High Tranverse Momentum Suppression in Au+Au Collisions

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Great interest has attached to recent Au+Au, \( \sqrt{s} = 200 \text{ A GeV} \) measurements at RHIC, obtained with the PHENIX, STAR, PHOBOS and BRAHMS detectors. For central collisions and vanishing pseudo-rapidity all experiments indicate a considerable lowering in charged particle production at mid to large transverse momenta. In the PHENIX experiment similar behavior has been reported for \( \pi^0 \) spectra. In a recent work [1] on the presumably simpler D+Au interaction, to be considered perhaps as a tune-up for Au+Au, we reported on a hadronic cascade mechanism which can explain the observed but somewhat reduced \( p_T \) suppression at higher pseudo rapidity as well as the Cronin enhancement at mid rapidity. Here we report on the extension of this work to the more massive ion-ion collisions.

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I. INTRODUCTION

The specific question at hand in this work is the suppression of medium to high transverse momentum yields observed in the experimental measurements [2, 3, 4, 5] for Au+Au at 130 GeV and 200 GeV. The experimental results have focused on the \( \eta \) and \( p_{\perp} \)-dependence of the ratio

\[
R[AA/NN] = \left( \frac{1}{N_{\text{coll}}} \right) \left[ \frac{d^2N^{ch}/dp_{\perp}d\eta}{d^2N^{ch}/dp_{\perp}d\eta} \right] (\text{AA}) \left[ \frac{d^2N^{ch}/dp_{\perp}d\eta}{d^2N^{ch}/dp_{\perp}d\eta} \right] (\text{NN}),
\]

where \( N_{\text{coll}} \) is a calculated number of binary NN collisions occurring in Au+Au at a designated energy and centrality. One can also, of course, just refer directly to the data without reference to the ratios.

The simulation code LUCIFER, developed for high energy heavy-ion collisions has previously been applied to both SPS energies \( \sqrt{s} = (17.2, 20) \text{ A GeV} \) [8] and to RHIC energies \( \sqrt{s} = (56, 130, 200) \text{ A GeV} \) [9, 10]. Although nominally intended for dealing with soft, low \( p_T \), interaction it is possible to introduce high \( p_T \) hadron spectra via the NN inputs, which form the building blocks of the simulations, and to then examine the effect of rescattering on such spectra [1].

We present a brief description of the dynamics of this Monte Carlo simulation. Many other simulations of heavy ion collisions exist and these are frequently hybrid in nature, using say string models in the initial state [11, 12, 13, 14, 15, 16, 17, 18] together with final state hadronic collisions, while some codes are purely partonic [19, 20, 21, 22, 23, 24] in nature. Our approach is closest in spirit to that of RQMD and K. Gallmeister, C. Greiner, and Z. Xu [25] as well as work by W. Cassing [11, 25, 26]. Certainly our results seem to parallel those of the latter authors. Both seek to separate initial perhaps parton dominated processes from hadronic interactions occurring at some intermediate but not necessarily late time.

The purpose of describing such high energy collisions without introducing the evident parton nature of hadrons, at least for soft processes, was to set a baseline for judging whether deviations from the simulation measured in experiments existed and could then signal interesting phenomena. The division 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 configuration [27, 28, 29]. For both D+Au and Au+Au systems we separate the effects of a second stage, a lower energy hadronic cascade, from those of the first stage, a parallel rather than sequential treatment of initial (target)-(projectile) NN interactions.

In the present work, even absent some energy-loss effects which one might anticipate, we do find considerable suppression of the Au+Au transverse momentum spectrum at central rapidity. One might say that the first stage of our simulation, involving the parallel interaction of the initially present nucleons, produces a “hot-gas” of prehadrons which are considerably cooled in an inevitable final state cascade. This cooling constitutes the observed “jet” suppression, a suppression, not surprisingly appreciably greater for Au+Au than for D+Au /citebrahms2,luc4brahms. The second stage II, a true cascade also, critically includes energy loss effects. The latter inevitably soften at least the lower \( p_{\perp} \), as II involves considerably reduced energy processes.
II. THE SIMULATION

A. Stage I

The first stage I of LUCIFER considers the initial interactions between the separate nucleons in the colliding ions A+B, but is not a cascade. The totality of events involving each projectile particle happen essentially together or one might say in parallel. Neither energy loss nor creation of transverse momentum \((p_T)\) are permitted in stage I, clearly an approximation. A model of NN collisions, incorporating most known inclusive cross-section and multiplicity data, guides stage I and sets up the initial conditions for stage II. The two body model, clearly an input to our simulation, is fitted to the elastic, single diffractive (SD) and non-single diffractive (NSD) aspects of high energy \(PP\) collisions and \(PP\) data. It is precisely the energy dependence of the cross-sections and multiplicities of the NN input that led to our successful prediction of the rather small (13\%) increase in \(dN^{ch}/d\eta\) between \(\sqrt{s} = 130\) and \(\sqrt{s} = 200\) A GeV, seen in the PHOBOS data.

We find that the addition to stage I baryons of transverse momentum by collision dependent random walk produces in fact a rather “hot” gas of mesons, in effect a strong A-dependent Cronin effect, a gas which is subsequently cooled by the final state cascading collisions in stage II. The comparison of the initial and final \(p_T\) spectra provides an alternative measure of suppression to the above ratio \(R[AA/NN]\).

A history of the collisions that occur between nucleons as they move along straight lines in stage I is recorded and later used to guide determination of multiplicity. Collision driven random walk in \(p_T\) fixes the \(p_T\) to be ascribed to the baryons at the start of stage II. The overall multiplicity, however, is subject to a modification, based, as we believe on natural physical requirements.

If a sufficiently hard process, for example Drell-Yan production of a lepton pair at large mass occurred, it would lead to a prompt energy loss in stage I. Hard quarks and gluons could similarly be entered into the particle lists and their parallel progression followed. This has not yet been done. One viewpoint and justification for our approach is to say we attempt to ignore the direct effect of colour on the dynamics, projecting out all states of the combined system possessing colour. In such a situation there should be a duality between quark-gluon or hadronic treatments.

The collective/parallel method of treating many NN collisions between the target and projectile is achieved by defining a group structure for interacting baryons. This is best illustrated by considering a prototype proton-nucleus (P+A) collision. A group is defined by spatial contiguity. A proton at some impact parameter \(b(x)\) is imagined to collide with a corresponding ‘row’ of nucleons sufficiently close in the transverse direction to the straight line path of the proton, \(i.e.,\) within a distance corresponding to the NN cross-section. In a nucleus-nucleus (A+B) collision this procedure is generalized by making two passes: on the first pass one includes all nucleons from the target which come within the given transverse distance of some initial projectile nucleon, then on the second pass one includes for each target nucleon so chosen, all of those nucleons from the projectile approaching it within the same transverse distance. This totality of mutually colliding nucleons, at more or less equal transverse displacements, constitute a group. The procedure partitions target and projectile nucleons into a set of disjoint interacting groups as well as a set of non-interacting spectators in a manner depending on the overall geometry of the A+B collision. Clearly the largest groups in P+A will, in this way, be formed for small impact parameters \(b\); while for the most peripheral collisions the groups will almost always consist of only one colliding NN pair. Similar conclusions hold in the case of A+B collisions.

In stage II of the cascade we treat the entities which rescatter as prehadrons. These prehadrons, both baryonic or mesonic in type, are not the physical hadron resonances or stable particles appearing in the particle data tables, which materialize after hadronisation. Importantly prehadrons are allowed to interact starting at early times, after a short production time, nominally the target-projectile crossing time \(T_{AB} \sim R_{AB}/\gamma\). The mesonic prehadrons are imagined to have \((q\bar{q})\) quark content and their interactions are akin to the dipole interactions included in models relying more closely on explicit QCD and certain lattice gauge studies, but are treated here as colourless objects.

Some theoretical evidence for the existence of comparable colourless structures is given by Shuryak and Zahed and by certain lattice gauge studies. In these latter works a basis is established for the persistence of loosely bound or resonant hadrons above the QCD critical temperature \(T_c\) to \(T \sim (1.5 - 2.0) \times T_c\). This implies a persistence to much higher transverse energy densities \(\rho(E) \sim (1.5 - 2.0)^4 p_c\), hence to the early stages of a RHIC collision. Accordingly we have incorporated into stage II hadron sized cross-sections for the interactions of these prehadrons, although early on it may in fact be difficult to distinguish their colour content. Such larger cross-sections indeed appear to be necessary for the explanation of the apparently large elliptical flow parameter found in measurements.

The prehadrons, which when mesonic may consist of a spatially close, loosely correlated quark and anti-quark pair, are given a mass spectrum between \(m_x\) and 1 GeV, with correspondingly higher upper and lower limits allowed for prehadrons including strange quarks. The Monte-Carlo selection of masses is then governed by a Gaussian distribution,

\[
P(m) = \exp\left(-\frac{(m - m_0)^2}{w^2}\right),
\]
with \( m_0 \) a selected center for the prehadron mass distribution and \( w = m_0/4 \) the width. The non-strange mesonic prehadrons is taken at \( m_0 \sim 500 \text{ MeV} \), and for strange at \( m_0 \sim 650 \text{ MeV} \). 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 prehadron interactions when they finally decay into ‘stable’ mesons. The same proviso is in place for prebaryons which are restricted to a mass spectrum from \( m_N \) to 2 GeV. However, in the present calculations the prebaryons are for simplicity taken just to be the normal baryons. The mesonic prehadrons have isospin structure corresponding to \( \rho, \omega, \text{or } K^* \), while the baryons range across the octet and decuplet.

Creating these intermediate degrees of freedom at the end of stage I simply allows the original nucleons to distribute their initial energy-momentum across a larger basis of states or Fock space, just as is done in string models, or for that matter in partonic cascade models. Eventually, of course, these intermediate objects decay into physical hadrons and for that purpose we assign a uniform decay width \( \sim \Gamma_f \), which then plays the role of a hadronisation or formation time, \( \sim 1/(\Gamma_f) \).

### B. Elementary Hadron-Hadron Model

The underlying NN interaction structure involved in I has been introduced in a fashion dictated by the proton-proton modeling \[30\]. A division is made into elastic, single diffractive (SD) and non-single diffractive components. Fits are obtained to the existing two-nucleon data over a broad range of energies (\( \sqrt{s} \)), using the same prehadrons introduced above. No rescattering, only decay of these intermediate structures is permitted in the purely NN calculation. Specifically the meson-meson interactions are scaled to \( 4/9 \) of the known NN cross-sections, thus no new parameters are invoked. Indeed, since only known data then constrains the prehadronic interaction, this approach is a parameter-free input to the AA dynamics.

### C. Groups

Energy loss and multiplicity in each group of nucleons is estimated from the straight line collision history. To repeat, transverse momentum of prebaryons is assigned by a random walk having a number of steps equal to the number of collisions suffered. The multiplicity of mesonic prehadrons cannot be similarly directly estimated from the number of NN collisions in a group. We argue \[42\] that only spatial densities of generic prehadrons \[8,9\] below some maximum are allowable, viz. the prehadrons must not overlap spatially at the beginning of stage II of the cascade. The KNO scaled multiplicity distributions, present in our NN modeling are sufficiently long-tailed that imposing such a restriction on overall multiplicity can for larger nuclei affect results even in P+A or D+A systems. In earlier work \[8,10\] the centrality dependence of \( dN/dy \) distributions for RHIC energy \( \text{Au+Au} \) collisions was well described with such a density limitation on the prehadrons, which was not carried out as meticulously as in the present work, especially with respect to highly peripheral collision.

Importantly, the cross-sections in prehadronic collisions were assumed to be the same size as hadronic, e. g. meson-baryon or meson-meson etc., at the same center of mass energy, thus introducing no additional free parameters into the model. Where the latter cross-sections or their energy dependences are inadequately known we employed straightforward quark counting to estimate the scale. In both SPS, Pb+Pb and RHIC \( \text{Au+Au} \) events at several energies it was sufficient to impose this constraint at a single energy. The inherent energy dependence in the KNO-scaled multiplicities of the NN inputs and the geometry then take over.

### D. High Transverse Momenta

One question which has yet to be addressed concerns the high \( p_\perp \) tails included in our calculations. In principle, LUCIFER is applicable to soft processes i.e. at low transverse momentum. Where the cutoff in \( p_\perp \) occurs is not readily apparent. In any case we can include high \( p_\perp \) meson events through inclusion in the basic hadron-hadron interaction which is of course an input rather than a result of our simulation. Thus in Fig(1) we display the NSD \((1/2\pi p_\perp)(d^2N^{\text{charged}}/dp_\perp d\eta)\) from UA1 \[32\]. One can use a single exponential together with a power-law tail in \( p_\perp \), or alternatively two exponentials, to achieve a fit of the output in PP to UA1 \( \sqrt{s}=200 \text{ GeV} \) data. A sampling function of the form

\[ f = p_\perp(a \exp(-p_\perp/w) + b/(1 + (r/\alpha)^\beta)) \]

(3)
gives a satisfactory fit to the PP data in the Monte-Carlo.
Additionally, since we constrain our comparisons to the production of neutral pions in Au+Au we also present, in Fig.(2) the PHENIX /citephenixpp midrapidity π0 yield for NN together with our representation of this spectrum. These NN generated p⊥ spectra, inserted into the code, were first applied to the meson p⊥ distribution in D+Au and now of course to Au+Au. No correction is made for possible energy loss in stage I, an assumption parallel to that made by the BRAHMS and all other RHIC experiments, in analysing p⊥ spectra and multiplicities irrespective of low or high values. However some explicit energy loss is present in the collisions of stage II, in the dynamics through energy conservation, but still employing the NN meson representation introduced above.

Since we impose energy-momentum conservation in each group, a high p⊥ particle having say, several GeV/c of transverse momentum, must be accompanied in the opposite transverse direction by one or several compensating mesons. Such high-p⊥ leading particles are not exactly jets, to the extent that they did not originate in our simulation from hard parton-parton collisions, but they yield much of the same observable experimental behaviour. It must be emphasized that the totality of p⊥ events is small, certainly for the NN collisions seen in Figs.(1,2)) and also as we will see for any AA events. In fact some 90% of all final given p⊥ yields occurs for p⊥ < 0.7. This implies that our treatment of such processes is indeed a perturbation, unlike to alter the overall dynamics.

E. Initial Conditions for II

The final operation in stage I is to set the initial conditions for the hadronic cascade in stage II. The energy-momentum taken from the initial baryons and shared among the produced prehadrons is established and an upper limit placed on the production multiplicity of prehadrons and normal hadrons. A final accounting of energy sharing is carried out through an overall 4-momentum conservation requirement. We emphasize that this is carried out separately within each group of interacting nucleons.

The spatial positioning of the particles at this time could be accomplished in a variety of ways. We have chosen to place the prehadrons in each group inside a cylinder, initially having the longitudinal size of the nucleus, for a A+B collision, and having the initial longitudinal size of the interaction region at, and then allowing the cylinder to evolve freely according to the longitudinal momentum distributions, for a fixed time τf, defined in the rest frame of each group. At the end of τf the multiplicity of the prehadrons is limited so that, if given normal hadronic sizes ∼ (4π/3)(0.7)3 fm³, they do not overlap within the cylinder. Such a limitation in density is consonant with the general notion that produced hadrons can only exist when separated from the interaction region in which they are generated.

Up to this point longitudinal boost invariance is completely preserved, since stage I is carried out using straight line paths. The technique of defining the evolution time in the group rest frame is essential to minimizing residual frame dependence which inevitably arises in any cascade, hadronic or partonic, when transverse momentum is considered due to the finite size of the colliding objects implied by their non-zero interaction cross-sections.

III. STAGE II: FINAL STATE CASCADE

Stage II is as stated a straightforward cascade in which the prehadronic resonances interact and decay as do any normal hadrons present or produced during this cascade. Appreciable energy having being finally transferred to the produced particles these ‘final state’ interactions occur at considerably lower energy than the initial nucleon-nucleon collisions of stage I. As pointed out, during stage II the interaction and decay of both prehadrons and hadrons is allowed. In the present case, for Au+Au, the effect of prehadron-prehadron interaction is truly appreciable.

We are then in a position to present results for Au+Au 200 GeV collisions. These appear in Figs(3–6) for various double differential tranverse momenta spectra or their derivative ratios. Most contain comparisons with PHENIX /citephenixpa π0 measurements. In future work we consider also charged data, but there proton spectra play an increasingly larger role.

The initial conditions created to start the final cascade could have perhaps been arrived at through more traditional, perhaps partonic, means. The second stage would then still proceed as it does here. We reiterate that our purpose has been to understand to what extent the results seen in Figures (1-6) are affected by stages I and II separately. i. e. do they arise from initial or from final state interactions.

IV. RESULTS: COMPARISON WITH DATA

Fig(3) contains the simulated π0 transverse momenta spectrum for Au+Au at η = 0 alongside the PHENIX data /citephenixpa. To a large extent the suppression observed experimentally is paralleled by the simulated calculations. The production time τp introduced above is given two values 2(2R_{Au}/Γ) and twice this value, indicating
the variation with this initial state time, a parameter in our modeling. The \( \Gamma \)'s are the longitudinal Lorentz factors defined above and introduced for each baryon group separately in its rest frame. For the symmetric Au+Au collision this distinction by group is only of small consequence.

What conclusions are to be drawn from these first results? Clearly one cannot ignore final state cascading. Moreover, for the assumptions we have made, the most crucial being the perhaps early commencement of such cascading, the suppression cannot be considered as necessarily a sign for production of a quark-gluon plasma: perhaps only a prehadron dominated medium after some initial delay. Since the PQCD approach is clearly more fundamental, provided a clear treatment of soft processes can be included, one cannot rule out its basis of interpretation. But surely it is interesting to pursue an alternative, albeit more phenomenological nuclear-system-oriented view. A view which simply suggests that more detailed and definite signs of QCD plasma must perhaps be sought.

It is instructive to deconstruct the elements of the simulation, i.e. to separate the spectrum at the conclusion of I from that resulting from both I+II. In Fig.(4) the \( \pi \) transverse momentum yield is shown for both these cases against the experimental data. It is immediately evident that the many virtual NN collisions in stage I produce a much elevated \( p_{\perp} \) output and that this is in turn reduced by more than an order of magnitude by collisions, with presumably other prehadrons, in II. Part of this effect is through inclusion in the dynamics of at least a kinematical treatment of energy loss. Thus above we referred to an initial hot gas cooled by expansion and final state interactions.

One might well turn this around and declare that the final state scattering of a given prehadron with comovers has cut down the Cronin effect, a reduction which suggests the applicability of the term ‘jet suppression’ by final state interactions. One notes parenthetically that particles lost at high \( p_{\perp} \) are compensated for by an increase at the lowest \( p_{\perp} \)'s.

A second and equally important criterion for the simulation is the maximum densities created as initial conditions for II. Fig(5) casts some light on this and on another issue, the actual transverse energy density attributed to the earliest stages of the collision. We have included in this figure the charged \( dN/dy \) spectra: (a) for the totality of “stable” mesons in I+II, (b) the same result for I alone when only decays of prehadrons are permitted, and finally (c) for the prehadrons in I only with no decays. It is evident that some 2/3 of the summed transverse energy \( E_{\perp} \) is generated in the second expanding phase II when the system is increasing both longitudinally and transversely. The initial \( E_{\perp} \) is then reduced commensurably, falls well below the Bjorken limit and is hence not all available for initial “plasma” generation. In present calculations at the initialisation of II, and keeping in mind the average masses assigned to prehadrons, 0.5 to 0.6 GeV, the ambient transverse energy densities are \( \leq 1.8 \text{ GeV/fm}^3 \) for the shortest initial time \( \tau_p \) chosen and correspondingly less for longer times.

It is also clear that the density of prehadrons, each of which in I as seen from Fig.(5) decays into some 2.5 stable hadrons. The rather lengthy formation time assigned, \( \tau_f \sim 1 \text{ fm/c} \), ensures that these stable particles enter only sparingly in the dynamics of II. Thus the bugbear of too much rescattering is reduced to manageable proportion.

V. CONCLUSIONS

It is hard to conclude definitively from what is presented here that the standard pQCD + some soft process treatment is not a more fundamental approach. But at question is just this coupling to soft processes, not unrelated to possible early appearance of an excitation spectrum of hadronic-like structures. The latter, if generated sufficiently early may alter the role of soft processes even on high \( p_{\perp} \) objects passing through a much more dense cloud of soft hadronic structures. Certainly there is still a silent elephant lurking in the dynamics, the observation of rather large elliptical flow in the meson spectrum \([41]\). These flow measurements are most easily achieved theoretically if hadronic cross-sections are present.

In the work on D+Au \([1]\) the use of such an excitation spectrum exposed most clearly the simple role of geometry in ratio of BRAHMS \( p_{\perp} \) spectra. For Au+Au its presence may muddy the waters, but surely more experimental exploration is required. Certainly the RHIC experiments are probing unusual nuclear matter, at high hadronic and energy density, and in exciting terms.

It would seem however that the direct attempt at a pQCD explanation of this behaviour must claim that, at the very least, all soft mesons are produced in essentially hard collisions. The presentation here provides an interesting case for relying on the geometry of soft, low \( p_{\perp} \) processes, essentially mirrored in hard processes, to produce the major features of the D+Au and Au+Au data. True enough, the high \( p_{\perp} \) tails in distributions are merely tacked on in our approach, but legitimately so by using the NN data as input to the nucleus-nucleus cascade. In any case one should again very much be cognizant of the small number of high \( p_{\perp} \) particles present in even central collisions. Some 5% of the integrated spectrum of mesons comes from \( p_{\perp} \geq 1 \text{ GeV} \).
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FIG. 1: PP Pseudorapidity spectra: Comparison of UA1 minimum bias 200 GeV NSD data /citeua1 with an appropriate LUCIFER simulation. The latter is properly a fit to the experiment and an input to the ensuing AA collisions; thus does not constitute a ‘set’ of free parameters.
FIG. 2: A similar transverse momentum $\pi^0$ spectrum from PHENIX PP vs simulation.
FIG. 3: Central PHENIX $\pi^0$ 200 GeV for Au+Au vs simulation for two choices of $\tau_p$, the prehadron production time. Centrality for PHENIX is here 0% – 10%, roughly impact parameter $b = 4.25$ fm. for the simulation.
FIG. 4: The $\pi^0$ transverse momenta yields for stage I, no final cascade, vs those for the full stage I+II calculation. Clearly there is considerable suppression in the final cascade. Recalling that the experimentalists quote a 'direct' suppression of $5 - 6$ for the ratio in Eqn.(1), there is at the end of I an enhancement $\sim 2.5 - 3$, i.e. a Cronin effect in this stage.
FIG. 5: Pseudorapidity and rapidity spectra for charged mesons and prehadrons at various stages of the collision. The gaussian fit to the charged pion rapidity distribution approximates preliminary BRAHMS results, at least in its FWHM.