Elliptical Flow in Relativistic Ion Collisions at $\sqrt{s} = 200$ GeV

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A consistent picture of the Au+Au and D+Au, $\sqrt{s} = 200$ A GeV measurements at RHIC obtained with the PHENIX, STAR, PHOBOS and BRAHMS detectors including both the rapidity and transverse momentum spectra was previously developed with the simulation LUCIFER. The approach was modeled on the early production of a fluid of pre-hadrons after the completion of an initial, phase of high energy interactions. The formation of pre-hadrons is discussed here, in a perturbative QCD approach as advocated by Kopeliovich, Nemchik and Schmidt. In the second phase of LUCIFER, a considerably lower energy hadron-like cascade ensues. Since the dominant collisions occurring in this latter phase are meson-meson in character while the initial collisions are between baryons, i.e. both involve hadron sized interaction cross-sections, there is good reason to suspect that the observed elliptical flow will be produced naturally, and this is indeed found to be the case.

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I. INTRODUCTION

RHIC experiments [1, 2, 3] have identified a transverse momentum asymmetry, designated as ‘elliptical flow,’ and characterized by the variable $v_2$. This quantity has deservedly attracted considerable interest. Early heavy ion experiments at the LBL TEVALAC [4, 5] defined flow in terms of the asymmetry of the transverse momentum distributions observed for a variety of particles, both baryons and mesons, produced in relativistic heavy ion collisions at these relatively low energies. Investigations of flow were subsequently extended to the AGS heavy ion program [6, 7] and eventually flow was studied in experiments at the CERN SPS. LBL and even the AGS energies per nucleon were of course well below those achievable at RHIC. At lower energies, however, it was possible to examine an event by event phenomenon, and to extract what was generally referred to as directed or sideways flow [4], separately for baryons and mesons. This was of critical importance in understanding the dynamics of relativistic ion collisions at those energies. Much theoretical effort was expended in understanding this phenomenon in terms of hydrodynamics [8] employing particular equations of state for high density nuclear matter and setting some set of initial conditions for the hydrodynamics.

Considerable success, however, was also obtained [7] and a description of the sideways flow using only a cascade oriented simulation, also proved to be possible, with its own inherent treatment of the nuclear medium. Here we discuss at $s^{1/2} = 200$ GeV only the prominent, designated elliptical, flow extracted from a combined history of many events. We are also limited to overall particle distributions, necessarily dominated by final stable mesons.

Flow may be formally introduced by expressing the observed transverse momentum distributions as a function of a transverse azimuthal angle $\phi$, relative to the angle $\psi_R$ fixing the inclination of initial reaction plane.

$$\frac{dN}{d(\phi - \psi_R)} = \frac{1}{2\pi} \left[ 1 + \sum_n 2v_n \cos(n(\phi - \psi_R)) \right]$$  \hspace{1cm} (1)

Of particular interest at RHIC is the second term in this expansion, i.e. $v_2$, which if non-vanishing indicates an elliptical asymmetry. The first term, if non-zero, would signal the presence of directed or sideways flow, and has been estimated in the RHIC detectors [1, 2, 3], the corresponding parameter $v_1$, is found to be small in these experiments. Data has been accumulated by three of the RHIC detectors [1, 2, 3] producing experimental studies of the ellipticity for different degrees of centrality, and also as a function of $p_\perp$. A comparison is made here between the PHOBOS measurements and LUCIFER simulations. Reasonable descriptions of both the observed $DN/D\eta$ spectra in $Au+Au$ as well as the ratios of $p_\perp$ distributions in $D+Au$ and $Au+Au$ at 200 GeV were already obtained with LUCIFER simulation. [9, 10, 11].

We previously cited [9, 11] the theoretical difficulties that arise in producing sufficient flow in a straight-forward parton cascade models, e.g. the studies done by Molnar [12]. This author suggested the possible use of parton...
coalescence as a mechanism to produce the otherwise too large observed ellipticity. Otherwise, as Molnar notes, the parton-parton cross-section must be made as large as 49 mb\(^{13}\) to yield the measured ellipticities. In the sense that we are in fact exploiting the properties of a strongly interacting pre-hadronic fluid at a second, but still early, stage in our simulation, this hypothesis of Molnar\(^{12}\) and our approach do have considerable overlap, practically speaking. A relatively large size for the interacting objects present in the cascade dynamics is surely a key ingredient in reproducing the required elliptical flow.

We note from the outset, though, that an appreciable degree of flow, perhaps more than 30\%, is already generated by the phase I nucleon-nucleon interactions, and subsequently transmitted to the produced pre-hadrons colliding in Phase II of the simulation. These initial interactions are mediated by the even larger baryon-baryon cross-sections, by the phase I nucleon-nucleon interactions, and subsequently transmitted to the produced pre-hadrons colliding in non-zero impact parameter.

The approach presented here may be of less validity for the lowest \(p_{\perp}\) charged particles, but becomes increasingly accurate with rising \(p_{\perp}\). Nevertheless we display results from the modeling for even low \(p_{\perp}\).

In what follows we outline the dynamics behind our earlier calculations which yielded a successful description of both \(D + Au\) and \(Au + Au\) data at \(\sqrt{s} = 200\) GeV. Of course the same dynamics is employed in the present determination of the ellipticity. Subsequently, actual calculations of elliptical asymmetry are displayed for a variety of kinematic cuts in centrality and transverse momentum and compared, in particular, to PHOBOS measurements.

II. THE SIMULATION

The simulation code LUCIFER, developed for high energy heavy-ion collisions has previously been applied to both SPS energies \(\sqrt{s} = (17.2, 20)\) A GeV\(^{14}\)\(^{15}\) and to RHIC energies \(\sqrt{s} = (56, 130, 200)\)A GeV\(^{9, 11, 16}\). Although nominally intended for dealing with soft, low \(p_{\perp}\), interaction it is possible to introduce high \(p_{\perp}\) hadron spectra via the NN inputs, which form the building blocks of the simulation, and to then examine the effect of re-scattering, and concomitant energy loss, on such spectra\(^{8, 11}\). The simulation is divided into two phases I and II, with most re-scattering and explicit two body energy loss restricted to the second and considerably reduced energy stage. The first stage sets up the participants, both mesonic and baryonic, their four momenta and positions for the commencement of the cascade in II, and hence then also involves energy loss through transfer to the produced particles. The second stage energy loss and interactions within a pre-hadronic fluid played a key role in the reproducing the observed suppression of the \(p_{\perp}\) distribution in our description of \(Au + Au\) collisions.

The purpose of describing such high energy collisions without introducing the parton structure of hadrons, at least for soft processes, is to set a baseline for judging whether deviations from the simulation measured in experiments existed and could then signal interesting phenomena. The dividing line between soft and hard processes, the latter being in principle described by perturbative QCD, is not necessarily easy to identify in heavy ion data, although many authors believe they have accomplished this within a gluon-saturation picture\(^{17, 18, 19}\).

A. Pre-hadrons: Production and Hadronisation Time Scales

Such a mechanism for the suppression of high transverse momentum jets may seem to run counter to the conventional pQCD description. There does exist, however, some theoretical justification for a picture in which colourless pre-hadrons, may be produced at rather early times in a AA collision, and then play a key role in the further development of the system. First, there is the work of Shuryak and Zahed\(^{20}\) on the persistence of hadron-like states above the critical temperature in a dense quark-gluon medium as well as similar results from lattice-driven studies on the persistence of the J/\(\Psi\) and other special hadronic states\(^{21}\).

Recently a much more transparent treatment has been given, on which we now mainly rely, by Kopeliovich, Nemchik and Schmidt\(^{22}\) as well as Berger\(^{23}\), who directly consider the temporal dynamics of pre-hadron production from a pQCD point of view. In particular Kopeliovich et al., outline the fate of leading hadrons from jets, in deep inelastic scattering (DIS) on massive ions and discuss the relevance to relativistic heavy ion collisions. These works have the distinct advantage of relying on pQCD. We attempt to reproduce their development as it is germane to our treatment of NN, NA and AA interactions.

Figure (1), essentially borrowed from Reference\(^{22}\), displays the production of a jet, here at least a moderately high energy quark jet, originating in a pp or pA event, as well as the time scales relevant to the process. Kopeliovich et al. begin by explicitly considering eP or eA, in which case the initiating particle in the jet creation is an off-shell photon (\(\gamma^*\)). In pp or AA one could equally well employ a gluon at the first vertex. The kinematics\(^{22}\) remains essentially the same then for nuclear induced events and we elaborate this case somewhat.
The hadronisation time is related to the QCD scale factor and is usually estimated as:

\[ z = \frac{1}{Q^2} \]

where \( z \) is the fraction of quark energy imparted to the hadron. Integrating the gluon radiation spectrum one obtains for the energy loss per unit length \( z \), a time independent rate \( \frac{2\alpha_s}{3\pi}Q^2 \) rising quadratically with the hard scale \( Q \),

\[ \frac{dE}{dz} = \frac{2\alpha_s}{3\pi}Q^2. \]

The colour neutralisation time is then given by:

\[ t_p \sim \frac{E_q}{Q^2}(1 - z_h), \tag{2} \]

where \( z_h = E_h/E_q \) is the fraction of energy imparted to the hadron.

The hadronisation time is related to the QCD scale factor and is usually estimated as:

\[ t_f \sim \frac{E_h}{A^2_{QCD}}, \tag{5} \]

and is much longer than the colour neutralisation time, given that the QCD scale is close to 200 GeV.

The authors of Reference (22) argue that the brevity of the de-colourisation time scale is a consequence of the effects of energy conservation, coherence and Sudakov suppression.

Importantly, a much reduced time scale for pre-hadron creation is likely to remain true even for non-leading partons provided Equation (4) remains valid, i.e., when \( Q \) is comparable to \( E_q \). Thus many of the radiated hard or moderately hard gluons, in the early stages of a pp or AA collision will initiate similar pre-hadrons, and in a nuclear medium such large sized objects will be numerous and of critical importance to the dynamics. One should keep in mind that the overall multiplicity is not large at \( p_{\perp} \gtrsim 1 \text{ GeV}/c \), where the NN \( p_{\perp} \) spectrum, as seen in Figure (2) [25], has already dropped well below that at the softest transverse momenta measured: by close to two orders of magnitude at \( p_{\perp} \sim 1 \text{ GeV} \) and for 200 GeV Au+Au as seen in Figure (3) [26] by somewhat more. One concludes that the production and hadronisation processes are to some degree separate: with generally \( t_p \) less than \( t_f \) and frequently much less. Corresponding time scales in, say, the center of momentum frame for an A+A system will of course be considerably contracted, given respectively by \( \tau_{p,f} \sim [1^{-1}]t_{p,f} \). Although the colourless pre-hadron in Figure (1) is generated by an initially perturbative process with an anti-quark, it is the subsequent interactions with other such pre-hadrons that leads to the observed suppression for mesons of appreciable and even moderate transverse momentum. The pre-hadron perturbatively begins life with the \( q\bar{q} \) at small relative distance, and thus has a small initial size, but in light of the ambient momenta for such high or even moderately high energy partons, the transverse diameter rapidly increases to the scale of a typical hadron. Reference (22) suggests the entire growth to pre-hadronic size occurs quickly.

One can pursue the evolution of the system of pre-hadrons via a Glauber-theory [22, 27] based treatment of their interactions, or, as we do, via a standard cascade model. The end result is little different: what has been labeled jet suppression results. In Glauber theory the hadron-sized cross-sections produce strong absorption: hard pre-hadrons simply do not remain in the final state, they are too often absorbed. In the cascade described hereafter the pre-hadronic medium is sharply cooled by the interactions and instead of one hard meson, many softer mesons appear at lower \( p_{\perp} \).
To obtain the final cascade yields for both D+Au \cite{9} and Au+Au \cite{11}, it’s essential that the characteristic time $t_p$ is considerably less than $t_f$. Indeed, this constraint, and the appropriately large pre-hadron interaction cross-sections also are critical in generating the surprisingly large elliptical flow that has been measured at RHIC \cite{1, 2, 3, 12}. Kopeliovich \textit{et al.} provide a perturbative QCD justification for both conditions: early de-colourisation and large pre-hadron interaction cross-sections.

### B. Simulation Dynamics

For completeness we present a brief overview of the dynamics of our Monte Carlo simulation, which has in fact already been described extensively in earlier works \cite{1, 11, 15}. Many other simulations of heavy ion collisions exist and these are frequently hybrid in nature, using say string models in the initial state \cite{28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41} together with final state hadronic collisions, while some are either purely or partly partonic \cite{36, 37, 38, 39, 40, 41} in nature. Our approach is closest in spirit to that of RQMD and K. Gallmeister, C. Greiner, and Z. Xu \cite{42} as well as work by W. Cassing \cite{43} and G. Wolschin \cite{44}. The latter authors seek to separate initial perhaps parton dominated processes from hadronic interactions occurring at some intermediate but not necessarily late time, and/or rely on some hadronic dynamics.

Whereas in the simulations of the $D + Au$ and $Au + Au$ ion-ion collisions our purpose was to present a background hadronic setting from which deviations in observations would signal interesting QCD phenomena, the measured flow, which is certainly appreciable, seems ab initio to demand a pre-hadronic source. In stage I in the incoming target and projectile nucleons interactions are tracked, while in II produced particles, considered as pre-hadrons interact in a hadron-like cascade. Basic inputs in the entire simulation \cite{14, 15, 16} are the measured hadron-hadron cross-sections \cite{25, 45, 46} as functions of energy and the production multiplicities taken to conform to KNO \cite{47} scaling. The elementary NN dynamics is split, as in the classic work of Goulianos on the phenomenological treatment of NN \cite{48}, into elastic, single diffractive (SD) and non-single diffractive (NSD).

No energy loss is permitted in I, except at the completion of this stage when production of pre-hadrons is initiated, the collisions occurring essentially parallel in time. A history of each collision is retained, from which one can construct the particle $p_\perp$ from random walk and in the present case can also infer, for non-vanishing impact parameter, an asymmetry in the transverse momentum distributions. This $p_\perp$ and attached asymmetry can be appropriately passed on to the pre-hadrons generated at the end of phase I.

The transition from stage I to stage II is accomplished with the guidance of the two-body inputs. The multiplicities, energies and character of the produced particles are determined, as well as the initial, transverse-asymmetric momentum distribution. The entities produced in I are principally a set of vector pre-hadrons, and also after a time $\tau_f$ decay into the normal "stable" mesons. The decays take account of the vector nature of the pre-hadrons. In this work the baryons are limited to the usual flavour octet. the comparison with elementary NN measurements severely limits any freedom in the mass, number and spectra of the produced mesons.

Pre-hadrons, which when mesonic presumably consist of a spatially loosely correlated quark and anti-quark pair, are given a mass spectrum between $m \sim m_\pi$ and $m \sim 1.2$ GeV, with correspondingly higher upper and lower limits allowed for pre-hadrons including strange quarks. The Monte-Carlo selection of masses is then governed by a Gaussian distribution,

$$P(m) = \exp(- (m - m_0)^2 / w^2),$$

with $m_0$ a selected center for the pre-hadron mass distribution and $w = m_0/4$ the width. For non-strange mesonic pre-hadrons $m_0 \sim 700$ MeV, and for strange $m_0 \sim 950$ MeV. Small changes in $m_0$ and $w$ have little effect since the code is constrained to fit hadron-hadron data. Too high an upper limit for $m_0$ would destroy the soft nature expected for most pre-hadron interactions when they finally decay into 'stable' mesons.

To reiterate: the cross-sections in pre-hadron collisions are taken to be the same magnitude as hadronic cross-sections, at the same center of mass energy, thus introducing no additional free parameters into the model. Where hadronic cross-sections or their energy dependences are inadequately known we employ straightforward quark counting to determine the cross-section magnitudes. Further details on this early stage of the simulation can be found in earlier work \cite{9, 11, 14, 15, 16}.

It should also be noted that the rather small $DN/D\eta$ observed by PHOBOS \cite{49} was in fact predicted \cite{15} in our simulation directly from the rise in multiplicities with energy inserted into LUCIFER via the experimentally constrained NN inputs. This very small rise puts some doubts on the achievement of a standard QCD plasma at RHIC. The increase of entropy expected in a phase transition from confined to unconfined partons should show up as a rather sharp increase in produced mesons.
III. STAGE II: FINAL STATE CASCADE

Stage II is a straightforward two body cascade in which the pre-hadrons, and of course any normal hadrons present, may interact and decay. The pre-hadron decay time, taken at rest or in fact in the colliding Au+Au frame uniformly as $\tau_{p} \sim 1.0$ fm., can be viewed as a hadronisation or formation time. Appreciable energy having been finally transferred to the produced particles these ‘final state’ interactions occur at considerably lower energy than the initial nucleon-nucleon collisions in stage I. The final cascade of course conserves energy-momentum and leads to additional transverse energy and meson production. For Au+Au, the effect of pre-hadron interactions is appreciable, greatly increasing multiplicities and total transverse energy, $E_{\perp}$, through both production and eventual decay into the stable meson species. These ‘final state’ interactions of stage II were the principal agent in the suppression of high $p_{\perp}$ production [9, 11].

The spatial positions of the particles at this time could be assigned in various ways. We have chosen to place the pre-hadrons inside a cylinder, extending in the transverse and longitudinal directions far enough to contain the final stage I positions of the initial baryons in the group. We then allow the cylinder to evolve freely longitudinally according to the corresponding momentum distributions, for a fixed time $\tau_{p}$, i.e. roughly the pre-hadron production time in the colliding frame. At the end of $\tau_{p}$, the total multiplicity of pre-hadrons is limited so that, given normal hadronic sizes appropriate to meson-meson cross-sections $\sim (2/3)(4\pi/3)(0.6)^{3}$ fm$^{3}$, hadrons do not overlap within the cylinder. Such a limitation in density is consonant with the notion that produced hadrons can only exist as particles when separated from the interaction region in which they are generated [50]. One may conclude from this that the pre-hadronic matter acts like, at its creation, as an incompressible fluid, viz. a liquid, as depicted in the earliest calculations with LUCIFER [4, 14].

IV. FLOW DETERMINATION

We have run simulations for central, mid-central and peripheral cuts used by PHOBOS [2] to correspond to centralities of 3%-15%, 15%-25%, and 25%-50% respectively. Calculated results are displayed in Figure(4) alongside the PHOBOS determinations. The theoretical curves shown are best smooth fits to the LUCIFER results, which of course display statistical errors. Given the larger non-statistical experimental errors and the difficulty of calculation at large PHOBOS determinations. The final catalogue of course conserves energy-momentum and leads to additional transverse energy and meson production. For Au+Au, the effect of pre-hadron interactions is appreciable, greatly increasing multiplicities and total transverse energy, $E_{\perp}$, through both production and eventual decay into the stable meson species. These ‘final state’ interactions of stage II were the principal agent in the suppression of high $p_{\perp}$ production [9, 11].

The agreement between measurement and simulation is quite striking. With the code already completely specified and constrained by the previous calculations of rapidity and transverse momenta spectra [9, 11] for both D+Au and Au+Au, there is nothing to adjust to yield the asymmetric elliptical flow.

Of course we must also confront the dependence of ellipticity on transverse momentum, $p_{\perp}$, evidenced in the experimental data. This comparison is given in Figure(5). The present model, without intervention, handles this behaviour more than adequately. There is an agreement in both magnitude and $p_{\perp}$ variation, in particular the clear saturation of ellipticity above 1-2 GeV/c. For the moment we cannot follow the functional variation of $v_{2}$ to very high $p_{\perp}$, since it requires a considerable increase in computation time. Nevertheless, the deviation of our model from a naive hydrodynamic picture is already evident. More importantly there is unambiguous confirmation of the presence of hadron-like degrees of freedom, at an early stage in the 200 GeV Au+Au collision. The observed magnitude of flow could not have obtained without hadron sized interaction cross-sections in both phase I and II of the simulation.

The non-hydrodynamic saturation of $v_{2}$ with increasing $p_{\perp}$ presents an interesting puzzle. Our best guess is that at the higher transverse momenta there is less time for interaction within the stage II hadronic medium and correspondingly less tying of the ellipticity to the initial geometry for the highest $p_{\perp}$ mesons. Also decays of pre-hadrons play an important role here: both decreasing the flow at low $p_{\perp}$ and increasing it at high $p_{\perp}$.

There are two clear lessons to be learned. First that the second phase, the pre-hadronic cascade, must begin early, at a time $\tau_{p} \sim (\Gamma)^{-1}t_{p}$ with $\Gamma$ the average Lorentz factor for pre-hadrons in the collision center of velocity frame for the colliding gold nuclei. This is in accord with what was found earlier in simulations of the single particle spectra in d+Au and Au+Au. Second that large cross-sections must be employed in phase II and indeed also in the initiating NN collisions in phase I.

The flow is apparently a consequence of and requires large interaction cross-sections, between objects which cascade starting at early times. This picture either obviates or is in accord with the phrase “strongly interacting quark-gluon plasma” which has been popularly employed to described the dense matter produced in the RHIC energy ion-ion collisions, depending on one’s point of view. The aptness of the description of the pre-hadron medium as a liquid was made clear in our earlier work, where the pre-hadron multiplicity was limited by a constraint that the pre-hadrons could not overlap [9, 11, 12].
A. Time and Interaction Dependence of Ellipticity.

By way of a theoretical experiment, we have in Figure (6) explored the variation in produced flow with the initial delay $\tau_p$ before the start of phase II and also with the magnitude of the meson-meson cross-section in this phase II. The results are clear. Halving the cross-sections decidedly reduces the flow, $v_2$, to a value well below the measured results. A similar effect occurs when the pre-hadron production time $\tau_p$ is increased. In a dense many body system there is a natural screening with the cross-section being effectively limited by that corresponding to the average distance between particles. Should the production of flow occur early on, when the density is high, the limiting cross-section will be $\sim \pi a^2$ with $a$ the average interparticle distance. As a result little effect will be evident from a cross-section increase.

The $\tau_p$ dependence exhibited in Figure (6) is striking, the flow diminishes very appreciably with a large delay in the commencement of phase II. The geometrical, free expansion of the system reduces both the densities and the interaction frequencies, thus increasing the mean free path for pre-hadrons; in hydrodynamic terms this lessens the pressure which produces the flow. The connection between ellipticity and the initial spatial configuration of the ion-ion collision is thus lost by the time the interactions begin. One should note that the cascade calculations in an appropriate limit should yield hydrodynamics. Of course the hydrodynamic limit for flow is achieved experimentally only for low $p_\perp$ and in Figure (5) both measurements and LUCIFER simulation drop well below the earliest hydrodynamic predictions at higher low $p_\perp \sim 2 \text{ GeV/c}$.

Very soft early gluons and quarks are not a part of the colour neutral medium, but their eventual hadronisation is approximated by our treatment of soft hadronic processes, guided by known hadron-hadron interactions and production multiplicities. Finally, completely eliminating phase II reduces the ellipticity $v_2$ by some 25-30%, depending on the centrality, the remaining flow being ascribable to the initial nucleon-nucleon interaction which already occurred in phase I.

V. COMMENTS

Overall the very natural fashion in which the elliptical flow is produced in the model speaks strongly to the important role played by pre-hadrons, i.e. colour neutral objects having hadron-sized interaction cross-sections, and their presence from an early time in Au+Au collisions at RHIC energies. Elliptical flow is, after all, the one truly collective phenomenon to have been observed at RHIC, and it is precisely such collective properties that may indicate the existence of some medium or fluid, in this case a plasma apparently characterized by objects having hadron sized interaction cross-sections during much of its existence. The very earliest times in an A+A collision, tracked in the first stage of our simulation, also play a non-negligible role in the production of elliptical flow. The nucleon-nucleon interactions occurring in this stage likely lead to a Cronin-like [51] enhancement [11] of the high $p_\perp$ spectrum and also transmit the spatial geometry of the collision to the produced pre-hadrons. It would be interesting to evolve this first stage with allowances made for mutual crossing between parallel quark-gluon and hadronic simulations. Future work will pursue such an avenue. Also, in agreement with the PHOBOS observations [2], the simulation produces only very small direct flow, i.e. $v_1$, at $s^{1/2} = 200 \text{ GeV}$.

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FIG. 1: Schematic drawing, borrowed from Kopeliovich et al. [22], of the perturbative formation of a pre-hadron from an off-shell gluon $g^*$ incident on a quark in the rest frame of nucleus B in an A+B or P+B event. The quark radiates gluons and eventually combines with a perturbatively produced anti-quark to form at first a small colourless pre-hadron which rapidly expands to hadronic size. The time $t_p$ signifies the production time of the pre-hadron and $t_h$ its later hadronisation time. It is argued in the text that in general $t_p$ is much less than $t_h$, and the existence of two such time scales is critical to the parton–hadron dynamics.
FIG. 2: pp Pseudo-rapidity spectra: Comparison of UA1 minimum bias 200 GeV NSD data with an appropriate LUCIFER simulation. The latter is properly constrained by experiment and is an input to the ensuing AA collisions; thus does not constitute a ‘set’ of free parameters.
FIG. 3: Central PHENIX $\pi^0$ 200 GeV for Au+Au vs simulation. Curves for different choices of the production time $\tau_p$ differ very little, since in effect the cascade effectively begins somewhat later, near $0.25 - 0.35$ fm/c and continues much longer to tens of fm/c. Centrality for PHENIX is here $0\% - 10\%$, roughly for impact parameters $b < 4.25$ fm. in the simulation.
FIG. 4: PHOBOS 200 GeV charged flow, $v_2$, as a function of pseudo-rapidity for peripheral, mid-central, and central versus LUCIFER simulations, with actual points calculated indicated in central and peripheral but for an already busy graph only a fit is shown for mid-central.
PHOBOS charged 0%-50%
HYDRO
LUCIFER baryons
LUCIFER charged
LUC FIT.

FIG. 5: PHOBOS 200 GeV $v_2$ as a function of transverse momentum for 0-50% centrality versus LUCIFER simulations for both charged mesons and baryons. Hydro calculations are also indicated [8].
Variation with x-section and time

FIG. 6: Variation in LUCIFER central simulations with scale changes for the overall pre-hadron-pre-hadron cross section by a factor of one-half and the time factor by 2.0. This decrease in interaction strength, especially, and lengthening of the time lead to considerable reduction in the elliptical flow.