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The Firecracker Model, a Possible Collective Effect in High Energy Heavy-Ion Collisions

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Abstract

We present a possible collective gluon emission effect based upon a string-like scenario (available if the QCD vacuum works like a color-superconductor type II, i.e. when the color force fields work like vortex-lines) and provide some detailed predictions on the Cronin effect, as well as on an increased (mini)jet production in the center of phase-space in high energy heavy ion collisions.

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1 Introduction

Investigations of high energy heavy ion collisions are usually motivated by the possibility to study QCD in a new and exciting environment, ie when there is a large energy density or a large baryon number density available. It is already known from the present experimental data, compared to extrapolations from single hadron-hadron collisions at the same energy, that some collective phenomena are present. Thus the data exhibit some large $p_\perp$, strangeness and antibaryon enhancement. It should be noted that the energy density, expected to be needed for quark-gluon plasma (QGP) formation, seems to be available in the present SPS-experiments at least in the central 200 AGeV S-Au collisions.

Before claiming that the experiments are evidence for the formation of a QGP it is, however, necessary to investigate whether these results can be understood inside a more "conventional" scenario. There are at present few possibilities (beside the static lattice QCD calculations) to provide predictions for the detailed experimental observables from more basic dynamical principles. Therefore we have to take recourse to phenomenological models for such investigations.

We will in this paper consider a string dynamical scenario. In particular we will extend and provide a detailed structure for the "Fire-Cracker Model" (FCM) for collective multiple gluon emission, [1]. The idea is that the QCD vacuum might work as a color superconductor type II. Then the basic objects should be the QCD force-fields working in a way similar to vortex-lines in a superconductor. Such objects must have dynamical properties very similar to the mass-less relativistic string, which is at the basis of The Lund Model. When many string-like QCD force fields are available in a small space-time region it is conceivable that they interact. As we will discuss below this may result in some non-trivial collective bremsstrahlung emission phenomena.

It is known from e^+e^--annihilation reactions that perturbative QCD really provides a "string-like" scenario, which also explains the present data very well. Thus bremsstrahlung emission, in accordance with the strong angular ordering conditions of perturbative QCD, tend to produce states containing many partons connected by fields of a stringlike character.

Given the color ordering, the Webber-Marchesini model provides a "chain" of hadron clusters along the same regions where the final state hadrons will emerge according to treatment of the more "solid" Lund String Model. This is the reason why the models, although conceptually very different, nevertheless provide similar predictions. The preliminary results from HERA (and the earlier low-energy DIS experiments) also support such a string-like structure for the QCD force fields.

The question is, however, whether this "string" should be considered as similar to a vortex line in a color superconductor. This has been suggested theoretically from considerations of the basic QCD equations a long time ago [2]. But the fact that there are gluonic field configurations with properties similar to a superconductor and with a lower energy than the "empty" state does not imply that this is the structure of the QCD vacuum, ie the lowest energy state. Further it is not known whether such a QCD vacuum behaves as a superconductor type I (providing transversely wide "flux tubes") or more like a type II (with a truly "thin" vortex-line string structure).

For an electro-magnetic superconductor type II there are three regions of interest when one considers the magnetic field $\mathcal{H}$ as the order parameter. When the field is below a certain (material-dependent) value, $\mathcal{H}_1$ the Meissner effect works but in a region $\mathcal{H}_1 \leq \mathcal{H} \leq \mathcal{H}_2$ the quantized vortex lines start to penetrate the superconducting state and exhibit a repulsive relative interaction. Above $\mathcal{H}_2$ the field is so strong that the whole region "melts" into a state of the same character as the break-down of a superconductor type I. This "melted" vacuum state is often used as an intuitive picture for the QGP.

The FCM might work inside the corresponding intermediate region (with the energy density as the order parameter). This means that the strings at this stage interact but still keep some individuality. As we will show below the model then provides a very effective way to *disperse a large energy density by fast and hard gluon emission.*

Several of the models for hadronic collisions are based upon string-like behaviour (the Lund FRITIOF, [3][4] and PYTHIA [5] models). The authors of Dual Parton Models ([6]), working from the Gribov Reggeon scenario and the $1/N$-expansion, prefer to call the final state structures "chain-like" but the results nevertheless have strong similarities to a string scenario. With due account of Rutherford parton scattering and bremsstrahlung these models can account for most experimental results in hadron-hadron collisions all the way from the PS up to the largest presently available energies.

Several of the models have been extended to hadron-nucleus and nucleus-nucleus collisions. It is then assumed that these reactions can be treated as superpositions of binary nucleon-nucleon collisions with the impinging probe moving along a straight-line path. In this way the bulk of the results ("minimum bias events") are dominated by the collision geometry. When also secondary interactions among the final state particles, cf eg Ref [7], are accounted for, the models tend to describe almost all the (inclusive distribution) phenomena which have been seen up to now.

The FRITIOF model does not explain the present $p_\perp$-enhancements in high energy heavy-ion collisions very well but we will in this note show that the introduction of the FCM will make up for that. The Pb-beam experiments at CERN and to an even larger extent the RHIC experiments will be able to study essentially larger energy densities. It will then be possible to study the emergence of much more interesting collective effects and in particular to test the FCM in detail.

The bremsstrahlung gluons, stemming from color separation, are in The Lund Model described as (internal) excitations on the string force field. We will use the ordinary Lund emission model for bremsstrahlung gluons, the Dipole Cascade Model (DCM) which is implemented in the Monte Carlo simulation program ARIADNE.

Then the initial 3 (q) and $\bar{3}$ ($\bar{q}$) charges form a dipole emitter and after the first emission of the gluon g_1, the qg_1 and the $g_1\bar{q}$ form two *independent* dipoles. They may again emit a second gluon, thereby providing three independent dipoles etc. In this way the strong angular condition for the gluon emissions is taken into account in a simple and straight-forward way. We briefly describe the DCM in section 2.1.

We note that a given dipole with a mass square W^2 will in its cms be able to emit gluons with transverse momentum $k_\perp$ and rapidity y inside the region

$$k_\perp \cosh(y) \leq W/2 \tag{1}$$

ie approximately within the region

$$k_\pm \equiv k_\perp \exp(\pm y) \leq W \tag{2}$$

In the plane spanned by the rapidity, (y), and the logarithmic transverse momentum, $\kappa = \log(k_\perp^2)$, this restriction corresponds to a triangular region, cf Fig. (1). We note that in a "general frame", obtained by boosting along the dipole axis the right-hand side of Eq (2) is changed into the lightcone energy-momentum components $P_\pm$.

Soft hadronic collisions in the FRITIOF Model corresponds to large longitudinal and small transverse momentum transfers, ie to the stretching (and decay) of (longitudinally) extended string-like force fields along the beam direction. This corresponds to color separation but contrary to the e^+e^--annihilation events the charges and energies are not expected to have a pointlike character in the hadronic interactions.

This means that the bremsstrahlung gluons are emitted from extended sources. It is well-known that this means a damping of wave-lengths much smaller than the source size, ie for the emission of large transverse momenta (the wave-length $\lambda \propto 1/k_\perp$). In The Lund Model this feature is treated by means of the Soft Radiation Model (SRM), which is briefly described in the section 2.2.

The main point is that, with the (transverse) extension parameter $1/\mu$ of the state, the allowed emission region for a dipole is changed compared to Eq (2) into

$$k_\pm \leq \frac{\mu}{k_\perp} W \tag{3}$$

In high energy nuclear collisions there will in the FRITIOF Model be many strings stretched out and in case they work like vortex lines there may be some interaction between the strings (the repulsive interaction between the "ordinary" electro-magnetic vortex lines means the storing of some energy in the space between them). We note that the factor μW in Eq (3) effectively corresponds to an energy density over the region $1/\mu$. Consequently the SRM requirement in Eq (3) means for an isolated string that the largest transverse momentum gluon fulfills $k_{\perp max} \leq \sqrt{\mu W}$.

In the FCM it is assumed that in the very early stage of the collision when several (n) excited strings (energy momenta $P_{\pm j}$) are close by *it may be possible for them to emit gluons using their common total energy density* $\mu W_{tot} \equiv \mu\sqrt{\sum P_{+j} \sum P_{-j}}$.

In order to estimate the effect we may for simplicity assume that the strings are at rest relative to each other with the same masses $W_j \equiv W$. This means that *each string may be able to take energy from the common pool* nW. Thus one may in principle be able to emit n gluons, each with a transverse momentum limited by $\sqrt{n\mu W}$!

This provides only a tail effect in the present small A experiments at the SPS (although it means that the present FRITIOF predictions come very close to the data) but it should be quite noticeable for the Pb-beam experiments and very exciting at the RHIC.

It is also of interest that the well-known Cronin effect, that the transverse momenta behave like A^{α} with $\alpha(p_{\perp})$ increasing with the transverse momentum, comes out very close to the data.

When it comes to heavy ion collision predictions the FCM will correspond to an essential enhancement of (mini)jets in the center of phase space. Actually in that region of phase space the effect completely drowns both the Rutherford scattering and the "ordinary" bremsstrahlung and it is then easy to disentangle the Firecracker Model effects in any experiment with effective transverse momentum detectors.

The FCM is implemented as a Monte Carlo simulation program, LUCIAE, connected to FRITIOF and is available from A. Tai, [8].

We consider the FCM structure in detail in section 3 and some of its consequences in section 4. Finally we end with a few concluding remarks in section 5.

2 The Dipole Cascade Model, The Soft Radiation Model and FRITIOF

2.1 The Dipole Cascade Model (DCM)

Bremsstrahlung emission is an inherent feature of all gauge theories. A sudden change in (as in Deep Inelastic Scattering when an initial charged parton is deflected by the scattering with a highly virtual photon) or a sudden buildup of a Coulomb field (as in e^+e^--annihilation reactions into a quark(q)-antiquark($\bar{q}$) pair) results in fluctuations in the fields corresponding to waves with gluonic(g) quantum numbers moving outwards.

The cross section for emitting a $qg\bar{q}$-state can be factorised into the production of the $q\bar{q}$-pair forming a dipole and then the dipole emission (inclusive) probability

$$dp = C\frac{\alpha_s}{2\pi}dx_1 dx_3 \frac{x_1^2 + x_3^2}{(1-x_1)(1-x_3)} \tag{4}$$

Here C is a color factor ($C = 4/3$), α_s the strong coupling constant and x_j the cms energy fractions of the final state particles with the g fraction x_2 fulfilling

$$x_2 + x_1 + x_3 = 2 \tag{5}$$

Defining for a given total squared cms-energy s the invariant transverse momentum $k_\perp$ and the rapidity y of the g by means of

$$k_\perp^2 = s(1-x_1)(1-x_3) \tag{6}$$

$$y = \frac{1}{2}\log\left(\frac{1-x_1}{1-x_3}\right) \tag{7}$$

the probability in Eq (4) can be rewritten into the approximate form ($x_1 \simeq x_3 \simeq 1$)

$$dp \simeq \frac{C\alpha_s}{\pi}\frac{dk_\perp^2}{k_\perp^2}dy \tag{8}$$

The phase space constraints are given by Eq (1) (Eq (2)). It is evident that we may interpret the results so that inclusively the gluons should populate the triangular region in Fig. (1) with a density given by the coupling constant times a color factor.

In QED which is an abelian gauge theory the process can be repeated by further photon emission but in QCD with 8-charged gluons *the emission of the first gluon already changes the original emission current.* It is, however, a very good approximation ([9]) for the emission of two g's that the cross section factorises so that the second gluon can be considered as emitted from anyone of two independent dipoles:

$$dp(qg_1g_2\bar{q}) = dp(qg_1\bar{q})(dp(qg_2g_1) + dp(g_1g_2\bar{q})) \tag{9}$$

spanned between the qg_1 and $g_1\bar{q}$. The constraint is that the transverse momenta must be ordered, ie $k_{\perp 1} > k_{\perp 2}$ (or else the emissions occur in "the reverse order"). We also note that the two dipole emitters are not at rest with respect to each other or to the common cms.

In the DCM the emission of the second gluon then results in the production of three independent dipoles etc. The dipole masses in general quickly decrease and consequently the transverse momenta of the emitted gluons quickly become small. In that way the internal excitations on the Lund Model string become "small" and soft and collinear emissions are not noticeable in the fragmentation process ("infrared stability"). It has been shown, [9], that in case one would introduce a transverse momentum cutoff, $k_{\perp cut}$, in the gluon emission process the same results (with minor and understandable changes in the fragmentation parameters) are obtained for a wide range of values of the cutoff, $0.5 < k_{\perp cut} < 7\ GeV/c$.

2.2 The Dynamics of FRITIOF and The Soft Radiation Model (SRM)

While the energy transferred to the $q\bar{q}$-pair in an e^+e^--annihilation event is expected to be localised in a pointlike manner, the transferred energy-momentum in a hadronic inelastic event should be spread over some region. In FRITIOF the longitudinal energy momentum transfer will change the original hadron (treated as a string-like force field) into two (transverse) fronts moving forward and backward along the beam direction.

There are at least two dynamical mechanisms available for this change which both of them in a dual manner will lead to the same final state. The process may be considered either as a measuring process or it may be described in terms of multiple parton scatterings over some region.

When the two hadronic states impinge upon each other there will be some transverse overlap between the strongly Lorentzcontracted states. If we assume that the two hadrons approach each other with the original (very large) lightcone energy momenta P_{+1} and P_{-2} then the typical overlap "lightcone times" will be $\delta t_{-2} \sim 1/P_{+1}$ and $\delta t_{+1} \sim 1/P_{-2}$. (Note that quantum theory allows the localisation of one of the pairs $(P_\pm, t_\pm)$ simultaneously for each incoming hadronic state).

On a short time basis there should be quantum mechanical fluctuations into all the hadronic states with the "right" quantum numbers. In case we consider the interaction as a measuring process, then all the hadronic states with a (virtual) lifetime longer than the interaction times will be available and therefore possible to project into. Therefore the possible final states should be the string states with (p_{+j}, p_{-j}) with $p_{+2} < P_{+1}$ and $p_{-1} < P_{-2}$. Introducing the momentum transfer $(Q_+, -Q_-)$ from $1 \rightarrow 2$ we obtain the states with $(P_{+1} - Q_+, Q_-)$ and $(Q_+, P_{-2} - Q_-)$ with the requirements that $m^2/P_+ < Q_+ < P_{+1}$ and $m^2/P_+ < Q_- < P_{-2}$.

Despite the Lorentz contraction properties it may well be that the transversely (space)extended fronts "only gradually" meet and define each other. Then a multiple scattering parton scenario is a more relevant description. The surprising result on a stringlike force field is that both situations will lead to the same kind of final state, ie a gradual stretching out of a longitudinal string field (besides internal transverse excitations in the form of bremsstrahlung gluons, cf below).

In case there are multiple parton scatterings a large set of partons from 1, with energy momenta k_{1j} will scatter against another set k_{2j} from 2 with the momentum transfers q_j, such that $\sum q_j = Q$. In case the scatterings are uncorrelated then it is reasonable to expect $\vec{Q}_\perp \simeq 0$ (also "locally") but the longitudinal transfers should be nonvanishing in order to keep the partons on the mass-shell.

Now a string is locally a strongly correlated dynamical object. In case there is a set of longitudinal excitations over some region then the string will be dragged out "piece by piece" using up the energy momentum of the excitations in turn of color ordering along the field. The difference between applying a large momentum transfer $Q_\pm$ at the end of a string moving "forward" with $P_\mp - Q_\mp$ and the application of a set of momentum transfers $q_{\pm j}$ (with $\sum q_{\pm j} = Q_\pm$) over a connected region is small as long as there are no large transverse excitations along the front.

In both cases the final state string will (in case it does not break up) have a longitudinal extension in the cms of the order $2W_j/\kappa$ with κ the string constant and with $W_1^2 = (P_+ - Q_+)(Q_-)$ and $W_2^2 = (Q_+)(P_- - Q_-)$. On the other hand the transverse extension will be of the order of m/κ with m the restmass. This means that the final state in both cases will look very similar to a Lund Model string as used in e^+e^--annihilation reactions and we will consequently treat the strings in the same way with respect to fragmentation.

In FRITIOF the basic dynamics is provided by the longitudinal momentum transfers $Q_\pm$ which are assumed to be distributed in a scaling way:

$$\propto \frac{dQ_+ dQ_-}{Q_+ Q_-} \tag{10}$$

There is further incorporated the possibility that there is a single hard Rutherford scattering between the partons, ie one of the multiple collisions is "hard". We treat it by means of the simulation routines in PYTHIA. Then the final string states will contain this hard excitation. If the parton is a valence constituent the excitation is placed at the ("backward") end-point of the string while for a g it is placed inside the final state string (with the longitudinal transfers distributed around it).

The appearance of such an excitation also implies that the longitudinal momentum transfers must increase. Suppose that a parton from hadron 1 (2) with original energy momentum $x_1 P_+$ ($x_2 P_-$) is scattered into the energy-momentum state $(k_{+1}, k_{-1}, \vec{k}_{\perp R})$ $((k_{+2}, k_{-2}, -\vec{k}_{\perp R}))$. Then the lower bound on the variables $(Q_\pm)$ in the distribution in Eq (10) is given by (k_{+2}, k_{-1}) instead of $(m^2/P_\mp)$ in case there is no Rutherford parton scattering. This feature accounts in the FRITIOF model for the so-called "pedestal effect", ie the increased activity in the surroundings of large jets.

In order that a particular Rutherford scattering should be a relevant perturbative contribution it is essential that the possible bremsstrahlung in the hadronic states are less hard, ie corresponds to smaller transverse momenta than the Rutherford $\vec{k}_{\perp R}$. This is incorporated in the FRITIOF Model and in this way it is always the largest transverse momentum excitation (whether from bremsstrahlung or from Rutherford scattering) which governs the remaining features of the state.

The bremsstrahlung spectrum in FRITIOF is given by the ordinary DCM pattern together with the damping condition in Eq (3) in the regions governed by the longitudinal momentum transfers. A Rutherford scattered parton (and an already emitted bremsstrahlung gluon) is always treated as "hard" and pointlike, however. In a dipole containing such a parton as one endpoint the condition in Eq (2) is applied.

Consequently a single hadronic collision in the FRITIOF Model will lead to a final state containing two (longitudinally) extended string states with some internal excitations corresponding either to a single Rutherford scattered gluon (in case it is the largest $k_\perp$) and to gluons emitted in accordance with the DCM and the SRM.

This scenario is extended to hadron-nucleus and nucleus-nucleus collisions by the assumption that the projectile (and target) hadrons may undergo several collisions according to a geometrical picture. This will lead to final states defined by the logarithmic $Q_\pm$ spectrum with the longitudinal momentum transfers increasing (ie after a second collision the hadrons will obtain values of $Q_\pm$ according to Eq (10), with the lower limit defined by the earlier one etc) and the "hardest" Rutherford is retained.

3 The Fire-Cracker Model

3.1 The Partitioning of the Strings into Interacting Clusters

In a high energy nuclear interaction the interaction time is much shorter than any typical relaxation time in the nucleus. Therefore the nucleus can be considered as a "frozen" bag of free nucleons probed by the fast moving projectile. The impinging probe will further due to Lorentz contraction hit all the relevant nucleons at almost "the same time" or at least there will in the final state be a large (phase space) overlap region between several of the excited nucleons.

If this situation is considered inside a classical dynamics scenario then it is nevertheless doubtful that the different nucleons should be able to influence the combined gluon emission. Hard gluons are typically emitted inside a time scale of the order of the inverse transverse momentum, ie in small fractions of a fm-time. *We will, however, in the FCM assume that it is possible to partition the final state into clusters each corresponding to a quantum state with interaction.* Such a cluster contains a set of excited strings and we will in this subsection consider the partitioning. This can be done in different ways but it is evident that only strings which are "close by each other in transverse space" are able to interact and form a common energy pool.

In a hadron nucleus collision we assume that all the participant nucleons from the target form a single interacting system after the collision. The impinging hadron is assumed to move along a straight line path and to interact with the nucleons along the path in accordance with an overlap function mechanism in impact parameter space. Therefore we assume that all the participating nucleons are close to each other transversely (while the projectile and a string with Rutherford scattering larger than the possible bremsstrahlung is treated independently).

In a nucleus-nucleus collision, however, the projectile nucleons have different impact parameters with respect to the target nucleus. The strings excited in the projectile and in the target have in general a large relative longitudinal motion and we will assume that they form independent clusters. We will then partition the final state strings from each nucleus into groups with a small transverse motion with respect to each other. In order to do that consistently we apply the algorithm which was introduced in Ref [10]. There are three main steps in this momentum space clustering scheme:

1. For every pair of projectile or target nucleons, k and l, the distance variable d_{kl} is defined by means of the pseudorapidities η, azimuthal angles ϕ and the

transverse momenta p_t:

$$d_{kl} = min(p_{tk}, p_{tl})\sqrt{(\eta_k - \eta_l)^2 + (\phi_k - \phi_l)^2} \tag{11}$$

Find the pair with the minimum distance d_{kl} !

2. If this minimum d_{kl} is smaller than a value d_{cut} we combine k and l into a single "pseudoparticle" with a four-momentum p_{kl} given by

$$p_{kl} = p_k + p_l \tag{12}$$

3. Repeat the procedure for all nucleons and pseudoparticles until all remaining pairs have a distance larger than d_{cut}. The remaining objects now define the clusters.

It is possible to introduce a clustering procedure also in the corresponding (coordinate) impact parameter space. The resulting clusters will (although not event by event) be very similar to the one obtained above. As it is more in the spirit of the model to consider energy momentum space (and also because for simulation reasons it is easier to implement it) we chose to use the momentum space clustering.

In case there is a Rutherford parton interaction on one of the strings we assume that the coherence between that and the rest of the cluster is lost. Such a string is not taken into account in connection with the "collective" gluon emission in the FCM (although we test if the Rutherford $k_{\perp R}$ is relevant, ie larger than the possible bremsstrahlung $k_\perp$, in order to fulfil the requirements of perturbation theory).

3.2 Multigluon Emission from a Cluster in The FCM

We now assume that there is inside a small (Lorentz contracted) space time region a set of n excited FRITIOF strings formed during the high energy nuclear interaction in accordance with the clustering in subsection 3.1. We neglect their transverse motion and we parametrise their longitudinal motion in terms of lightcone coordinates (P_{+j}, P_{-j}) along the beam direction. The total energy momentum of the cluster is

$$P_{\pm tot} = \sum_{j=1}^{n} P_{\pm j} \tag{13}$$

We next assume that the set forms a quantum state of n interacting objects. The repulsive interaction may be small but we assume that the state properties imply that the strings will be aligned so that they all of them may use the common total energy density $\mu P_{\pm tot}$ in the emission of bremsstrahlung gluons.

We further assume that energy-momentum in connection with the emissions is "locally" conserved. Therefore a gluon emitted according to the FCM can be related to a particular string only if (in the corresponding string cms) the Eq (1) is fulfilled.

In case we produce a gluon in accordance with the SRM, using the total energy density then there are several possibilities to relate the gluon to anyone of the strings. We have considered several such schemes

A We emit the "hardest gluon" ($k_\perp$-ordered) from the total $P_{\pm tot}$ and try to find a string in the cluster for which Eq (1) is fulfilled. If there are several then we take the largest mass string and emit the gluon and remove the string from the set. If there is no string available that "fits" to the gluon then we remove the largest mass string. Next we emit the "next hardest gluon" and repeat the procedure with the "new" energy density.

B The original string set is ordered from the largest mass downwards and any gluon is emitted from the total $P_{\pm tot}$ and is related to the largest mass string. In case it fulfils Eq (1) it is "accepted" and the emission allowed. Then the largest mass string is removed and a second gluon is emitted inside the SRM with the "new" energy density etc.

C We do not order the strings (masses) or the gluons ($k_\perp$) and "allow" emission if stochastically the gluon is related to a string so that it fits to Eq (1) (without any removal of strings from the common source).

There is in our experience no large differences between different procedures, ie the "ordering" can be just as well done stochastically, which is the option (C) retained in LUCIAE (note that we always test for a "harder" Rutherford scattering, however).

The result is that the original set of strings is partitioned into those endowed with a collective FCM gluon (or Rutherford scattered parton) and those for which the test failed and therefore they are still "longitudinal strings". These latter strings can then also emit gluon bremsstrahlung but only according to the "individual" application of the SRM. In all cases the dipole cascades are continued downwards to a suitable cutoff. Afterwards all the strings will be fragmented according to The Lund Model.

4 The Results

The Firecracker Model is implemented as a simulation (sub)routine, LUCIAE [8], to be used together with FRITIOF, related to the ARIADNE [11] and the JETSET[12]

Monte Carlo packages. It is not conceivable to cover all possible predictions from the model in this paper. We have chosen to present a few of the most noticable ones and we refer the interested reader to make use of the simulation possibilities to see all the details.

The LUCIAE package also include the possible rescattering, between the final state particles in a dense hadronic surrounding. Such a scenario is evidently inherent in the FRITIOF model when the energy and the nuclear number increases for hadron-nucleus and nucleus-nucleus collisions and we will briefly mention some consequences below.

4.1 Hadron-Nucleus Collisions, the Cronin Effect

It has been known for a long time, [13], that in case one would parametrise the large transverse momentum, $k_\perp$, spectra for the particles emerging from nuclear collisions as $A^{\alpha(k_\perp)}$ then there is a noticeable change in the power α both for small and for large values of $k_\perp$. There are also systematical differences between different flavors.

In Fig.2(a) and (b) we exhibit some of the emerging spectra (π^- and K^-) in this way in proton collisions with a tungsten (W) target at an incident proton energy of 300 GeV together with the predictions from "ordinary" FRITIOF as well as when we include firecracker contributions and/or rescattering contributions. We note that, although "ordinary" FRITIOF does not contain any noticeable changes in α there is when the firecrackers are included a rise for large $k_\perp$ (above 0.6 GeV/c) in the pion and kaon spectra while the small $k_\perp$ behaviours for the pion as well as kaon spectra are mostly affected by the rescattering contributions. Further the low $k_\perp$ enhancement of the kaon spectrum is stronger than that of the pion spectrum. The low $k_\perp$ enhancement of the pion spectrum is found to mainly stem from in our calculations the decay of Δ resonances produced from the rescattering while the low energy $\pi\pi$ scattering in the final state is responsible for the low $k_\perp$ enhancement of the kaon spectrum.

4.2 Nucleus-Nucleus collisions

In Fig.3(a) we show the (inclusive) $k_\perp$ spectrum of the firecracker gluons in full rapidity space compared to that of the bremsstrahlung gluons and the Rutherford hard gluons for $\sqrt{s}$=100 AGeV cms Pb-Pb scattering. The firecracker dominance at large $k_\perp$ is clearly seen. In Fig.3(b) the transverse energy distribution in rapidity space of the firecracker gluons with transverse momentum $k_\perp > 2$ GeV/c is shown for the same reaction together with that of the bremsstrahlung gluons and the Rutherford hard gluons. Evidently the firecracker gluons do play the role of an essential minijet production. If we have a larger $k_{\perp cut}$, say 4 GeV/c, the bremsstrahlung gluons and the Rutherford hard gluons will almost provide no contribution to the transverse energy.

The fact that the firecracker gluons can be disentangled by means of a simple $k_\perp$ cut means that they are easy to find (if they are there!) and we will therefore be satisfied with this remark and ask the interested reader to find more precise predictions from the Monte Carlo simulation using LUCIAE.

5 Concluding Remarks

We have proposed a possible mechanism for collective multiple gluon emission from the colour fields of interacting strings, which predicts an essential enhancement of minijet production in high energy heavy ion collision. The model shows that the Firecracker gluons contribute significantly to the production of transverse energy in the high $k_\perp$ region of phase space.

The minijets with a large $k_\perp$ are produced at the very early stage of collisions (with proper formation time $\tau_0 \approx 1/k_\perp = 0.1$fm if $k_\perp = 2$GeV/c). We may imagine the possibility that instead of being " thermalized", those FCM gluons would rapidly leave the interaction region, thereby disperse the energy density obtained in the initial encounter. If so, then the energy density of "thermalized" gluons will be only a fraction of the maximum energy density reached during collisions (we call it the "thermalized" energy density). The situation would make it more difficult to reach the second phase transition, ie to "melt" the vacuum into a plasma state if the QCD vacuum is a color superconducting vacuum of type II.

Fig.4 shows how the "thermalized" energy density of the gluons produced at $\sqrt{S}$=100 GeV central Pb+Pb collisions varies with a $k_\perp$ cut. Those gluons with $k_\perp > k_{\perp cut}$ are assumed to provide no contribution to the energy density. The energy density is defined as

$$\epsilon = \frac{dE_\perp/dy}{V_0}, \qquad V_0 = \pi(1.15A^{1/3})^2\tau \tag{14}$$

We have used the conventional value, τ=1 fm, in the calculation.

We see from the calculation that the energy density would be reduced by a large amount if all the firecracker gluons are taken away from the "thermalized" energy density. The effect will increase with the energy.

6 Acknowledgments

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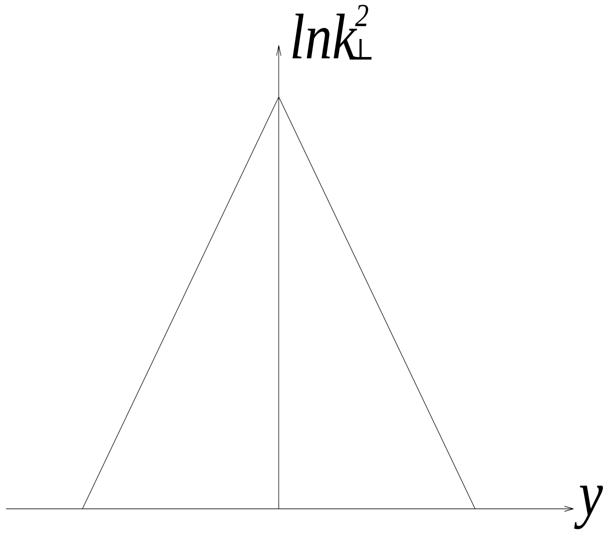
Figure Captions

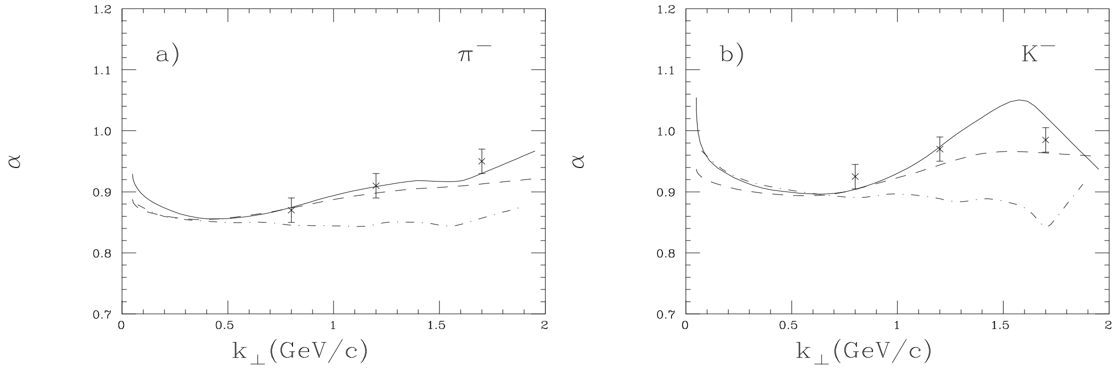
Fig.1: The phase space limit for the emission of a gluon from a colour dipole.

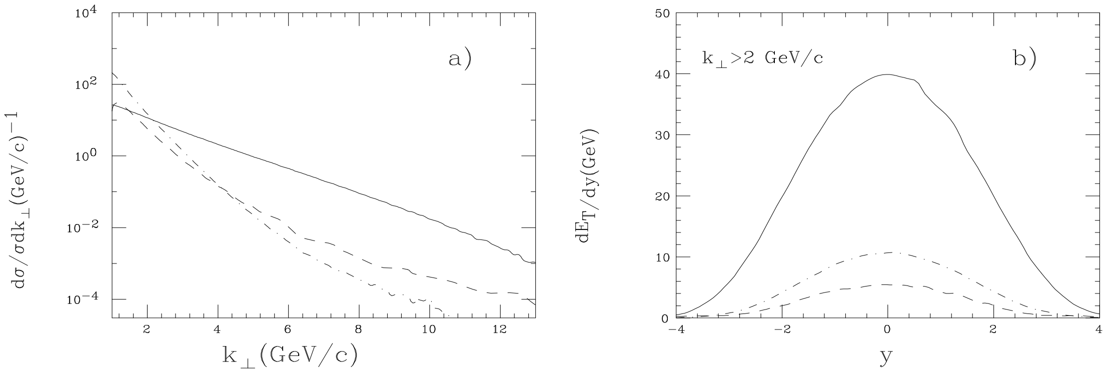
Fig.2: The Cronin effect: The solid line is from LUCIAE calculation, the dashed line is the LUCIAE calculation without the rescattering and the dash-dotted line is FRITIOF prediction. (a) for π^- and (b) for K^- . The data points are from [13]

Fig.3: The $k_\perp$ spectrum (a) and the transverse energy distribution with $k_\perp > 2$ GeV/c (b) of the firecracker gluon (the solid line), the Rutherford hard gluon (the dashed line) and the soft bremsstrahlung gluon (the dash-dotted line) for $\sqrt{s}$=100 AGeV cms Pb-Pb scattering.

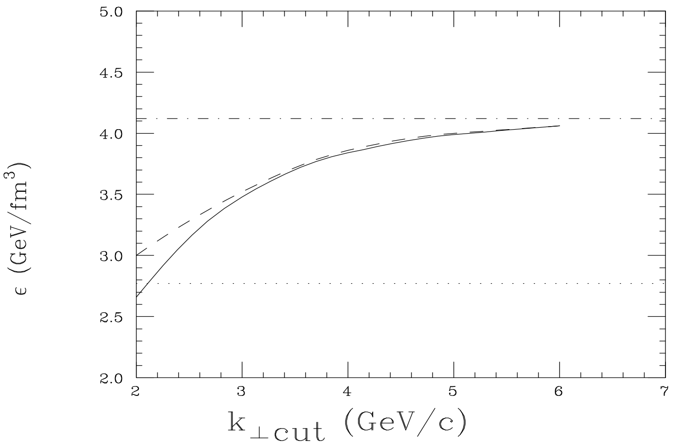
Fig.4: The "thermalized" energy density of the gluons produced at $\sqrt{S}$=100 GeV central Pb+Pb collisions as a function of a $k_\perp$ cut. The gluons with $k_\perp > k_{\perp cut}$ are assumed not to give contribution to the energy density. The dashdotted line corresponds to the maximum energy density of gluon. The dotted line corresponds to the energy density without firecracker gluon. The dashed line corresponds to the energy density without the firecracker gluon with $k_\perp > k_{\perp cut}$. The solid line corresponds to the energy density without any gluon at all with $k_\perp > k_{\perp cut}$.


$\ln k_\perp^2$
y


a)
π^-
b)
K^-
α
$k_\perp$(GeV/c)



a)
$d\sigma/\sigma dk_\perp (GeV/c)^{-1}$
$k_\perp$(GeV/c)
b)
$k_\perp$>2 GeV/c
dE_T/dy(GeV)
y



ϵ (GeV/fm^3)
$k_{\perp cut}$ (GeV/c)