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Simulation of Heavy Ion Collisions at $\sqrt{s} = 20\text{-}200$ GeV

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Abstract

A new hadronic cascade code (LUCIFER) is introduced, for simulation of relativistic heavy ion collisions at CERN energies and up to RHIC. It is based on a simple, experimentally and theoretically motivated picture of hh interactions. Final state hadrons are produced by decay of intermediate state clusters, or lumps of excited hadronic matter. These are similar to resonances, but have a continuous mass distribution. Clusters are the objects that re-interact in the cascade. Single diffractive dissociation is used to fix the cluster properties. The model has just two parameters: τ_d , the decay time of the clusters, and τ_f the formation time of the clusters. Comparison is made with recent CERN data in the Pb+Pb system. The first consistent cascade simulation, of J/ψ production/suppression is presented. It appears likely that a purely hadronic interpretation can be given to recent CERN data on apparently anomalous J/ψ suppression in Pb+Pb.

I. INTRODUCTION

The hadronic cascade ARC [1] has been remarkably successful in describing nucleus-nucleus collisions at AGS energies, $\sqrt{s} = 5.0\text{-}5.4$ GeV/A. Such energies, of course, are very low in comparison to the highest energy considered in this talk, so perhaps one cannot borrow directly from this previous experience. Surely, for example, it must be the eventual aim of any viable simulation at SPS to RHIC energies to include both quark and gluon degrees of freedom explicitly. Such an outcome is in fact being actively pursued here with Klaus Geiger. The program, LUCIFER, considered here is intended to serve as the hadronic component in a mixed hadronic/partonic cascade. Nevertheless, it is of considerable interest to elaborate the hadronic aspects and to push this approach as far as is possible on its own. Even if one accepts what we are being told about RHIC collisions [2], namely that as much as 50% of the energy flow involves semi-hard 'minijets' or the like, there remains half of the total energy in essentially soft QCD processes. The 50% labelled hard presumably also contributes appreciably to low p_t spectra *via* eventual hadronisation of partons. However energy flow beginning and remaining at low p_t is by no means all non-interacting, since large multiplicities are also observed for example, in pp events with no obvious hard scattering. These soft interactions must also be addressed.

FIG. 1. Underlying cluster model for hh collisions in LUCIFER. Diagrams represent production of N intermediate state clusters. Leading clusters always have quantum numbers consistent with the incoming hadrons, *e.g* for a pp collision they would be baryonic. Internal additional clusters are always mesonic.

In this workshop, Al Mueller [3] has called, as a starting point, for a simulation initialized by instantaneously converting all hadrons into partons. This is after all the Bjorken [4] approach. It has been carried out in the past [5], and will no doubt continue to be redone in the future [6]. Although, in a RHIC nucleus-nucleus event, the time over which the totality of baryon-baryon collisions takes place is extremely short, nevertheless there may be a very rich structure: multiple coherent soft interactions may take place contemporaneously with incoherent parton cascading. If this structure is ignored it may deny one the chance to produce realistic initial conditions for the ensuing parton cascade. In particular, since the larger RHIC detectors are concentrated heavily on mid-rapidity, one should have an accurate count of the mesons produced there in the absence of interesting high energy-density mechanisms such as plasma, before believing such effects truly are present. It is just at such rapidities that soft processes may produce ambiguities. Despite what has been said in the workshop summaries, what gets to mid-rapidity does not *always* start at mid-rapidity. This is a minimum lesson to learned from what follows here.

The purpose of this presentation is to seek an efficient means of dealing with soft interactions, a means which, unlike strings [8,9], can mesh naturally with the parton cascade already implemented in VNI [10]. There are undoubtedly formidable problems facing a cascade of any sort at ultra high energies, including a partonic cascade, not the least of which may be the relativistic covariance of its output. We will discuss the latter in light of the useful points raised by T. D. Lee [7], and discussions held during the workshop. However a more fundamental difficulty, in my point of view, is to characterise the nature of the soft interactions, the interactions of matter which remains at low p_t .

II. PHYSICS OF THE CASCADE

The essential features of the code LUCIFER can be summarised quickly. Basic hadron-hadron interactions are assumed to proceed through the production of intermediate state clusters or lumps of *hadronic* matter (see Fig 1). Clusters then produce the final state hadrons by a sequential decay mechanism, which is not necessarily isotropic. These clusters

are the objects which re-interact in the cascade. Two types of cluster are posited, mesonic and baryonic, corresponding to $(q\bar{q}$ / multi- g) or (qqq) valence parton content of the cluster. Both are imagined to be color singlets, consistent with only a soft interaction having taken place between the incoming hadrons. The interaction cross-section is chosen universally, in the spirit of the additive quark model, to be one of: σ_{pp} , $\sigma_{\pi p}$, or $\sigma_{\pi\pi}$, evaluated at the appropriate energy. With that picture in mind we can proceed to a more extensive discussion of the underlying physics.

In the low energy cascade ARC, it had already become apparent that energy-momentum released in the initial nucleon-nucleon collisions re-interacted through resonances and stable hadrons, dominantly the Δ , N^* and ρ . Special properties of the particular resonant states involved had apparently little effect on the overall behaviour of the system. Indeed, one could just as well have used a single generic baryon resonance and a single generic meson resonance, both having average widths. The essential point was that energy flow was retained in the resonances, as was required by the proper treatment of relativistic time evolution. This played a central role in ion-ion dynamics at the AGS [1], and indeed led simultaneously to the enhancement of strangeness production and broadening of p_t spectra which had been initially proposed as signals of plasma formation. For these energies the formation times for produced particles were often included in the resonance lifetimes, which of course for rapidly moving resonances considerably delay the production of pions, and hence reduce their rescattering. Despite dire warnings voiced by detractors, this early approach gives very useful hints on how to proceed at the highest energies. One can also borrow from previous research to justify a possible route to high energy; particularly instructive are the works of Berger and coworkers [11], Quigg and coworkers [12], Beusch *et al.* [13], on the existence of 'clustering' in pA data. This clustering also naturally arises in the multiperipheral models.

Above all, Gottfried, in (1974), put forth a very simple exposition [14] of a scheme for pA collisions (see Fig. 2), anticipating the approach taken in LUCIFER and ARC by many years, which provides a phenomenological paradigm for extending the cascade to higher energies. Contemporaneously, Koplik and Mueller [15] considered the pA collisions at high energy, formalising some of Gottfried's phenomenology within a multiperipheral, Regge-Gribov [16] framework. We present some of this development here, for the moment limited to the context of pA collisions. This restriction is made, because it is conceptually simpler to track one hadron through a target.

Gottfried noted that although a hadron-nucleon collision within a nucleus cannot immediately produce the final state hadrons one would see in free space, it might still be possible to extrapolate this final state backwards in time and use this information to guide the time evolution of the 'leading' hadron through its subsequent collisions with other target nucleons. He proposed that what mattered most for the reinteraction was the flux of energy-momentum through the nucleus. The experimental evidence [14,17] from pA is that high energy, forward pions, accompanying the leading proton, are suppressed, the pion multiplicity not being enhanced much over pp . Additionally, only a weak dependence on A is observed. In LUCIFER, this behaviour is accounted for at least partly by grouping the final particles into clusters, and introducing a formation time τ_f for the non-leading clusters. The relativistic dilation $\gamma\tau_f$ then makes it unlikely for fast produced particles to materialise inside the nucleus, interact, and add to the multiplicity.

Secondary collisions in the target by the leading proton must still be dealt with, and we

$$\Delta\zeta=1/\gamma$$

$$\Delta\zeta=\Delta\zeta(\tau)$$

FIG. 2. Gottfried's model for pA collisions. The incoming proton is Lorentz contracted to size $\Delta\zeta \sim 1/\gamma$ fm in the lab frame before its first collision. Afterwards its energy density is in an expanding cylinder of length $\Delta\zeta(t)$. This model is essentially implemented in LUCIFER by means of cluster production and formation times.

propose doing this, like Gottfried, essentially by introducing an energy-momentum tensor to describe the energy flux associated with the leading baryon after its first collision. In his picture, the entire energy density is initially contained in the volume occupied by the original incoming proton (a sphere, highly Lorentz contracted longitudinally in the lab frame, so essentially a disk, or cylinder). The real questions now come with ensuing collisions, for which Gottfried enunciated two guidelines:

- (I) *After the initial proton-nucleon collision the incoming (leading) baryon exists in an expanding cylinder, with initial longitudinal width $\Delta z_0 \sim s^{-1/2} \sim \frac{1}{\gamma}$ fm. This cylinder already contains the expected final produced particles of the pp collision, though these are as yet unformed. The initial velocities are obtained from the final state rapidity distributions and the cylinder grows by classical propagation of the final particles.*
- (II) *This energy flux scatters from further target nucleons in its path 'as if it were a set of hadrons' $\{h_i(t)\}$. The division into separately existing hadrons is made by slicing the cylinder into pieces Δz_0 : a first non-leading hadron (meson-like) to be allowed, for example, when the cylinder reaches twice its original width.*

Gottfried [14] terms rule (II) a *universality* hypotheses: a hadronic state occupying the same volume and travelling with the same rapidity as a nucleon or pion, has collisions close in character to those of the corresponding ordinary hadrons. This is precisely the approach taken in LUCIFER and ARC for cluster or resonance cross-sections. The volume occupied, and the nature of constituent partons contained therein, determine the character of the cluster cross-sections. One can also invoke the additive quark model for support of such cross-sections. The detail-insensitivity of the excited hadron-hadron interactions is in keeping with the multi-gluon exchange nature of soft, confining QCD interactions. Those who believe the present approach to be laden with adjustable parameters should study this point very carefully. Rule (II) defines the interaction of an excited nucleon or excited hadron

FIG. 3. Pomeron exchange diagrams leading to various types of cluster production in pp scattering. The cut triple pomeron diagram is prototypical and leads to single diffractive scattering. The forward proton is separated by a rapidity gap from the diffractive baryonic cluster. In LUCIFER, the multiperipheral dynamics is simulated by the decay of the baryonic cluster. Diagrams are shown for double diffractive scattering with the production of a purely mesonic cluster, and for double diffractive dissociation. More general pomeron exchanges lead to the multi-cluster production model used in LUCIFER. The dominant process is taken to be $pp \rightarrow B_1 + B_2 + M$.

(cluster) very narrowly, making an initial *ad hoc*, but reasonable, hypothesis and thenceforth allowing no further freedom of adjustment.

In Gottfried's model, the energy-momentum tensor was used to decide at what point the flux arising some previous collision should be divided into two parts and so forth. This procedure was then iterated and he was able to obtain a closed analytic treatment of the problem in one dimension. The cascade can do this automatically, producing the set $h_i(t)$, and making each constituent available for interaction at the appropriate time. Nor is it restricted to one dimension. Gottfried uses, as do all cascade practitioners, classical motion, rule (I), between collisions. He presents what he calls 'alibis' for this with which we concur, the main excuse being the high energy and short wave lengths involved in the longitudinal motion.

Produced hadrons may begin to reinteract, for high incoming energy, well before they materialise into final state mesons. However, prior to expansion to $2\Delta z_0$ the energy momentum is retained in the original proton. Extrapolation to further collisions, or for that matter to AB events is straightforward. LUCIFER incorporates the above principles but adds a cluster model of the pp intermediate state, introduced to include and build upon existing experimental and theoretical descriptions of pp scattering. The cluster properties are taken from the data on single diffractive scattering. This can be considered the prototypical soft process.

In constructing LUCIFER then, the following rules are added to (I) and (II):

- (III) *The pp collision proceeds to the final baryon + meson final state through a choice of excited states depicted in Fig(3). The existence of such new excited entities, both baryonic and mesonic, was suggested, from data, by many authors [11–13]. Beusch [13] cites hA data at quite low energy (~ 15 – 20 GeV) for 3π and even 5π clusters which appear to have interacted surprisingly little in the nucleus, perhaps propagating throughout as a compact $q\bar{q}$ pair.*

- (IV) *The decay of the clusters sequentially, one at a time, into low mass mesons produces the final pp state. The lifetime, in the decaying cluster rest frame, is taken as*

$$\tau_d = \alpha M_{cl}^{-1} \quad (1)$$

That is, the highly excited clusters decay rapidly, while the low mass clusters emit final hadrons more slowly.

To rules (III) and (IV), must be added rules for the longitudinal and transverse phase space and cluster mass distributions. We emphasize that almost all of the apparent freedom in building the model, including of course these distributions, is to be constrained by pp , $p\bar{p}$, and πp measurements. The only model parameters, at this stage, left to be determined in $h + A$ collisions concern the time structure of pp , for example, the cluster formation time τ_f and the proportionality constant α , which at low mass ought to produce a decay time in the range of low mass resonance lifetimes such as τ_Δ or τ_ρ . We note that following Gottfried's prescription for the separation of the energy flux obviates to some extent the need for a cluster formation time τ_f .

For the cluster mass distributions in LUCIFER is added a fifth rule:

- (V) *The mass distribution of the clusters in Fig 3, whether for simple single diffractive scattering or for multiple cluster production, is taken from theoretical (pomeron exchange) and experimental knowledge of single diffractive scattering. When N clusters are produced, the **maximum** energy available for internal excitation of any particular cluster is taken to be $\sqrt{s}/N$.*

This rule will be expanded upon in the next section.

Much grumbling was directed at the clusters during the workshop, as though very high mass clusters dominated the NN interaction. Nothing could be further from the truth. The spectrum of diffractive cluster masses falls roughly as M_{cl}^{-2} and high masses are improbable. Most of the action for clusters lies in mass ranges generally attributed to minijets. Moreover, *in actual measurements of single diffractive scattering*, by definition and notably a low p_t process, such high mass objects *really are produced*. At least momentarily then, the concomitant high energy densities must exist, and their consequences cannot be ignored or avoided. Possibly, however, since (IV) leads to high p_t tails for decay of the largest M_{cl} , the fusion of partonic to hadronic cascades will quickly shunt the energy in the highest masses to the partonic side. Anticipating this eventuality, we have not retained the roughly constant high mass tail seen experimentally in the diffraction dissociation distributions, which are selected below as prototypical of the cluster behaviour, but instead allowed the cluster mass spectrum to be cut off as $1/M_{cl}^2$.

One might also relate this modelling to the dual string approaches [8,9]. The energy-momentum flow created at initial proton-proton collisions within a nucleus has been alternatively described as residing in colourless strings. Such a picture however is not easily meshed with partonic cascading and any prescription for reinteracting strings tends to be cumbersome. In the remainder of this article we will detail the specific choices in rapidity and transverse momentum distributions made for pp , guided by the existing pp and $p\bar{p}$ data and theoretical analyses, and first apply this to pA at FNAL and CERN energies, and

FIG. 4.

(a) Top: Feynman x distributions for the undisturbed proton in single diffractive scattering: x_F is related to the diffractive cluster mass by $M^2 = s(1 - x_F)$. The distribution falls off rapidly, $\sim 1/M^2$, for large cluster masses, and peaks at the Δ mass. Bottom: Empirical diffractive cluster mass distribution for $\sqrt{s} = 200$ GeV. (b) Multiplicity vs mass for diffractive clusters. LUCIFER sequential decay is adjusted to agree with the charge multiplicity in single diffractive pp scattering.

then to S+S and Pb+Pb at CERN. Subsequently, some minimal predictions are presented for $s^{1/2} = 200$, i.e. at RHIC. It is also tempting to include essentially the first complete hadronic cascade estimates of J/ψ production at CERN energies. The work of Gavin and Vogt [18], based on the Glauber formalism, also relies on only hadronic processes but has no real internal means of calculating the important transverse energy. We also discuss the frame dependence of calculated results for pA and S+S at the highest, here RHIC, energies.

III. NUCLEON-NUCLEON INTERACTION FROM DIFFRACTION

As a first guess we have tried to construct the entire intermediate cluster structure of NN (and for that matter hh) from the properties of states observed experimentally in single diffractive scattering, which in our modeling arises from the triple pomeron diagram (Fig. 3). This diagram with appropriate kinematic constraints, produces a final state like that seen in experimental hh diffractive scattering. Such a method of fixing the cluster properties is not mandated. Any scheme for NN, consistent with the data and not doing violent damage

FIG. 5. LUCIFER fits to pn data from FNAL and $p\bar{p}$ data from UA5 obtained using the cluster production model. The high energy data is a prediction, using the same model parameters as the low energy data.

to widely held theoretical concepts, would be acceptable. The parametrisation of pp and πp data constitute the input to LUCIFER, are fixed by elementary data, and then are frozen. The purpose of the cascade is to gain information about the many body system from the two body system. In the process of accomplishing this, data for

$$pp \rightarrow pX, \quad p\bar{p} \rightarrow \pi X, \quad \pi p \rightarrow \pi X, \quad (2)$$

from $\sqrt{s} = 20 \rightarrow 900 \text{ GeV}$ and for $p\bar{p}$ to $\sqrt{s} = 1.8 \text{ TeV}$ [19–21], are considered.

The experimental [19–22] mass and multiplicity distributions for diffraction are exhibited in Fig 4 and Fig 4. Using these measurements the mass distributions for clusters are fixed. The mass distribution may be deduced from the differential cross-section $d\sigma/dtd(M_x^2)$ for the diffractive process $pp \rightarrow pX$, for which we take the form:

$$P(z) = \frac{4z}{1 + 4z^2}, \quad z = (s/M_\Delta^2)^2(1 - x), \quad M_x^2 \sim s(1 - x), \quad (3)$$

a formula essentially derived from pomeron exchange analysis of diffraction, in this instance involving the triple pomeron exchange [22,23,16]. The variable x is the usual Feynman variable $x_F = p_{||}/p_{max}$. The crucial features of the spectrum are a $1/M_x^2$ dependence of the cluster mass at large masses, and a peak adjusted to be near the Δ mass, independent of s . The ρ mass is used for mesonic clusters. This form is roughly observed in the data, where real resonant states are seen for forward enough $x \sim 1$ values of the undisturbed arm. The excitation mass in the ‘dissociated’ arm is given by simple kinematics:

$$M_x^2 - m_p^2 \cong (1 - x)s \quad (4)$$

$S+S$ at $s^{1/2} = 19.4$ Gev

NA35 (1994) Central ($b < 2$)

FIG. 6. Sulfur + Sulfur data from NA35 compared with LUCIFER calculation (fitted) for negative hadron production. Strangeness production is not yet included in LUCIFER.

If one takes the minimum, in this case longitudinal, momentum transfer to be

$$q_{||} = (1 - x)m_p \cong m_p(M_x^2 - m_p^2/s), \quad (5)$$

then diffraction becomes increasingly evident when $q_{||}^{-1}$ is less than the approximate interaction radius m_{π}^{-1} , i.e. for $(1 - x) \sim (m_{\pi}/M_p) \sim 0.15$. The proper quantum context, tying elastic and diffractive scattering (closely) together and both to the total cross-section is well described in many places, [16,23] but we have relied particularly on Goullianos [22]. The rapidity gap between the unexcited proton and the diffractive cluster M_x implies that the relevant pomeron graph to be cut involves a triple exchange. The quantum dynamics of high energy pp (hh) collisions is contained in the cascade within the two body processes and then by the Gottfried rules to the interaction of cylinders of rapidity-unseparated leading clusters. The high energy leading s -dependence is exploited wherever possible to simplify the underlying structure of hh .

In dealing with a multi-cluster diagram in Fig 3 the longitudinal phase space is obtained by assigning the mid-rapidity clusters first, and then using energy-momentum conservation to specify the outer two. One parameter freedom exploited, but again we emphasise, for hh only, is the ratio of outer to inner cluster masses. This can be used to help ensure that the leading particle behaviour matches that seen in experiment. The final ratio selected, which could be s -dependent, is close to unity. The *maximum* energy available to any cluster for internal excitation, is near $\sqrt{s}/N$, N being the number of clusters in an event. This lower energy, not the full s , is used in Eqn. 3 to fix the mass distribution for the sub-clusters. Once again we remind the reader $\sqrt{s}/N$ is the maximum mass available for cluster excitation, not a typical mass. Since large masses are much less probable, most of the

Pb+Pb at $s^{1/2} = 17.2$ Gev

NA49 (1995) Central

FIG. 7. LUCIFER Prediction for Pb+Pb, obtained using parameters determined by the fits to pp and S+S.

cluster energy-momentum is kinematic at any stage of a hadron-nucleus collision. Moreover, the meson-like clusters or any produced clusters will, given the formation time assigned to them, rarely decay or reinteract within the nuclear medium. Their energy-momentum will also only separate from the hadrons which produced them according to rule (I), which generally severely restricts the energy available for excitation and eventual production. To ensure leading particle behaviour, the rapidity of produced particles in hh is restricted to lie within the range defined by the final values for the two initial hadrons.

Cluster Decay

The decay of clusters in LUCIFER is also, consistently controlled by diffractive processes taken as prototypical. Clusters decay sequentially, for the moment into π 's, eventually into strange mesons, antibaryon pairs, etc.,

$$\begin{aligned} B &\rightarrow B_1 + \pi_1 \rightarrow B_2 + \pi_1 + \pi_2 \rightarrow \dots \\ M &\rightarrow M_1 + \pi_1 \rightarrow M_2 + \pi_1 + \pi_2 \rightarrow \dots \end{aligned} \quad (6)$$

The mass step δm in these chains,

$$\delta m \sim m^\beta, \quad \beta(m) = 0.5 + \beta_0 \ln(m), \quad (7)$$

is selected to reproduce the observed average multiplicity $N(m)$ produced from a diffractive excitation of mass $M_x = m$, as is shown in Fig. 4. In practice, the step δm is multiplied by a random number, so that the multiplicity fluctuation is also approximately reproduced.

The decay constant $\tau_d = \alpha M_x^{-1}$, essentially the only parameter left to be determined in either pA or light heavy ion reactions, is in fact fixed here using S+S data at $\sqrt{s} = 20$ [25]

1 Au+Au Event @ RHIC

Central Au+Au $s^{1/2} = 200$ GeV

FIG. 8. LUCIFER Prediction for Au+Au at RHIC, using the same parameters for pp and the decay lifetimes as described in the text.

as $\alpha = 0.07$, only slightly lower than the value ~ 0.10 which would reproduce the Δ , N^* , or ρ lifetimes.

IV. LUCIFER RESULTS AT CERN AND RHIC

The level of accuracy of the fits to charged pion production in nucleon-nucleon scattering is displayed in Fig. 5(a,b). All 'parameters' of the fit were fixed from the lower energy data, so the results in Fig 5(b) can be viewed as 'predictions' of the model for pp outlined here. It can be seen that not much s dependence of the parameters is required to get a good description at both energies. For this preliminary workshop version of LUCIFER, only production of π -mesons was considered. Strangeness and other heavy quark production processes can be straightforwardly included in the cluster scheme for pp .

Finally then the results in Fig. 7 and Fig. 8 represent LUCIFER predictions for π production in Pb+Pb [26] at CERN energies, and for Au+Au at RHIC where of course data doesn't exist. The Pb+Pb [26] measurements are described quite well, having been constructed from the pp input and from experimental knowledge of the negative hadrons in S+S. The RHIC numbers are taken from a single simulated event and certainly must be viewed as highly preliminary. Since one expects appreciable strangeness production $\sim 30\%$, the number of π 's must be reduced by at least this amount. Careful implementation of the Gottfried rules could cut down production further, so for the moment Fig. 8 should be regarded as an appreciable upper limit.

CERN $\sqrt{s} = 20$ GeV pion production [25] data were used to determine α , and hence the

FIG. 9. LUCIFER leading particle spectra in $p+A$ collisions. In general there is no great difficulty in fitting the results for $p+Pb$. Note that the pion data are extremely forward, and constitute only a very small fraction of the total produced pions.

decay rate of the LUCIFER clusters. The matching of the LUCIFER calculation to $S+S$ data at $\sqrt{s} \cong 20$ GeV is shown in Fig. 6. In principle, a full implementation of rules (I), and (II) would eliminate the need for a formation time, here taken as $\tau_f \sim 1$ fm, replacing it instead by the hadronic scale, ~ 1 fm in the collision center of momentum frame, governing separation of the clusters from the leading hadron. The number of pions produced in $S+S$ is highly sensitive, as one might expect, to the one truly free parameter, α , but the value settled on ~ 0.07 is eminently reasonable for the typical cluster masses.

Since much of the introductory structure for LUCIFER was laid out for pA , we include results for inclusive proton production for this exemplary case in Fig. 9, the data taken from 100 GeV/c FNAL experiments [17]. There seems in the main, to be no trouble in reproducing these, but rules (I), and (II) are especially important for the most forward, though very few, π 's.

V. FRAME DEPENDENCE OF THE CASCADE.

All cascade models attempt to construct the time evolution of a complex many particle system from elementary interactions (collisions) of the constituent particles. Therefore, some method must be found for triggering these elementary collisions, and determining when they occur. The method most generally used in relativistic cascades, and which is used in LUCIFER and ARC, is to trigger a collision when two particles approach to a distance less than the geometrical interaction cross-section, all distances being evaluated in

Frame Dependence at RHIC $s^{1/2}=200$ GeV

FIG. 10. Frame dependence of LUCIFER results in p+Ag and S+S collisions at RHIC energies. For pA results there is virtually no frame dependence, while S+S exhibits about a 25% effect. Even for the heavier Ag+Ag system, the effect increases only moderately. One expects that screening of the in medium cross-section, and implementation of the Gottfried approach will considerably reduce this dependence.

the collision center of momentum frame. When a collision occurs, several outgoing particles may be produced. One must then decide where in detail they materialise, but locality of the underlying interactions demands that produced particles emerge near to the collision point. Additionally, the cascade is always imagined to proceed in some global frame. This might be, for instance, the equal velocity frame of the two incoming nuclei, or the lab frame.

Obviously, such a procedure can never be made completely frame independent. This is because the interaction between two incoming particles occurs at a spacelike separation. A signal propagates between the particles faster than the speed of light, and the collision 'time' is frame dependent. In any frame besides the collision center of momentum frame, there are at least two times at which one might say the collision occurred: t_1 , when one of the incoming particles feels the interaction, and t_2 , when the other particle feels it.

If we view the cascade from the global frame it seems reasonable to demand that we see no apparent violation of causality in that frame during the cascade. Particles should not appear before the collision in which they are produced, nor should produced particles be allowed to collide with the original particles that produced them. Neither should particles be influenced by collisions that have not yet occurred. This legislation against first order causality violations might be called an *anti-grandfather clause*:

- *The grandfather paradox is not allowed in the cascade. The time order of collisions is strictly causal in any global frame.*

If we accept the anti-grandfather clause, then there is only one possibility for the collision time: the earlier of t_1 and t_2 must be taken.

However, it is then clear that in some other global frame we may have to take the opposite choice. In that frame, the collision in question may occur before some other collision rather

than after it. In general, if many particles collide, and a list is drawn up of the times of all the possible collisions, we find that the time-order of the list is not the same in different global frames. So the time evolution of the cascade is different, and the results are dependent on the choice of global frame. The special relativistic constraint $v < c$ for physical signals, disallowing *action at a distance*, has been violated, and this is the penalty. The question is only: how frame dependent are the results? Any method short of a fully consistent field theoretical, or perhaps string-theoretical, treatment of the ion-ion collision will suffer from this defect to some extent. It may nevertheless be that the frame dependence is not so serious, and even if so, it is not logically ruled out that it can be reduced by a clever choice of algorithm.

The case of pA collisions is again illustrative. It turns out that such a cascading system can in practice be rendered virtually frame independent (Fig.10), i.e. relativistically covariant, by a production scheme which places emitted particles on a hyperboloid of constant proper time, and eliminating some acausalities originally present in ARC cascading, which did not obey the anti-grandfather clause. We consider the results obtained in two external frames for pA collisions

The frame dependencies in $S + S$ collisions at RHIC energies are on the order of 25% for the lightest mesons, the pions, (Fig.10), and only moderately higher for the more massive $Ag + Ag$ pair. One can trace the frame dependence to a slight readjustment of the cluster formation time with changes in the global frame, slowly varying with the combined mass of the system considered. The frame dependence might thus be considerably tamed by a simple global tuning, based on knowledge of data in some low mass nuclear collision at the higher energies.

VI. J/ψ PRODUCTION

It is tempting to turn LUCIFER to the currently, experimentally, interesting topic of J/ψ production near $\sqrt{s} = 20$ GeV. The recent data of Gonin *et al.* [27] for Pb+Au has been widely interpreted as heralding presence of QCD plasma [28,29]. This is eminently a case for test use of a pure hadronic simulation, like LUCIFER. Gavin and Vogt [18] have made a model calculation within a Glauber-like framework which normalizes the elementary J/ψ production from pA measurements [27] and produces breakup hadronically, against nucleons and co-movers. Presumably, if the purely hadronic description, reasonably parametrised, describes the increased suppression measured in Pb+Au, then it is difficult to argue plasma has been created. Aside from quibbling over S+Pb vs Pb+Au the Glauber estimates would seem to describe the data adequately. One major problem with Glauber theory is its inability internally and consistently to calculate the abscissa in Fig. 11, the all important E_t . A clear second problem is the use of the 'co-mover' density as a free parameter. The cascade can eliminate both of these problems, providing the relationship of suppression to E_t directly, and calculating the co-moving density dynamically. The calculation presented here is surprisingly, we believe, the first self-consistent hadronic simulation of J/ψ to be done with relativistic ions. H. Stoecker, at this workshop [30] has presented a simulation in which J/ψ 's were injected rather arbitrarily *in medias res*, at some 'zero' of time in an event: a quick and dirty first step towards a more consistent treatment.

Borrowing the J/ψ elementary production cross-sections $\sigma_{pp \rightarrow J/\psi}$, and $\sigma_{\pi p \rightarrow J/\psi}$ from data

FIG. 11. The survival probability of the J/ψ in a Pb+Pb collision at CERN energy plotted against the 'theoretical' E_t produced in the collision. Data points have been translated from 'b' to the more physical E_t scale by S. Gavin [18].

[31], and choosing the J/ψ breakup cross-section $\sigma_{br} \sim 5 \text{ mb}$ against either baryons, or hadronic comovers, the results in Fig 11 were obtained. These results are built on the same assumptions as in Ref 18. Such a breakup cross-section appears to be consistent in the Glauber picture with pA data on J/ψ . Another critical parameter is the J/ψ formation time $\tau_{J/\psi} \sim 1 \text{ fm}$. Both of these parameters, it should be noted, are *a priori* unknown, from the point of view of a hadronic simulation. The conclusion, reinforcing Gavin and Vogt, is that reasonable assumptions for input and breakup cross-sections can perfectly well accommodate the latest NA50 data. One would have to establish unambiguously that, for example, the J/ψ breakup cross-sections were well below the 3-5 mb range for alternative explanations of the suppression to be viable. There are of course also relevant data on dilepton and direct photon production which should be examined with LUCIFER. No single signal for plasma formation is likely to be probative. Summarising, one can also conclude the J/ψ measurements are explainable by hadronic cascade only if most breakup is on final state mesons, light ones at that, and if the formation time is within a tight range near 1 fm/c. Since the cascade indicates breakup is dominantly at late stages in the simulations, the introduction of a mass threshold for the annihilation biases against π 's and in favour of ρ 's as the important comovers. Such points merit further study, and of course could also argue against a conventional hadronic explanation of the data. For the moment there would appear to be too much theoretical freedom to draw absolute conclusions, and certainly not

in favour of QCD plasma.

VII. THE IMMEDIATE FUTURE

The first task is to expand the scope of the hadronic cascade, and establish its adherence to the obvious principles which determine the space-time structure of high energy collisions. Relativistic invariance has been demonstrated for pA reactions (see Fig. 9); placing the produced hadrons on a 4-d hyperboloid of constant proper time in the cm frame of the two colliding hadrons reduces frame dependence virtually to nil, even at RHIC energies. S+S collisions at RHIC still exhibit $\sim 25\%$ frame variation, for extreme choices of frame. At high particle densities one may have to introduce classical screening [32] of the two-body interactions, which will cut down relativistic effects by limiting the two-body cross-section to be no larger than one corresponding to the interparticle separation. As a byproduct overall production rates may further drop, another reason Fig. 8 is probably an overestimate at RHIC. In any case cross-sections in general should not exceed πd^2 , where d is the average distance between interacting particles, be these hadrons or partons, if a two-body picture is to be retained.

The second major task, already undertaken, is to merge LUCIFER and VNI, K. Kinder-Geiger's partonic cascade. Hadron-hadron collisions leading to transverse momentum p_t higher than some preselected cutoff will be moved from the hadronic to the partonic cascade. The obvious theoretical experiment to perform, is to compare the results of the pure hadronic and mixed hadronic/partonic models. Beside these, of course, will also be placed Al Mueller's desired pure partonic cascade followed by eventual hadronisation and pure hadronic cascading. Energy loss formulae for high energy partons appropriate to the high density environment [33,34] can be introduced and studied for their possible effects in the high density medium produced by the cascade. Differences between the three pictures should guide experiments where to look for unusual effects at RHIC.

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REFERENCES

- [1] Y. Pang, T. J. Schlagel, and S. H. Kahana, *et al*, *Phys. Rev. Lett* **68**, 2743 (1992); S. H. Kahana, D. E. Kahana, Y. Pang, and T. J. Schlagel, *Annual Reviews Of Nuclear and Particle Science*, **46**, 1996, (ed C. Quigg)
- [2] K. Eskola, *Proceedings, RHIC Summer Study'96*
- [3] A. H. Mueller *Proceedings, RHIC Summer Study'96*
- [4] J. D. Bjorken, *et al*, *Phys. Rev.* **D27**, 140 (1983)
- [5] D. Boal, *Proceedings of the RHIC Workshop I*, (1985) and , *Phys. Rev.* **C33**, 2206 (1986); K. J. Eskola, K. Kajantie and J. Lindfors, *Nucl. Phys.* **B323**, 37 (1989); X. N. Wang and M. Gyulassy,, *Phys. Rev.* **D44**, 3501 (1991); K. Geiger and B. Mueller *Nucl. Phys.* **B369**, 600 (1992); K. Geiger *Phys. Rev.* **D46**, 4965, and 4986 (1992).
- [6] K. Geiger, These proceedings.
- [7] T. D. Lee, These proceedings.
- [8] B. Andersson, G. Gustafson, G. Ingleman, and T. Sjostrand, *Phys. Rep* **97**, 31 (1983); B. Andersson, G. Gustafson, and B. Nilsson-Almqvist, *Nucl. Phys* **B281**, 289 (1987)
- [9] J. Ranft and S. Ritter, *Z. Phys.* **C27**, 413 (1985); J. Ranft *Nucl. Phys.* **A498**, 111c (1989); A. Capella and J. Tran Van, *Phys. Lett.* **93B**, 146 (1980) and *Nucl. Phys* **A461**, 501c (1987); K. Werner, *Z. Phys. C* **42**, 85 (1989)
- [10] K. Geiger, *Proceedings of Quark Matter'83*, *Nucl. Phys.* **A418**, 257c (1984); K. Geiger, *Phys. Rev.* **D51**, 2345 (1995)
- [11] E. L. Berger and G. C. Fox, *Phys. Lett* **47B**, 162 (1973)
- [12] A. Wu. Chao and C. Quigg, *Phys. Rev.* **D9**, 2016 (1974)
- [13] W. Beusch, *Acta. Phys. Pol* **B3**, 1679 (1972)
- [14] K. Gottfried *Phys. Rev. Lett.* **32**, 957 (1974); and *Acta. Phys. Pol* **B3**, 769 (1972)
- [15] J. Koplik and A. H. Mueller *Phys. Rev.* **D12**, 3638 (1975)
- [16] V. N. Gribov, B. L. Joffe and I. Ya. Pomeranchuk, *Sov. J. Nucl. Phys.* **2**, 549 (1966); V. N. Gribov, *JETP* **26**, 414 (1968); J. Kogut and L. Susskind, *Phys. Rep* **8C**, No. 2 (1973); H. D. Abarbanel, J. D. Bronzan, R. L. Sugar and A. L. White, *Phys. Rep* **21C**, No. 3 (1975); H. Chen and T. T. Wu *Phys. Rev. Lett* **24**, 1456 (1970).
- [17] D. S. Barton *et al*, *Phys. Rev.* **D27**, 2580 (1983); W. Busza *et al*, *Phys. Rev. Lett.* **34**, 836 (1975); W. Busza *Proceedings of Quark Matter'83*, *Nucl. Phys.* **A418**, 635c (1984)
- [18] S. Gavin, *Proceedings, RHIC Summer Study'96*; S. Gavin and R. Vogt *Proceedings of Quark Matter '96*, Heidelberg, May 1996
- [19] CHLM Collaboration, *Nucl. Phys.* **B108**, 1 (1976); J. W. Chapman *et al* *Phys. Rev. Lett.* **32**, 257 (1973); T. Kafka *et al* *Phys. Rev.* **D16**, 1261 (1977)
- [20] G. Eksporg for the UA5 Collaboration, *Nucl. Phys.* **A461**, 145c (1987); G. J. Alner for the UA5 Collaboration, *Nucl. Phys.* **B291**, 445 (1987)
- [21] Y. Eisenberg *et al* *Nucl. phys.* **B154**, 239 (1979)
- [22] K. Goullianos, *Phys. Rep* **101**, No. 3, (1983), 169-219
- [23] G. Alberi and G. Goggi, *Phys. Rep* **74**, No. 1, (1981), 1-207; P. V. Landshoff and O. Nachtmann, *Z. Phys.* **C35**, 405 (1987)
- [24] A. Schwimmer *Nucl. Phys.* **B94**, 44 (1975)
- [25] J. Baechler for the NA35 Collaboration, *Phys. Rev. Lett.* **A461**, 72 (1994); S. Margetis for the NA35 Collaboration, *Snowbird 1994, Proceedings, Advances in Nuclear Dynamics*, 128-135

- [26] S. Margetis for the NA49 Collaboration *Proceedings of Quark Matter '95*, , Edited by A. M. Poskanzer, J. W. Harris and L. S. Schroeder, (North Holland, 1995), 355c ; and *Phy. Rev. Lett***75**, 3814 (1995)
- [27] M. Gonin, for the NA50 Collaboration, *Proceedings of Quark Matter '96*, Heidelberg, May 1996
- [28] D. Kharzeev and H. Satz, *Proceedings of Quark Matter '96*, Heidelberg. May 1996
- [29] J. -P Blaizot and J. -Y Ollitrault, *Proceedings of Quark Matter '96*, Heidelberg, May 1996
- [30] H. Stoecker, These proceedings.
- [31] R. Gavai *et al*, *Int. J. Mod. Phys***A10**, 3043 (1995); S. Gavin *et al*, *Int. J. Mod. Phys***A10**, 2961 (1995)
- [32] S. H. Kahana, Y. Pang, T. J. Schlagel, *Phys. Rev.***C47**, R1356 (1993)
- [33] Y. Dokshitzer, these Proceedings.
- [34] Y. Dokshitzer, these Proceedings.