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Coherence and Chaos in the Interacting Gluon Model *

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Abstract

The quantum statistical concepts of coherence and chaos used to describe fluctuations in multiparticle production processes are exhibited in a generalized version of the Interacting Gluon Model. The two components in the multiplicity distributions found prviously are derived in this approach. We present the first Monte Carlo generator with coherence built in.

SINS Preprint - 2/PVIII/June 1992

FMILA 1992

Presented by G.Wilk at
The First German-Polish Symposium on Particles and Fields,
28 April - 1 May, 1992, Rydzyna Castle, Poland

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*Supported in part by the Bundesministerium für Forschung und Technologie (BMFT) under the contract POL-514/Projekt X081.12 and by the Polish State Committee for Scientific Research Grant No. 2 0957 91 01.

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be regarded as a suitable modification of the gluonic cluster model proposed some time ago [5]. Notice also its resemblance to the Weizsäcker-Williams method [6] of equivalent photons applied to the hadronic interactions with gluons playing the role of photons. The picture of violently interacting gluons is also consistent with the possible, intrinsically "chaotic" properties of the non-Abelian gauge fields found recently [7]. It suggests a more rapid dissipation of the kinetic energy of the colliding gluonic clouds and its redistribution among collective excitations on a time scale much shorter then that provided by estimations based on perturbative QCD.

We would like to demonstrate here that a suitably extended version of the IGM provides a solid and natural basis for the two-component model of multiparticle production developed in [3]. The extension consists in a more detailed description of multiparticle production processes. This is achieved by providing in the IGM a prescription for the dissipation of the predicted energy flow into the finally observed secondaries. Technically this is achieved through a Monte Carlo version of the model. [1]

2. Monte-Carlo event generator formulation of the IGM In the IGM: (*i*) The two impinging projectiles are represented by the valence quarks accompanied by the clouds of gluons (where by gluons we understand both the intrinsic gluons and the $q\bar{q}$ pairs of sea quarks). (*ii*) In the course of collision these gluonic clouds interact strongly forming a number of objects which we call *mini-fireballs* (MF's) and which populate mainly the central region of reaction. (*iii*) The valence quarks (together with the gluons which did not interact) form *leading jets* (LJ's) which populate mainly the fragmentation regions of reaction. (*iv*) Both MF's and LJ's hadronize, each LJ producing a corresponding *leading particle* (LP) (defined as the most energetic particle in a given hemisphere of reaction; notice that occasionally LP can also emerge from a MF). Point (*iii*) is the main new ingredient in the present version of the IGM; previously, we had just identified LP's with LJ's.

The IGM differs from other models of this type [8,9,10] in that it explicitly emphasizes the role of gluons as main degrees of freedom, although it can also be regarded as providing a dynamical basis for the models presented in [11,12,13].

To model point (*i*) we introduce a suitable statistical representation of a colliding hadron $|h>$ in terms of its partonic components: n valence quarks and m gluons [14] (with x_i's and y_j's being their respective energy-momentum fractions)

$$|h>= C\cdot\left[\prod_{i=1}^{n} x_i\right]^{\epsilon}\cdot\left(1-\sum_{i=1}^{n} x_i\right)^{\beta}\cdot\prod_{j=1}^{m}\left[y_j^{\gamma}\cdot(1-y_j)^{\eta}\right]\cdot\delta\left(1-\sum_{i=1}^{n} x_i-\sum_{j=1}^{m} y_j\right). \quad (1)$$

There are constraints on the parameters ϵ, β, γ and η resulting from the $(x,y)\to 0$ (Regge) and $(x,y)\to 1$ behaviour of the single valence quark and gluonic distributions

$$v(x) := \frac{1}{\sqrt{x}}(1-x)^{n_V} \quad \text{and} \quad g(y) := \frac{1}{y}(1-y)^{n_G}, \quad (2)$$

[1] An advantage of such an approach is that it allows for a straightforward application to nuclear collisions.

which can be derived from eq.(1). One expects therefore (assuming for simplicity only one flavour) that $\epsilon=-0.5$, $\gamma=-1$ and $n_V=(n-1)(1+\eta)+\beta=2(n-1)-1+\bar{\beta}$, where $\bar{\beta}=\beta-\frac{3}{2}(n-1)+1$ measures the departure from simple counting rules[2]. Similarly, in order to get $n_G\geq 5$, as expected [4], one has to adjust η to be in the range of $\eta\approx 3\div 5$. With these values of the parameters the average fraction of the energy-momentum of a hadron allocated to the gluonic component is equal to

$$<q>= 1-n\cdot<x>= 1-n\cdot\frac{\int_0^1 dx\,x\,v(x)}{\int_0^1 dx\,v(x)} \simeq \frac{3n-3+2\bar{\beta}}{4n-3+2\bar{\beta}}. \quad (3)$$

In what follows we shall consistently neglect all masses and transverse momenta of the colliding objects (both partons and nucleons, cf. [4]). They will, however, appear in the hadronization stage of the process. We shall always work in the hadron-nucleon c.m. frame. Our algorithm looks as follows:

(1) For both the projectile (P) and target (T) hadrons participating in the collision, we sample $x_i\in(0,1)$, $i=1,\ldots,n=n_{P,T}$ according to the dist.ibution,

$$P(x_i) := \frac{1}{\sqrt{x_i}}\cdot(1-x_i)^{2(n-1)-\frac{1}{2}(i+1)+\bar{\beta}}, \quad (4)$$

and calculate the fractional momenta of valence quarks, x_i, and the energy-momentum fractions of P (or T) allocated to gluons, $q=q_{P,T}$,

$$x_i = x_i\cdot\prod_{k=1}^{i-1}(1-x_k) \quad \text{and} \quad q = 1-\sum_{i=1}^{n} x_i. \quad (5)$$

With q determined we sample gluons with energy-momentum fractions $y_j\in(K^2_{min},1)$, $K_{min}=\frac{2\mu}{\sqrt{s}}$, according to the distribution

$$P(y_j) := \frac{(1-y_j)^{\eta}}{y_j}. \quad (6)$$

In doing so only gluons which can produce at least one MF of mass $M\geq 2\mu$ (which is the mass of the lightest possible fireball) are allowed. This process continues until $\sum y_j\leq q$. It results in two sets of gluons: $G_P(\{x_i\};i=1,\ldots,N_P)=[x_1,x_2,\ldots,x_{N_P}]$ from P and $G_T(\{y_j\};j=1,\ldots,N_T)=[y_1,y_2,\ldots,y_{N_T}]$ from T (notice the change in notation: $\{x_i\}$ and $\{y_j\}$ denote now the *gluonic* fractional momenta in P and T, respectively).

To describe the actual collision process (point (*ii*) above) we have to specify the nature of gluon interactions in our model. We shall assume that in every gluon-gluon interaction a MF (or clan, cluster,...) can be formed through a gluonic fusion process. In principle this MF can also resemble a 'short string' coming from the $gg\to gg$ (or other) types of processes.) These gluonic interactions represented summarily by cross section σ_{gg} should be understood as an effective interaction (our gluonic clouds, containing both genuine

[2] It is interesting to note that only with $\gamma=-1$ the single quark and gluon distributions given by eq.(2) do not depend on the actual number m of gluons in $|h>$, eq.(1).

gluons and sea $q\bar{q}$ pairs, are effective ones). Notice that σ_{gg} and the structure functions used are defined at a scale $Q \leq 1$ GeV where perturbative QCD breaks down and no reliable predictions are possible. Therefore σ_{gg} must be considered as a phenomenological function to be determined by fitting multiparticle production data. We shall therefore simply parametrize it as before [4] (with $M = \sqrt{x_i y_j \cdot s}$ being an invariant energy in the particular $g_i + g_j$ collision equal to the invariant mass of the produced MF),

$$\sigma_{gg}(M) = \tilde{\sigma} + \alpha \frac{K^2_{min}}{xy} + \tilde{\delta} \cdot \ln\left[\frac{xy}{K^2_{min}}\right] = \tilde{\sigma} + \frac{4\mu^2\alpha}{M^2} + \tilde{\delta} \cdot \ln\left[\frac{M^2}{4\mu^2}\right], \qquad (7)$$

and introduce the (unnormalized) probability of interaction between gluons with $x_i \in G_P$ and $y_j \in G_T$,

$$P_{ij} = P_{ij}(x_i; y_j) = \frac{\sigma_{gg}(M^2 = x_i y_j s)}{\sigma^{inel}_{hN}(s)}, \qquad (8)$$

with σ^{inel}_{hN} being the experimentally measured total inelastic hadron-nucleon cross section. With the probabilities P_{ij} defined above we continue our algorithm:

(2) For every $x_i \in G_P$, $i = 1, \ldots, N_P$, and for every $y_j \in G_T$, $j = 1, \ldots, N_T$, such that $x_i y_j \geq K^2_{min} = 4\mu^2/s$ (i.e., for all pairs of gluons from P and T capable of producing at least the lightest MF) we check if [*random number*] $< P_{ij}$. A positive answer means that this pair did interact, a negative one that it did not. We collect together all gluons from P and from T which did interact *at least once* among themselves and identify them with a kth *mini-fireball*, MF, of mass M_k and rapidity Δ_k,

$$M_k = \sqrt{x_k y_k \cdot s}, \quad \Delta_k = \frac{1}{2} \ln \frac{x_k}{y_k}; \quad x_k = \sum_{x_i \in k^{th}\mathrm{MF}} x_i, \quad y_k = \sum_{y_j \in k^{th}\mathrm{MF}} y_j. \qquad (9)$$

There will be $1 < N_c < \mathrm{Min}(N_P, N_T)$ sets of such gluons, therefore $k = 1, \ldots, N_c$. Gluons which did not interact join the corresponding valence quarks of P and T and together with them form *leading jets* (LJ's) with the corresponding energy-momentum fractions equal to

$$x_L = 1 - \sum_{k=1}^{N_c} x_k \quad \text{and} \quad y_L = 1 - \sum_{k=1}^{N_c} y_k \qquad (10)$$

for LJ's from P and T, respectively. We continue if the corresponding leading particles of mass m_L can be produced, i.e., if x_L and $y_L > \frac{2m_L}{\sqrt{s}}$, otherwise the event is rejected. If none of the gluons interacted, the event is not regarded as inelastic and is rejected.

Notice that this procedure is just the realization of a simple probabilisitic picture of a collision of two composite objects (as applied e.g. in [15] for nuclei). It does not depend on any particular space-time ordering of the elementary gluon-gluon collisions (this will change, however, in pA and AA collisions where nuclear scales will be involved).

The produced LJ's will be able to hadronize only if their (invariant) masses exceed the mass of the leading particle mass, $M_{LJ} \geq m_L$. Because the original IGM (where $M_{LJ} = 0$) does not allow such a possibility, it has to be built in. We follow the observation [17] that

even quite modest longitudinal momentum transfers can result in substantial excitations of the colliding systems and we allow for such a fractional transfer δ between the valence parts of colliding hadrons (treated for simplicity as well defined single objects) during the course of a collision. This transfer is assumed not to interfere with the production process operating between gluons [3]. As a result we shall obtain the following four-momenta P_{LJ}, invariant masses M_{LJ} and rapidities Y_{LJ} of LJ's:

$$P_{LJ} = \frac{\sqrt{s}}{2}\left[x_L, \vec{0}, \bar{s}(x_L - \delta)\right], \quad M_{LJ} = \frac{1}{2}\sqrt{s\delta(2x_L - \delta)}, \quad Y_{LJ} = \frac{\bar{s}}{2} \ln \frac{2x_L - \delta}{\delta}, \qquad (11)$$

where $x_L = x_L(y_L)$ and $\bar{s} = \pm 1$ for P and T respectively. From the requirements that $M_{LJ} \geq m_L$ and $Y_{LJ} > 0$ (i.e., that the produced LJ's be contained in the respective hemispheres of the reaction) one gets

$$\delta_{min}(\bar{x}_L) = \bar{x}_L - \sqrt{\bar{x}_L^2 - \frac{4m_L^2}{s}} < \delta < \delta_{max}(\bar{x}_L) = \bar{x}_L, \quad \bar{x}_L = \mathrm{Min}(x_L, y_L). \qquad (12)$$

(3) We now continue with the part of our algorithm corresponding to point (*iii*) by selecting the δ's (treated as free parameter)[4] and forming the respective LJ's of P and T with masses and rapidities given by eq.(11). This completes the description of the *formation stage of the collision process.*

We would like to note that, with the formation stage (1-3) completed, we have already provided *initial conditions* for statistical models of multiparticle production [11,12,13] as well as for a variety of stochastic [18] and cluster [19] models of multiparticle production in which some initial distributions of the number of clusters N_c are usually simply postulated and their masses and rapidity distributions are either left unknown or do not enter at all. The advantage of the present approach lies in the ability to provide *distributions* of all these three elements: the number of clusters N_c, their masses M_k and rapidities Δ_k.

(4) We conclude our algorithm with the hadronization of MF's and LJ's using, respectively, the Maximalization of the Information Entropy (MIE)[20] and Sequential Decay Model (SDM)[21] approaches. In this way we account for the dynamical differences between secondaries emerging from both the central and fragmentation regions of the reaction (which is the main point of the two-component model[3]).

3. A representative sample of results All the results listed below were obtained for the following values of parameters: $\tilde{\beta} = -0.5$, $\eta = 5$, $\mu = 0.6$GeV, $\tilde{\sigma} = 2$mb, $\sigma^{inel}_{hN}(s) = 39.5s^{-0.38} + 21.7s^{0.08}$(mb)[22], $\kappa = 1$, the mean multiplicity of secondaries from MF of mass M being equal to $N(M) \simeq 2.35M^{0.5}$ and their mean transverse momenta equal to $< p_T >= 0.35$ GeV/c (used as input in the MIE hadronization procedure); the LJ was fragmented into secondaries (in the SDM scheme) according to the distribution: $P(q) := (1 - q/M_{LJ})^f/q$ (where q is the momentum of the produced particle), f is a free parameter which is zero for pions; for nucleons it decreases with s from

[3] Notice that in order to have $M_{LJ} > 0$ (i.e., time-like) we must always *decrease* the corresponding x_L and y_L.

[4] Here we have assumed that in a given event $\delta = \kappa \cdot \sqrt{\delta_{min}}$ and treated κ as a free parameter. This leads to $M^2_{LJ} = const \cdot \sqrt{s}$, as in Ref. [17].

$f = -0.65$ at $\sqrt{s} = 20GeV$ to $f = -0.98$ to $\sqrt{s} = 1800GeV$. (This drastically different behaviour of the production of nucleons in comparison to pions was vital in obtaining, among other things, satisfactory results for the moments C_k of the multiplicity distributions). The probability of emitting a nucleon in a given SDM fireball was fixed at $w_{nucl} = 0.5$ (and taken zero once the nucleon was emitted) whereas its p_T was chosen from the $\exp[-(p_T/0.55)^2]$ distribution. In Fig. 1 we show the pseudorapidity distributions $dN/d\eta$: (a) - for several energies as compared with data [23] and (b) - at $\sqrt{s} = 540$ GeV with the

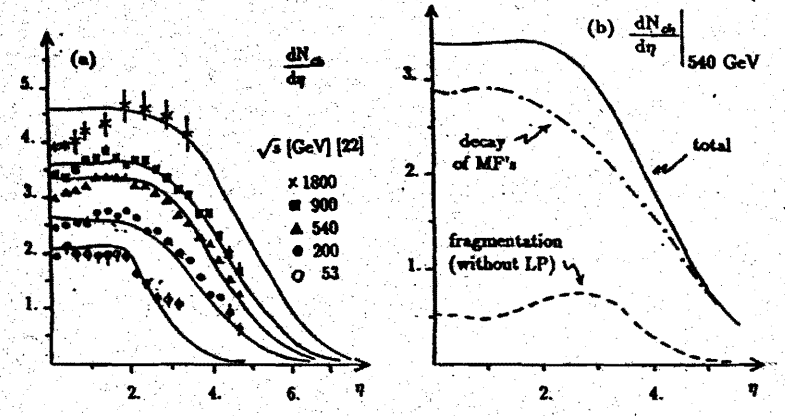

Figure 1: (a)- the pseudorapidity distributions for different energies; (b) - the different components of $\frac{dN}{d\eta}$.

contributions from MF's decays and LJ's fragmentation. In Fig. 2 we show the energy dependences: (a) - of the mean charged multiplicities and (b) - of the first five moments of the multiplicity distribution $P(n)$, $C_k = < n^k > / < n >^k$ [23]. The number of MF's (not shown explicitly) is Poisson distributed with $< N_c(s) > \simeq 0.86\sqrt{s}^{0.18}$ whereas the distribution of their masses resembles the gamma distribution with $< M_c > \simeq 0.1\sqrt{s}^{0.54}$, which effectively leads to a $P(n)$ from this component of a NB type [3] with $< n_{gg}^{ch}(s) > \simeq 1.\sqrt{s}^{0.5}$. On the contrary, the two LJ's provide together a Poisson-like distribution of secondaries with $< n_{LJ}(s) > \simeq 4.5 + 0.4 \ln \sqrt{s}$ (cf. Fig. 2a). The total (charged) multiplicity is therefore given by $< n(s) > = < n_{gg}(s) > + < n_{LJ}(s) > \simeq 2.8\sqrt{s}^{0.38}$ (cf. Fig. 2a) which coincides with that of Ref.[3]. We interpret this result (as in [3]) as an example of the convolution of the *chaotic* and *coherent* components. In Fig. 3 we present the energy (a) and rapidity (b) dependences of the chaoticity parameter p defined as $p = < n_{gg} > / < n >$ (for $\sqrt{s} = 540$ GeV and for the pseudorapidity window $\Delta\eta = 0.6$). In Fig. 3a we show, for comparison, also the energy behaviour of the relative gluonic inelasticity K_E defined as the ratio of the energy coming from the gg interactions and the total energy used for the production of secondaries. It shows essentially the same trend as p but seems to level off at much lower energies than p. On the other hand our $p(\eta)$ is systematically higher than that obtained in Ref.[3]. One should, however, keep in mind the fact that we have now for the first time included properly the energy conservation resulting in strong energy

fluctuations in both components. Therefore our chaotic and coherent components are

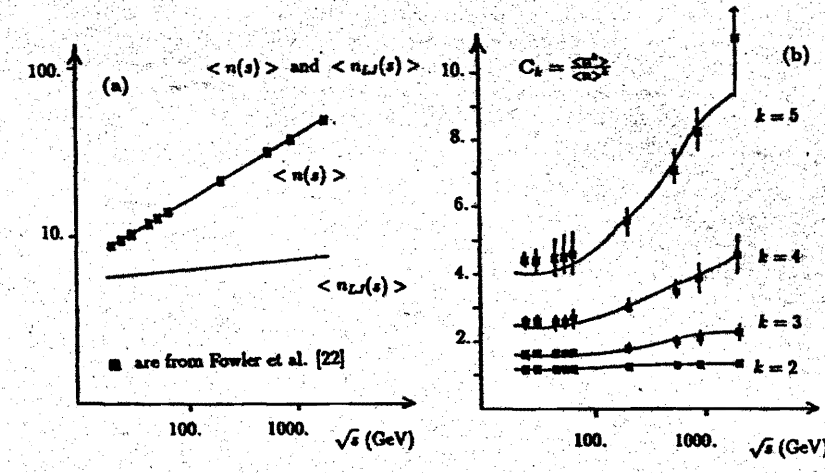

Figure 2: The energy dependence of $< n >$ and $C_{k=2,...,5}$.

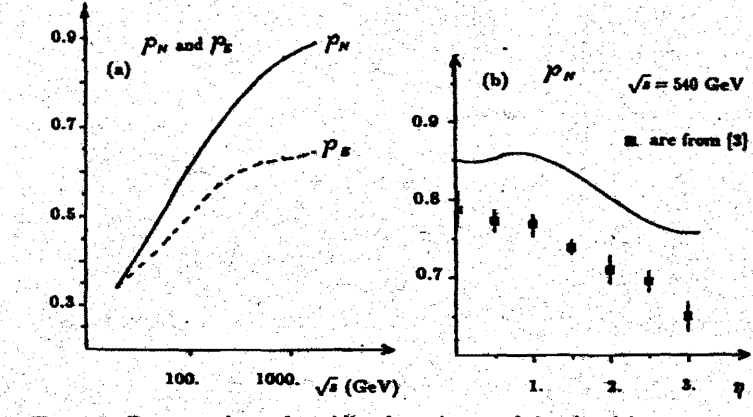

Figure 3: Energy and pseudorapidity dependences of the chaoticity parameter p_N and energy dependence of the relative gluonic inelasticity p_E.

necessarily averaged over the exact NB and Poissonian distributions used in Ref.[3].

4. Summary The two-component model of ref. [3] uses *chaoticity* and *coherence* as " macroscopic" characteristics of the collision process [2]. It does not specify, however, their dynamical origin and behaviour, limiting therefore the range of its possible appli-

cations. The phenomenological picture of the gluonic dominance of inelastic collisions presented here fills this gap and allows for much more detailed studies of multiparticle production processes. The Monte Carlo generator presented here is the first MC algorithm which accomodates QS coherence in multiparticle production processes. Incoming hadrons are necessarily coherent and it is reasonable to expect that they maintain this property in the bremsstrahlung like processes (in our case represented by the formation and decay of LJ's). However, they do lose coherence in the strong gg multiple collisions leading to the formation of MF's. But even here the resultant state cannot be regarded as being totally chaotic (although above it was treated as such) because the corresponding $P(n)$ is not thermal but of narrower NB type (cf. also the last paper in [3] where such a possibility was already mentioned). There is also a natural threshold in the incoherent gg interaction represented by the lightest MF. Its importance, however, fades away with growing energy leading in a natural way to the increase of chaoticity with energy (cf. Fowler et al. in [23]). On the other hand the details of the gg interaction resulting in a given mass and rapidity distribution of MF's and the mechanism of the excitation of the LJ's are mainly responsible for the observed behaviour of the chaoticity parameter as a function of rapidity. It would be therefore highly desirable to be able to measure this parameter more directly both as a function of $\sqrt{s}$ and rapidity, for example by exploiting the Bose-Einstein correlations [2].

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