be of interest now to review the development made in this field following the completion of experiments at CERN in 1991.

5.1 Experimental Investigation

In this section we discuss the progress made towards the end of 1992 and particularly in 1993 with reference to the reaction dynamics and the QGP formation signals. So far as the experimental information is concerned, mostly the results from 14.5A GeV $Si^{28}$ and 200A GeV $O^{16}$ and $S^{32}$ interactions have been presented.

5.1.1 Strangeness Production

The NA36 collaboration [117] has reported evidence for some unusually high strangeness content located at midrapidity in 200A GeV $S^{32}$ collisions with $Pb$.

5.1.2 Limiting Fragmentation

G. Huailin et al. [118] have studied the dependence of momentum of the $He$-fragments on multiplicities in terms of spectator-participant model. It has been found that with decreasing $He$-multiplicity the surface excitation energy of the spectator projectile increases, leading to an increase in the width of momentum distribution. Results of this experiment indicate that, regardless of the incident energy of projectile, the excitation energy remains constant for the same geometric conditions and this produces the limiting fragmentation of the momentum distribution as a function of $He$-multiplicity.

5.1.3 Multiplicity Distribution

In an experiment [119] charged secondary particles in $Si^{28}, O^{16}, S^{32}$ as well as 800 GeV proton interactions have been studied in terms of the higher generalized fractal dimensions. It has been concluded that though Fritiof and VENUS models satisfactorily reproduce the data of $S^{32}$ and $Si^{28}$ respectively, it seems that the compatibility between VENUS and the corresponding experimental results is comparatively better. Other two experiments [32, 120] deal with the study on factorial moments in the $S^{32}$ and $O^{16}$ interactions at 200A GeV and with $Si^{28}$ at 14.5A GeV respectively. In the first experiment [32] negative particle multiplicity distributions are described by the negative binomial form independently of the size of the phase space cell and dimensionality. The interpretation in terms of the clan cascading picture lead to an interesting similarity between the dependence of the model parameters on the cell size in nuclear collisions and simple partonic cascade.

In the later experiment [120] observations on cumulant moments of lowest order both in one dimensional $\eta$ and two dimensional ($\eta \cdot \phi$) phase space lead to the conclusion that correlation of order higher than two do not survive in the data. This observation discards the possibility of occurrence of any strong space-time fluctuations due to the creation of QGP.

EMU01 collaboration [31] have presented results on intermittency and discussed the importance of photon conversion in multidimensional intermittency analysis.

The results of these experiments indicate that some strangeness enhancement has been observed, the geometry plays an effective role, the DPM VENUS explains the data effectively, and there is no evidence for the QGP formation in the multiplicity distribution of charged particles at the highest available energy of 200A GeV with the heaviest available projectile $S^{32}$. These results carry considerable weight and must be considered when planning the new experiments.

5.2 Theory

Considerable amount of work has been done on theoretical side to interpret the old data at CERN energies, and to propose new ideas for experiments at CERN LHC and Brookhaven URHIC.

5.2.1 BNL and CERN Energies

Some theoretical work has been done to interpret the experimental data obtained at BNL and CERN energies with $O^{16}$ and $S^{32}$ beams. J. Letessier et al. [121] determined entropy per baryon due to formation of a fireball in the central 200A GeV $S^{32}$ collisions. They gave evidence that hadron gas model did not provide enough entropy and was inconsistent with the contained experimental results. In contrast the QGP hypothesis could explain them naturally. Exactly similar conclusions were drawn by Ishii and Nuroya [122] by applying a baryon rich QGP fluid model to explain $S + S$ collisions at 200A GeV.
5.2.2 Future Experiments

Most of the work has been done on theoretical side with experiments at CERN (LHC) and BNL (RHIC) in view. In contrast to the earlier calculations casting shadow on the QGP formation [36, 37], these calculations are based on the assumption that QGP phase transition should be an important feature in the heavy ion collisions at still higher energies.

(a) Nuclear geometry: Salmeron [40] has presented a remarkable effect. He has shown that dependence of the total and differential cross section on effective atomic mass of the target and beam nuclei can have a strong effect on the production ratio of two particles of different species. As a consequence it might stimulate a signature of QGP which is expected to be given by the yields ratio of two different particles. It is shown that this effect can explain quantitatively the $K/\pi$ ratios measured in $Si + Au$ and $S + W$ collisions as well as the decrease of the $J/\psi$ production relative to Drell-Yan lepton pairs measured in $O + CU, O + U$ and $S + U$ collisions.

(b) Models: Efforts have also gone into for creating new models for the future. Khadkikar et al. [123] have obtained equation-of-state for QGP in a relativistic harmonic confinement model. Mustafa and Ansari [124] have investigated the effects of surface and curvature to the single particle density states on various thermodynamic quantities of massless quarks and gluons confined in a spherical cavity. They found a first order phase transition of a hadronic bag to deconfined QGP phase which is very consistent with the lattice Monte Carlo results for SU(3) colour symmetry.

Flintoft and Birse [125] have studied the properties of giant colour flux tubes – colour ropes – using colour -dielectric model and showed that such ropes may be responsible for QGP formation during URHIC. Some improvements on Fritiof and VENUS models have also been suggested respectively by B. Anderson [126] and Aichelin and Werner [127] to study the high $p_T$ dynamics and reproduce the not understood distribution of $\Lambda , \bar{\Lambda}$ and $K$'s. These models thus fully support the QGP phase transition making it a more important phenomena still to be investigated.

(c) Strangeness production: Particular attention has been given to this signal. Cleymans et al. [38] have studied the hadronization process considering two scenarios for the QGP expansion. They have concluded that different freeze-out points for kaons and pions suggest that the much studied $K/\pi$ ratio is more difficult to interpret the hadronisation stage in high energy heavy ion collisions than ratios of only strange or only non-strange particles. It has also been suggested [128] that formation of QGP in URHIC may reveal itself in the azimuthal asymmetry of the ratio of the $\phi$ and $J/\psi$ meson yields which can be measured using RICH type detector. Bo and Huan Ching [129] have calculated the effect of secondary collisions of the pions produced in proton–proton collisions with secondary nucleons in the nucleus by an eikonal approximation. They found that the effect can change the $K^+/\pi^+$ ratio and that the final state interactions are important.

(d) $J/\psi$ suppression: This has been the other signal to receive due attention. Gerschel and Hufner [33] calculated the absorption cross section for $J/\psi$ per nucleon as $\sigma_{abs}^{J/\psi} = (6.2 \pm 0.3)mb$ from the baryon and photon induced reactions, and $\sigma_{abs}^{J/\psi} = (6.9 \pm 1.0)mb$ from the nucleus–nucleus collisions. From the equality of cross sections they concluded that additional $J/\psi$ suppression effects from a QGP are not expected. But Shen and Qiu [130] studied the $J/\psi$ production in URHIC and the suppression caused by the deconfinement and absorption mechanism. They analysed the effect on correlation in Bjorken’s $(1+1)$ dimensional approach successfully, giving evidence for suppression due to the QGP phase. Similarly, Cugnon and Gossiaux [131] have estimated the $J/\psi$ survival probability as a function of the time spent inside the plasma. The quantum mechanical effects are shown to lead to a smooth perpendicular momentum dependence of the $J/\psi$ suppression in agreement with the recent analysis of the NA38 data [132].

(e) Photons and dileptons: Appreciable work has been done [39, 133–136] on photon and dilepton emission as the QGP signal. Geiger and Kapusta in their calculation of the dilepton radiation in central $Au + Au$ collisions at RHIC energies have shown that there should be smooth evolution of the distribution from Drell–Yan towards quark–gluon plasma, with a clear domination of pairs from pre-equilibrium QGP over the Drell–Yan yield in the central rapidity region. Jan-e-Alam et al. [39] have claimed that at the LHC, photons having a $p_T$ larger than about 4 GeV will have their origin predominantly in the QGP. This value of $p_T$ is in agreement with the earlier estimates of $p_T > 2$ GeV [137] and $p_T > 2 - 3$ GeV [138]. Massrik et al. have shown that formation of QGP in heavy ion collisions should manifest itself by the increase of the ratio of medium to large mass dileptons, the former being produced predominantly in the QGP and mixed phase, whereas the latter produced by the Drell–Yan process. They have suggested that this increase in ratio should be visible either when comparing lighter with heavier ions ($O+O$
and \( P_b + P_b \) or when comparing low and large \( E_T \) events in \( P_b + P_b \) collisions.

(f) Intermittency: Dias de Dues [139], using one-dimensional Ising model for intermittency and scaling in rapidity distribution, has suggested that rapidity distributions show the relevance of short range correlations, but not any critical behaviour. Heiselberg [140] has studied the rapidity correlations of particle production in high energy hadronic collisions around 250 GeV in a simple model which include short range correlations in rapidity due to clustering and long range correlations due to energy conservation. He concluded that there is no need to introduce intermittency in the particle production in hadronic collisions at those energies and emphasized that long range correlations are very important at high energies. His model calculations agree reasonably well with experimental factorial moments which give much more satisfactory description that \( F_s \propto \delta e^{s} \), assuming self similarity. The factorial approach of self similarity behaviour is thus one of the useful candidates for QGP as proposed a couple of years ago [141].

This effect has been given due consideration in 2- and 3-dimensional phase space. The random-cascading model has been used [142] to describe the effect of projecting \( D \)-dimensional cascade onto \( D - 1 \)-dimensional. It leads to a nontrivial dimensional classification of projected events into three groups: bulk intermittent events, spike corresponding to a \( D \)-dimensional phase transition, and anomalous events related to shear \( D - 1 \) dimensional patterns. Application to hadron–hadron collisions is envisaged.

The above stated latest investigations carry much weight as these provide new dimensions to the QGP phenomena and have given hopes for the detection of a collective behaviour in the new heavy ion experiments at the ultra-relativistic energies.

6 The Final Word

It is widely believed that matter at higher density will certainly be produced in the new experiments. The possible operation of LHC at CERN will open the possibility to study central \( P_b + P_b \) collisions at 3.2A TeV in the near future. It will provide energy density ranging from 5 to 8 GeV/fm\(^3\), high enough to produce an ideal quark–gluon plasms [34]. The answers to other questions will also be found when uranium ion beam at 4 and 20A GeV CMS energy at CERN during probably 1998 [42] will provide the opportunities to find definite solutions to the QGP problem, if not already found earlier.

As to the question of what to measure in the future experiments and what to conclude from the results, the answers are summarized as follows [42, 144]:

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>MEASUREMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Volume</td>
<td>Hadron correlation</td>
</tr>
<tr>
<td>b. Thermalization</td>
<td>Particle ratios, strangeness evolution</td>
</tr>
<tr>
<td>&quot;Chemical and Thermal Equilibrium&quot;</td>
<td>( p_T ) spectra, nuclear stopping</td>
</tr>
<tr>
<td>c. Collective dynamics (flow)</td>
<td>Comparison of particle spectra</td>
</tr>
<tr>
<td>( \langle \pi/K/p/\ldots \rangle )</td>
<td></td>
</tr>
<tr>
<td>d. Initial temperature</td>
<td>Thermal dileptons and photons</td>
</tr>
<tr>
<td>e. Primordial state</td>
<td>( J/\psi, \psi', \gamma, \gamma' ) production, i.e. Drell–Yan; Jet production; stranglets</td>
</tr>
<tr>
<td>f. Energy density</td>
<td>Multiplicities and energies of the secondary particles, ( E_T ), nuclear stopping</td>
</tr>
<tr>
<td>g. Plasma expansion and hadronization</td>
<td>( p_T ) distribution of secondaries vs ( dN/dy )</td>
</tr>
<tr>
<td>h. Deconfinement</td>
<td>Appropriate signals</td>
</tr>
</tbody>
</table>

We now make certain suggestions for the future investigations with heavier ions at BNL and CERN energies.

6.1 Reaction Dynamics

Before giving attention to the QGP signals, it would be in the fitness of things to study the background first. Signatures of QGP transition would go unrecognized if we do not know what the background is like. It needs to investigate nuclear collisions and understand the data considering, as the first step, the conventional physics without the QGP formation. The multiparticle production, for example, would provide information on the hadronic structure and on the interaction and hadronization of their constituents. One of the associated problems is the production of low \( p_T \) hadrons whose explanation requires non-perturbative QCD, but which is still lacking. A full understanding of low \( p_T \) production may require the solution of the confinement problem.
The requirement of conventional physics to understand the background means to interpret the interactions by taking into account the incoherence, for which the multistring models Fritiof and VENUS are most suitable. But, as pointed out in the previous sections, compatibility between VENUS version of DPM and the experimental data is comparatively better. Using this model, Kawrakow et al. [143] have shown that, at LHC and RHIC energies, the energy density calculated in DPM fall well in the range where the QGP formation is expected. The improved version of Fritiof [126] and DPM VENUS [127] may well be tried in the future experiments, but a better choice would still seem to be the DPM VENUS.

It would be appropriate to try some other models also. The colour–dielectric model [125] and the microscopic fission chain model (PHASER) proposed in the recent years [144] for QGP formation and its rehadronization, may give some useful interpretation of the data to understand the background.

6.2 Nuclear Geometry

The nuclear geometry in URHIC is energy independent and a picture based on cross-talk between the overlapping volume of the two colliding nuclei (participant and spectator parts) may well be used as a guiding hypothesis for URHIC [70, 71]. This participant–spectator picture has been incorporated in most of the models [74].

6.3 Nuclear Stopping

In URHIC nuclear transparency sets in and it is important to study the nuclear stopping from the point of view of energy density estimation. It may be done by using the soft sphere model proposed for proton–nucleus and nucleus–nucleus collisions by Karol [145].

6.4 Signals

6.4.1 Intermittency

This property leads to the question about the production mechanism of relevant particles, which is highly desired to understand the reaction dynamics for QGP formation. The average transverse momentum per event play a decisive role in determining the intermittency strength.

The geometrical branching model (GBM) proposed by Hwa and Pan [146] with its Monte Carlo code ECCO [147] may be used to reproduce the properties of factorial moments $F_i$ as well as other features of multiple particle production. This model is best suited to determine the nature of multiplicity fluctuations in various parts of phase space taking the effect of multiple scattering into account. The results on multiplicity and $E_T$ distributions will prescribe the nature of conventional behaviour (successive nucleon–nucleon collisions) of multiplicity fluctuations without the formation of thermalized QGP system. Any deviation appreciably from the behaviour would be a signal for some production that is unconventional.

On theoretical side the critical fluctuations (intermittency), the relation of the fractal dimensions and the geometry of fragmentation must be understood in multifragmentation process [148].

The fractal moments are independent of $\delta y$ ($y$ being the rapidity) if the $y$-distribution is smooth, but follow the power law $\langle F_i \rangle \propto \delta y^{-\nu}$ if the distribution is fractal. The intermittency exponents are expected to behave like, $1/(n_i)$, $n_i$ being the number of collisions. However, if QGP were formed when a critical number $n_c$ of collisions were reached, a departure of the $n_i$ behaviour should be expected. Such a behaviour may be studied in terms of the DPM calculations.

6.4.2 $J/\psi$ Suppression

It is expressed in terms of the final state interaction of $\psi$ in nuclear matter. It is not unreasonable to think that the probability of final state interaction decreases with $p_T$. The problem, however, remains that no one has been able to obtain the suppression of the order of predicted 40% between large $E_T$ (central collisions) and small $E_T$ events. On the other hand, in final state interaction models, the effect should already be present in proton+U collisions, but that does not seem to be the case. It therefore requires a detailed experimental study of $\psi$ suppression in proton–nucleus and nucleus–nucleus collisions.

In order to clarify whether the $J/\psi$ suppression is due to the production of QGP, we should find the threshold energy density, below which there should be no deconfinement. Experiments should be carried out at lower energies first for central collisions to see whether there is a threshold for $J/\psi$ suppression. The existence of a threshold would be very much in favour of a QGP.

The formation of QGP in URHIC may reveal itself in the azimuthal asymmetry of the ratio of $\psi$ and $J/\psi$ yields [128]. This effect should be given due consideration.

A good test in future experiments would be to measure $N_\psi/N_{J/\psi}$ as a function of $p_T$ and as a function of $x_F$, where $x_F$ is the Feynman–$x$ [40]. If the decrease of ratio as $p_T$
decreases is due to QGP, it must show the same treatment as a function of \( x_F \) and as a function of \( p_T \), because for small \( x_F \) and small \( p_T \) the \( q \) and \( \bar{q} \) quarks would stay longer in the plasma: a constant or decreased ratio as \( x_F \) increases would be against the presence of a QGP.

If there is signal of QGP in \( J/\psi \) production, we should expect a signal also in dilepton pairs with mass smaller than the \( J/\psi \) mass. The argument of the \( J/\psi \) suppression would be strongly supported by experimental evidence on the presence of dilepton yield. It may be difficult to imagine that \( J/\psi \) would be suppressed by QGP, but there would be evidence for the increased dimuon yields due to the thermalization stages of the heavy ion collisions.

### 6.4.3 Dilepton Emission

This is an important signal and needs due attention. The collective effects could be experimentally studied by: (i) comparing dilepton spectra produced in central collisions (largest total \( E_T \)) of light (e.g. \( O + O \)) and heavy (e.g. \( Pb + Pb \)) collisions [134]. The effects should be visible when both spectra are normalized to the same value in the mass region dominated by the Drell-Yan mechanism, (ii) comparing dilepton spectra in peripheral and central heavy ion collisions, (iii) studying the dependence of the ratio of experimental dilepton production on the assumption of "no collective" effects being present. The ratio should significantly increase when comparing central to peripheral collisions. These studies should be performed for a particular dimuon mass bin, say for example, \( 1.5 < M < 1.9 \) GeV/c [134].

Under a few reasonable assumptions it may be assumed [149] that once the QGP is created in URHIC, the observed dilepton spectrum between the \( \phi \) and \( J/\psi \) peaks become dependent essentially only on its transverse mass \( M_T \) and shows \( M_T \) scaling. This scaling will not be observed if the QGP is not created in the collisions.

### 6.4.4 Transverse Momentum

It also needs to be given considerable attention. At CERN (LHC) energies, photons having \( p_T > 4 - 5 \) GeV are shown to have their origin predominantly in the QGP phase [39]. But the fragmentation of a final state quark in parton–parton scattering leading to a photon is to be the largest QCD background at LHC. So measures should be taken to discriminate between the two.

### 6.4.5 Particle Spectra

Particle production will be an interesting feature. K. Geiger [150] has studied particle production at LHC and RHIC energies in parton cascade-cluster hadronization model. It has been shown that in contrast to proton–proton, the hadronic momentum distribution in \( Au + Au \) collisions exhibit a resemblance with thermal spectra which indicate the reflection of thermalization properties of the partons during the nuclear reactions. This may offer the possibility to learn about a QGP phase transition from analysing the hadronic spectra of URHIC.

Enhanced production of strange particles, particularly strange and multi-strange antihyperons, which would be slow to equilibrate and are not easily produced in hadronic collisions, should be a good indicator of plasma formation. Experimental data on as many strange particle species as possible are therefore of considerable interest for QGP search. The \( K^+ + K^- \) yield in kaon production should be considered when discussing strangeness enhancement [41].

An important parameter in multiparticle production in the QGP search is the local charged particle density \( \rho \), since it can be related to the energy density [31]. New insight can be gained, fruitful for prediction on future accelerator based experiments for examining how \( \rho \) varies with incident energy, projectile and target masses, and global multiplicity.

The effective \( A \)-dependence of cross section can simulate the signatures of QGP which should be given by ratios of particle production. In particular it can explain quantitatively the experimental results on \( K^+ / \pi^+ \). The cross section for \( A_1 A_2 \) (nucleus–nucleus) collisions are functions of \( A_t \) and \( A_b \), which are respectively the effective target and beam (projectile) atomic masses [40]. The total and invariant differential cross section are parametrized as:

\[
\sigma(A_1 A_2) = \sigma(A_t \cdot A_b)^\alpha
\]

and

\[
E \frac{d^2\sigma}{dp^2} (A_t \cdot A_b) = E \frac{d^2\sigma}{dp^2} (A_t \cdot A_b) \left( \frac{(A_t \cdot A_b)\alpha_{(\pi \pi)}}{(A_t \cdot A_b)\alpha_{(\pi \pi)}} \right)
\]

There is an enormous lack of experimental information on the \( \alpha 's \) for the production of most of the particles, including the strange particles. If a QGP signature must unavoidably be given by the ratio of two particle production, then the precise measurement of \( \alpha \) and \( \alpha(x_F, p_T) \) in nuclear interaction should be made for the two particles, in the same regions of \( x_F \) and \( p_T \) as those in which the QGP is searched for. This is absolutely essential before any conclusion can be drawn.
The ratios of only strange or only non-strange particles should also be tried [38], and in particular an increase in \( \pi^+ / \Lambda \) ratio be studied as a signal for QGP formation [151]. Similarly the enhanced \( \phi \) meson production as \( \phi / (\rho + \omega) \) should better be investigated in the new experiments [41].

### 6.4.6 New Signals

A couple of new signals may be suggested for the future investigations at BNL and CERN with the larger ion beams.

(a) In heavy ion collisions each quark-quark or the quark-antiquark interaction give rise to cluster of hadrons and the fluctuations in number of such clusters produce long-range correlations [152]. The data can be described by a linear expression \( \langle N_D \rangle = a + b N_P \), where the slope 'b' measures the long-range correlation. Such long-range correlation should vanish at fixed multiplicity if some collective phenomena takes place. With the exception of a model independent approach [67], there is no model dependent data available and hence a study of these correlations is all the more important as it can be related to the detection of QGP formation.

(b) A signal related to the transverse momentum \( p_T \) distributions has been proposed recently [152] in connection with the QGP detection. After the ISR data, none of the more recent experiments has looked for it. If one studies the ratio between the dispersion \( D \) and the distribution as a function of \( 1/N \), \( N \) being the multiplicity, a straight line on statistical basis should be expected crossing the origin. If some collective effect takes place like the QGP formation, departure of the straight line should appear.

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### References

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Fig. 1 Distribution of rapidity density ratio $R(y)$ from p+Xe to p+p collisions. Maximum in target fragmentation region exceeds several times the value $v$ of the average number of inelastic collisions inside the nucleus.

Fig. 2 Illustration of the quark-quark interaction for nucleon-nucleon collision in the Additive Quark Model.
Fig. 3 Mechanism of (a) hardon-nucleus and (b) nucleus-nucleus collision in the Additive Quark Model.

Fig. 4 Mechanism of (a) nucleon-nucleon and (b) nucleon-nucleus collision in the Dual Parton Model.

Fig. 5 Comparison of experimental charge multiplicities with theoretical values in Dual Parton Model for (a) B+Ag and (b) Ca+Pb collisions at 0.3 A TeV.

Fig. 6 Comparison of experimental charge multiplicities with theoretical values in Dual Parton Model for (a) 3.6 A TeV Si+Ag(Br) and (b) 100 A TeV Ca+C collisions.
Fig. 7 The rapidity densities obtained in Additive Quark Model are compared with the Dual Parton Model calculations for various combinations of projectile and target masses.

Fig. 8 Exchange of strings between two excited hadrons: (a) in Dual Parton Model there is colour exchange between the two hadrons, (b) in Fritiof there is exchange of momentum between the incoming hadrons.

Fig. 9 Calculated rapidity density distributions for central O+Au collisions in Dual Parton Model and Fritiof.
Fig. 10 Calculated rapidity density distributions for central — and total — collisions of O+Pb at 200 A GeV. Difference in the leading baryon spectrum is due to the different momentum carried by the valence quarks and diquarks.

Fig. 11 Experimental rapidity distributions for central, medium and peripheral collisions of O+Au due to WA80 collaboration compared with model calculations —— Fritiof and —— Dual Parton Model. Difference between the experimental and calculated values in the central rapidity region is obvious.
Fig. 12 & Fig. 13 Comparison of experimental results from Helios collaboration for O+Pb collisions with the values calculated in Dual Parton Model. Agreement is close for a formation time $t_c = 2-3$ fm.

Fig. 14 Helios collaboration results on $E_T$ distribution in the target fragmentation region for O+Al, O+Ag, O+W and S+W collisions. Comparison of these experimental values with Dual Parton Model calculations without the cascading effect shows discrepancies.
Fig. 15 $E_T$ distribution for O+W collisions. Experimental values from Helios collaboration agree with Dual Parton Model values — with cascading for a formation time of $\tau = 3$ fm.

Fig. 16 Experimental data on multiplicities. The data lie on a KNO curve for $nP_n$ distribution as a function of $n/n_p$ for O+Pb collisions.

Fig. 17 Multiplicity Vs dispersion for a variety of projectile and target nuclei at CMS energies 31 GeV and 62 GeV. Evidently $D = \langle N \rangle$ due to scaling.

Fig. 18 Trend of the $P_T$ distributions for low and high multiplicities at 1.8 TeV based on NA35 collaboration results on single $P_T$ distribution for O+Au and $p+Au$ collisions.
Fig. 19 NA35 data for $P_T$ distribution from 200 A GeV O+Au collisions compared with Fritiof calculations as a function of high to low multiplicity ratio $R(P_T)$.

Fig. 20 Experimental results based on central O+Emulsion collisions comparison at 200 A GeV of p+Em data & O+Em data with Fritiof.

Fig. 21 Black prong number distribution for A: 14.6 A GeV Si, B: 60 A GeV O$^{16}$, C: 200 A GeV O$^{16}$ and D: 200 A GeV S$^{32}$ interactions in emulsion. Comparison with calculated distribution in VENUS show significant departure.
Fig. 22 Helios collaboration results from 200 A GeV O\textsuperscript{16} and S\textsuperscript{32} interactions in emulsion and in emulsion-tungsten chamber. Global parameters have been compared with the Dual Parton Model to investigate transverse energy, multiplicity and rapidity density distributions.

Fig. 23 Theoretical behaviour expected from $<p_T>$ distribution as a function of energy density $\varepsilon$ for QGP formation.
Fig. 24 Experimental $P_T$ distribution of $K^0$ as a function of invariant differential cross-section (a) 60 A GeV O + Au, O + C and p + Au collisions, (b) 200 A GeV O + Au, O + C and p + Au collisions, and (c) comparison of central with peripheral 200 A GeV O + Au collisions.

Fig. 25 NA 34 collaboration results on $P_T$ distribution of negative particles (mainly pions) as a function of invariant differential cross-section in central collisions of (a) 200 A GeV p + W, (b) 200 A GeV O + W, and (c) 200 A GeV S + W for the interval 1.0 < c < 1.9.
Fig. 26 NA 34 collaboration results on $P_T$ distribution as a function of $P_T$ ratios from proton-, O- and S-interactions.

Fig. 27 NA 38 collaboration data on $J/\psi$ production in 200 A GeV O + U collisions.

Fig. 28 Photon emission visualized from hot QGP. Such photons have a small probability to interact in the outer freeze-out region.

Fig. 29 NA 34 collaboration results on inclusive photon production (1.0<1.9) in (a) $p + W$, (b) $O + W$ and (c) $S + W$ collisions at 200 A GeV.

Fig. 30 WA 80 collaboration results on inclusive photon $P_T$ spectrum produced in (a) 200 A GeV O + Au, (b) 60 A GeV O + Au, (c) 200 GeV p + Au, (d) 200 A GeV O + C and (e) 60 GeV p + Au collisions.
Fig. 31 NA 38 collaboration results on J/ψ production in p + U, O + U, O + Cu and S + U collisions at 200 A GeV. (a) Number distribution dN/dM as a function of mass, (b) S-distribution as a function of E_{T} and (c) Ratio R of S-values as a function of P_{T}.

Fig. 32 KLM collaboration results on intermittency studies giving behaviour of slope in (a) p + Em interactions at 200 and 800 GeV/C, (b) O + Em interactions at 60 and 200 A GeV.

Fig. 33 WA 80 collaboration results on intermittency showing variation of slope ψ at 200 A GeV in (a) O + C and (b) O + Au collisions.
Fig. 34 EMUO1 collaboration results on factorial moment $<F_{aq}>$ distribution as a function of pseudorapidity bin size in 200 A GeV S + Au collisions. Results are compared with model calculations.

Fig. 35 Distribution of function $f(a_q)$ which characterize the multiplicity fluctuation as a function of $a_q$ (a) emulsion experiment results, (b) distributions calculated in Fritiof.

Fig. 36 Emulsion experiment results on scaled factorial moments ($F_j$) in (a,b) one dimensional and (c) two dimensional phase space.
Fig. 37 Emulsion experiment results on scaled factorial moments $\langle F \rangle$ in (a,b) one dimensional and (c) two dimensional phase space for 14.5 A GeV Si$^{28}(\oplus), 200$ A GeV O$^{16}(\bullet)$ and 16 A GeV S$^{32}(\ast)$ collisions.

Fig. 38 E 802 collaboration results on kaon to pion ratios compiled for p + p and p + Pb interactions at comparable energies.

Fig. 39 Double ratio $|\text{kaon/pion (E 802)}|/|\text{kaon/pion (Fritiof)}|$ plotted against $P_T$ to find a comparison of experimental results with model calculations.
Fig. 40 NA 34 collaboration results on kaon and pion emission in 22 A GeV S + W interactions (a) transverse mass spectra for kaon and pions, (b) positive and negative kaon to pion ratio as a function of transverse momentum.

Fig. 41 NA 35 collaboration results on K⁰ and λ production in 200 A GeV S + S interactions compared with model calculations — Fritiof NN model.

Fig. 42 WA 85 collaboration results on the production rate of λ and pions as a function of multiplicity of charged particles in 200 A GeV S + W central collisions. Figure gives average number per event of (a) negative hadrons <n⁻>, (b) of λ's <n₂> and (c) of the λ's <n₂>.

Fig. 43 WA 85 results on ratios of <n⁻>, <n₂> and <n₂> to the multiplicities in central S + W collisions at 200 A GeV.