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Ultrarelativistic Cascades and Strangeness Production

D. E. Kahana[a] and S. H. Kahana [b]

[a]Physics Department, State University of New York at Stony Brook,
Stony Brook, NY 11791, USA

[b]Physics Department, Brookhaven National Laboratory
Upton, NY 11973, USA

A two phase cascade, LUCIFER II [1], developed for the treatment of ultra high energy Ion-Ion collisions is applied to the production of strangeness at SPS energies $\sqrt{s} = 17-20$. This simulation is able to simultaneously describe both hard processes such as Drell-Yan and slower, soft processes such as the production of light mesons by separating the dynamics into two steps, a fast cascade involving only the nucleons in the original colliding relativistic ions followed, after an appropriate delay, by a normal multiscattering of the resulting excited baryons and mesons produced virtually in the first step. No energy loss can take place in the short time interval over which the first cascade takes place. The chief result is a reconciliation of the important Drell-Yan measurements with the apparent success of standard cascades to describe the nucleon stopping and meson production in heavy ion experiments at the CERN SPS.

1. INTRODUCTION

Many cascades [2–8] have been constructed to consider relativistic heavy ion collisions. As the eventual aim of experiments designed to study such collisions is the creation of a regime in which the quark-gluon structure of hadronic matter becomes evident, it is ultimately necessary to include the partonic degrees of freedom in such cascades. However, since at SPS and even at RHIC energies it is by no means clear that all initial or subsequent hadron-hadron collisions occur with sufficient transverse momentum to free all partons, at least a part of the eventual simulation must deal with collisions of both the initially present baryons (nucleons in fact) and in the end of all the produced hadrons (mesons) as well. In the course of laying out the algorithms for the hadronic sector of the cascade a very natural time-driven division between the hadronic and partonic sectors arises.

To begin with, however, we wish to discuss the global time scales which divide the cascade into what one could designate as 'hard", perturbative partonic or 'soft', non-perturbative or hadronic, processes. This separation has been often discussed in the literature [9–12], but for our purposes here a general outline will suffice. Experimental results [13] on both energy loss and forward pion production in high energy proton-nucleus scattering were the key motivation for this reasoning. Energy-loss and meson production at low transverse momentum p_t will in general represent 'slow' processes. To be contrasted are the 'fast' or hard processes of which Drell-Yan (DY) [14,15], which we will consider in

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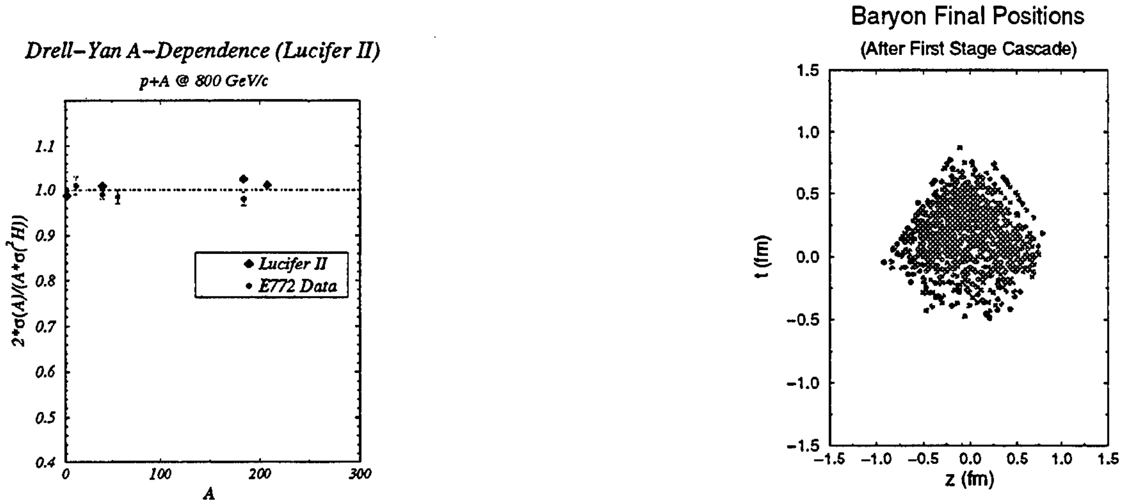


Figure 1. (a) The A-dependence of measured Drell-Yan from E772 (FNAL) vs a Lucifer II calculation, and (b) the nucleon-nucleon positions z vs t at the end of the first high energy cascade.

here, is a good example. The time scales for these processes can in the first approximation be inferred from the uncertainty principle. Small momentum transfer collisions take long times $\sim p_t^{-1}$, while production of lepton pairs with masses in excess of say 4 GeV take much less time, $\sim 4^{-1}$ GeV^{-1}. If one examines the Drell-Yan data [15], Figure 1, the apparent A-dependence of the DY cross-section ($\sigma \sim A$) in $p+A$ collisions, suggests that production takes place only at the highest energy. The incoming proton simply counts all the nucleons that it hits, and has an equal probability of producing a DY pair in every collision.

This stands in opposition to the expectation of a standard two body cascade, in which successive collisions take place at lower and lower energies, and which would predict that the cross-section rises more slowly than A. These results imply the incoming proton producing a DY pair, suffered no energy loss in its passage through the nucleus. Nevertheless, calculations with a purely hadronic cascade [8] very well describe the energy loss represented through the total pion spectrum seen in massive Pb+Pb collisions at SPS energies. It is as if, though the protons in their initial interactions inside a nucleus do not lose appreciable energy, they nevertheless remember full well what number and sort of collisions they have experienced. The question then is, can the initial energy retention but final eventual loss be described in a unified dynamic fashion.

These apparently contradictory features can be put together in a single particle or resonance-based multiscattering scheme, in a rather robust and modular fashion [1]. The method simply consists of running the cascade in two modes, a high energy fast-time stage in which the collisions histories are recorded and only fast processes allowed to engage. Using the entire space-time and energy-momentum history of this fast mode, a reinitialisation of the cascade is performed and a second normal hadronic cascading, at greatly reduced energy, carried out. Figure 1(b) shows the final positions of baryons in the first phase, and indicates the almost light-cone like paths for the particles engaging in this initial phase.

The intermediate reinitialisation, inserted between the fast and slow cascades, is most critical and is generated from the detailed particle collision and space-time history acquired during the initial high energy cascading. The energy loss from the expected inelastic nucleon-nucleon interactions for *any* nucleon can be computed, as well as the entire trajectory of each particle. The procedure followed then is to set up groups of nucleons, connected by similar local collision histories and then use these groups in a conserving fashion to construct the energy-momentum to appear in produced generic meson resonances. The latter will be the principal cascading objects in the second low-energy phase, along with of course the still present baryons from the first phase.

The model selected for describing elementary hadron-hadron collisions in the soft cascade incorporates generic mesons and baryons, which are the agents for rescattering. Indeed we might think of the generic mesons as consisting of an excited bag of a constituent $q\bar{q}$ pair and the generic baryons as similar objects constructed from three quarks. The known details of proton-proton collisions, from the initial energy down, provide information on the multiplicity distributions, production mechanisms and multiplicity-rapidity-energy loss correlations essential to the reconstruction of the final baryon four-momenta and hence of the energy and momentum to be deposited into mesons. The methodology followed is proceeds as closely as possible by reconstructing two-body scatterings experienced for each nucleon traced. Thus the fluctuations inherent in NN, in energy loss, multiplicity, character (flavour etc.) can be mirrored in the reinitialisation.

One might refer to this two stage cascade as a separation into short and long distance behaviour, a separation created by a factorisation of the time scales, or equivalently by the momentum transfer involved in each process. This feature has of course be much discussed in the literature [9–12]. This approach has a highly beneficial effect on what one might fear most in cascades, a possible strong frame dependence. Indeed, in preliminary calculations at RHIC energy, $\sqrt{(s)} = 200$, for a Au+Au b=0 collision, i. e. in our context a worst case scenario, one finds the global frame and the center of mass, very moderate at RHIC's high energies and virtually non-existent at the SPS. The reason is simple and generic. The first, high energy cascade, leads (Figure 1) to particles travelling uniquely on light cone paths. Any frame dependence then enters mainly through the second phase cascading, which involves greatly reduced energies.

The second phase involves generic resonances, both baryonic and mesonic, of delta and nucleon, ρ, π and K character, with masses between m_N and 1.6 GeV for baryons and 0.3 to 1.0 GeV for normal mesons, appropriately higher for strange mesons. That the non-strange generic meson resonance mass should be centered near $600 - 700$ MeV should be no surprise, and is in fact consistent with our simple picture for these objects, a constituent $q\bar{q}$ bound pair. The produced mesons are of course not allowed to interact until some formation time τ_f has passed, this is then one *real* parameter in the model, determinable perhaps from pA, or from light nucleus collisions (SS) [8]. Finally these resonances will decay into observable mesons, hyperons and nucleons. In this early work we limit ourselves to π's, and K's.

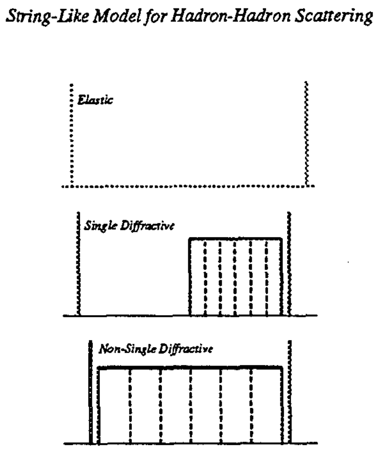
In the following sections we lay out a brief description of (1), the basic input to the cascading, i. e. the model for elementary two hadron interaction (2), the treatment of nucleus-nucleus collisions and finally (3), the results for production of both normal hadrons, protons and pions and strange particles (K's and Λ's) in massive ion-ion collisions at the SPS. For details of the cascade architecture we refer the reader to the previously cited work [1].

2. HADRON-HADRON INTERACTION MODEL

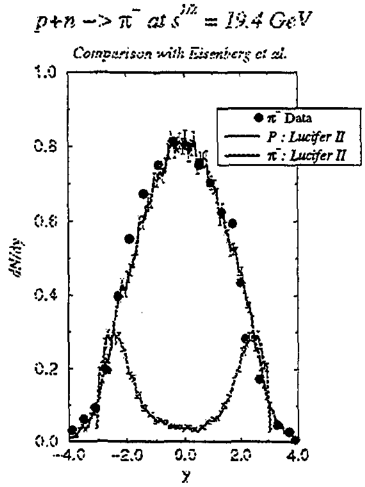
The objective of the cascade approach to nucleus-nucleus collision is to proceed from a knowledge of elementary hadron-hadron collision to a prediction of the far more complex many body event. This is, as will be clear, not completely possible in the environment of relativistic collisions. It is not possible to ignore the time structure of the elementary collisions nor the nature of the objects produced in the initial particle-particle collisions, and which then partake in ensuing collisions. At AGS momenta [7], $\sim 1.0 - 5GeV/c$, the introduction of the most evident, lowest lying resonances, the Δ, the N^* and the ρ, was often sufficient for a reasonably accurate picture of the dynamics. The essential time structure for a many body collision was then set by the resonance lifetimes, all ~ 1.5 fm/c. At the considerably higher SPS and RHIC energies the Lorentz contractions are much more severe and it is necessary to be guided by both experiment, in particular from pA and the lighter ion-ion case, and existing theoretical considerations on reinteraction of hadrons inside nuclei [9,10]. At these higher energies we must of course also allow for the possibility of partons being freed from hadrons in collisions of high enough transverse momentum. It is nevertheless interesting to restrict this first work, aside from Drell-Yan, to the collisions involving hadrons.

Many approaches have been put forward [5,6], some including strings [2,3], but we try to retain a particle nature for the cascade. The first element then is a model for the hadron-hadron system, beginning with nucleon-nucleon but easily extended to meson-nucleon and ultimately applied to any two body hadron-hadron collision. The basic processes are elastic scattering and inelastic production of mesons, the latter divided into the well known categories [16] diffractive scattering, referred to as single diffractive (SD), and non-single diffractive (NSD) [17], figuratively displayed in Figure 2(a). The SD process, leading to a rapidity gap between one of the leading hadrons and the produced mesons, is associated with a triple Pomeron coupling [19], while the NSD production is attributed to single (and double) Pomeron exchange and presumably results in the observed meson plateau. These diagrams then represent the basis for our development but must be supplemented by an intermediate picture which allows us to apply them, not only to hadron-hadron interactions in free space but also inside a nuclear environment. The generic mesons depicted in Figure 2(a) and the generic baryons, with rather light masses selected in the ranges suggested above, constitute the basic elements for rescattering in the second-phase cascade. We reemphasize the $q\bar{q}$ and qqq nature of the generic resonances, structures easily related to the constituent quark models frequently used for discussing soft QCD physics. Two examples of the fits to cross-sections we use are shown in Figure 3(a) and in Figure 3(b) for the total pp and inclusive Λ-K respectively.

The soft Pomeron-mediated interactions [19] involve small p_t, appreciable energy loss,



(a)



(b)

Figure 2. (a) Figurative representation of the elastic, single and non-single diffractive processes on which the elemntary hadron-hadron modelling is based. The generic mesons are contained kinematically within the vertical cross-hatched regions. Also(b) the fit obtained to known pn data near the SPS energies.

and hence are thought to proceed on a very slow time scale, ~ 1 fm/c in the rest frame of the relevant particles. To the generic mesons we also ascribe widths $\sim 125 MeV$ MeV. All of the results we obtain can in fact be well represented by using a single average mass for the generic mesons near 600 MeV. Strangeness bearing resonances, of course produced associatively, are defined with masses and widths not unlike those quoted above but appropriately higher. None of this two body information is afterwards, in nucleus-nucleus interaction, adjusted, at least not so as to destroy the fundamental connection with the two body measurements.

Care must be taken to describe the observed multiplicity distributions. We have chosen to impose KNO scaling [18] in our parametrisation of these distributions. The results obtained for the two hadron system are very similar to those in multiperipheral models [10,11,19].In Figure 2(b) we display the final fits to pn at the highest energies most relevant to this work [20], $\sqrt{(s)} \sim 20 GeV$. The total cross-section fit used was shown in Figure 2(a). The generic resonances decay into two or three 'stable' mesons, which include at the moment, π, ρ and K. There is of course a strong correlation between the number of generic resonances formed and their mass, the latter in turn determining the number of stable mesons produced by each generic meson.

The two most important features of the input hadron-hadron system for the ion-ion cascade are now set. These are (1) the energy loss and (2) the multiplicities, in soft processes. Also included of course are the necessary fluctuations in both these, from two body collisions and geometry, seen in measurement. In particular, the degree of energy

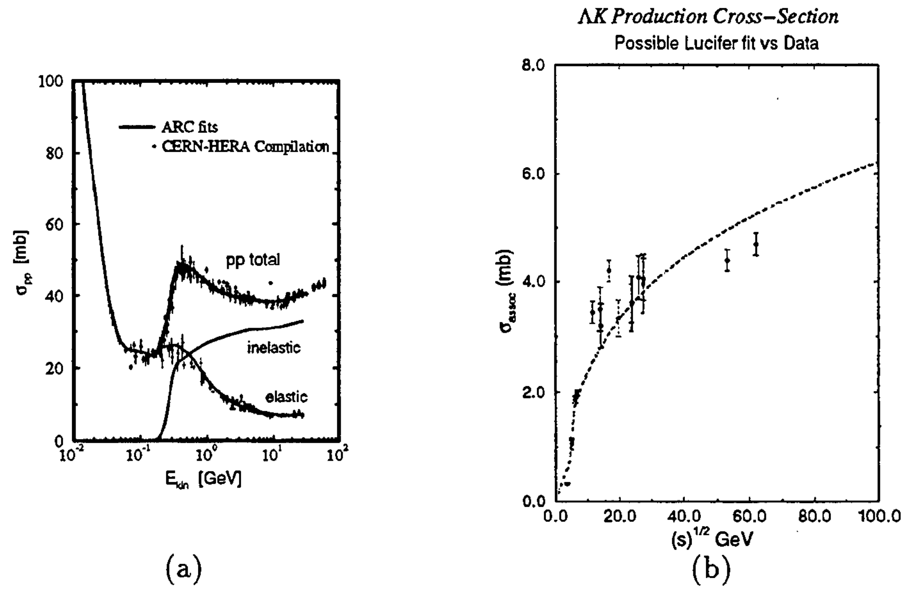


Figure 3. (a) The total proton-proton cross-section, and (b) the inclusive cross-section for associative $\Lambda + K$ production.

loss in SD and NSD, is highly influential in determining the width in rapidity of the final π^- distribution in this figure. This in turn plays a direct role in later allowing a sufficient and surprisingly high energy loss for protons in the rather light collision of SS depicted in Section IV. Many of the nucleons in a central collision end up with low rapidity in the center of mass [22,23], i.e. at mid rapidity.

3. NUCLEUS-NUCLEUS COLLISION SIMULATION

One of the evident puzzles we faced, and of course well known from examination of both Drell-Yan [14,15] and the nucleus-nucleus proton and meson data at the SPS [22–24], was the apparent contradiction between the production of the massive lepton pairs on nuclei and the energy loss [8] seen in nucleus-nucleus. The first of these latter processes is assumed hard and describable by perturbative QCD (PQCD), while the latter typified by the production of mesons is assuredly slow. We now try to exploit the differences in time scales, itself a function of collision energy, to create a global cascade incorporating both phenomena. To do this we separate the simulation into two phases, connected by an intermediate reinitialisation. The first cascade records the entire nucleon-nucleon history of the nucleus-nucleus collision. but permits energy loss only from sufficiently rapid processes.

The methodology used in the first phase is straightforward and indeed in outline closely resembles an eikonal or Glauber protocol while retaining the random, and therefore fluctuating, collision nature of a cascade. The correct cross-sections, at the incoming energy and employing Monte-Carlo, are used to trace out the collision history. This history is then used to fix the trajectory and final space-time positions of the nucleons. Importantly, the recorded history can also be used to *properly* reconstruct and evaluate the energy loss suffered by each nucleon. At the completion of this phase we have in hand the number of collisions suffered by each baryon.

In the reinitialisation one introduces collision-related groups. It is into these groups that the energy loss, history-determined particle by particle, is placed. The group structures are virtually dictated by consideration of pA where, in light of the relativistic γ's at the SPS and at RHIC, the incoming proton rapidly collides with a series of target nucleons in its path. The energy-momentum lost is transferred onto the generic mesons, whose multiplicity is also fixed by the collision record. One may note the resemblance to the wounded nucleon model [25]. Each incoming nucleon has essentially been marked with its multifaceted history. One might refer to this as a 'painted' or programmed nucleon model.

The group selection procedure in the initial step is mostly topological in nature. One first chooses the nucleon undergoing a maximum number of collisions and continues, in a first pass, by associating with it the nucleons with which it collided. Since we are considering only highest energy collisions, these colliders are all going (in an equal velocity frame) in a direction 'opposite' to the originally chosen particle. Clearly we have begun with particles near the colliding centers of the projectile and target. One more pass is made to augment and more importantly, kinematically to symmetrise the groups. The particles added in the first pass are again ordered by collision number, and the maximal collider in this ordering has its 'opposite' collidees included.

The energy-momentum loss for each nucleon is tied to its collision history, by reconstructing for each of its collisions, and with the use of the basic elementary NN model of Section II, the specific losses and multiplicities. This is done within the rest frame of the group, where also the transfer of this energy-momentum is deposited onto the appropriate number of generic mesons. The final distribution of these mesons in a group is mostly dictated by the constraints of the conservation laws. Particular problems of course occur at the edges of phase space in rare events.

Strangeness production, through associated $\Lambda - K$ or $K - \bar{K}$ choices, is also allowed and in fact important at the SPS. The baryon-baryon results are then boosted back to the group rest frame. Transverse momentum is added to the baryons as a random walk, according to collision number, with basic distributions taken from the two-body model.

The final step in the reinitialisation is to place the mesons and baryons in position and time, and to restart the cascade. The four-momenta, in the global frame, of all particles are known as are the final positions and times of the baryons. It was thought best to distribute the mesons in a group randomly along the space-time path followed by each baryon in the initial cascade (see Figure 1(b)).

4. LOW ENERGY CASCADE AND RESULTS

In this section we describe the last stage of the cascade in a mode, not unlike, but differing somewhat from the low energy cascade ARC [7]. Only major meson states and resonances likely to significantly effect the dynamics are included at this stage, i.e. the π, K and ρ. Almost without exception the ensuing collisions occur at relatively low center of mass energy, certainly less than $\sqrt{(s)} \sim 5-8$ GeV. The low energy cascadebegins only after the passage of a meson formation time, a parameter presumably somewhat tuneable about the standard value ~ 1 fm/c.

The results of the low energy cascade, for a range of CERN SPS energies, are displayed in Figures 4 and 5 for the SS and Pb+Pb systems. These represent the output both high and low energy stages. The calculated proton distributions for S+S in Figure 4(a) and Pb+Pb in Figure 4(b) exhibit the large, perhaps close to saturation energy loss [22,23], suggested by the experimentalists already for the light SS system. The corresponding pion spectra in SS and Pb+Pb are well reproduced, in both magnitude and shape, by the Lucifer II simulation. The average number of collisions in central S+S is near 3.5 and closer to 7.5 in Pb+Pb, with wide fluctuations about these averages seen for both nuclear systems. Despite this difference in average collision number one can begin to understand a saturation in stopping. At high energy considerable energy is lost, perhaps one-half, per elementary collision and little is left after a few collisions. However, the final soft cascading does rearrange and broaden the rapidity distributions, though not much is added to the production of any species.

Strangeness production is here confined to results for Pb+Pb collisions at 158 GeV/c per nucleon incoming laboratory momentum. Theoretical calculations for a transverse momentum Λ spectrum and a K rapidity spectrum are compared to measurements in Figure 5(a) and Figure 5(b). Elementary $K^+ + K^-$ is not so well known at the SPS energies $\sqrt{s} \sim 20$ GeV and provides a degree of uncertainty to the Pb+Pb prediction. One cannot ignore strangeness, sufficiently copious in the most massive ion collisions to srongly affect the number of non-strange mesons produced. That we are close to the measured rapidity densities for both K's π's and Λ's is a good sign. A more complete survey of strangeness producing collisions, both for pA and AB must still be done.

It has of course been the principal thrust of this work to create a unified dynamic approach, to ion-ion collisions at high energy, incorporating both the results of Drell-Yan and the slower processes. So far, this has been done allowing rescattering only via hadronic intermediate states. No partons have been explicitly included, except insofar as structure functions must be used for the calculation of Drell-Yan. This approach proves to be phenomenologically successful, leading to a reasonable description of a broad range of results obtained at the SPS. A secondary justification for following such a pure hadronic calculation is to investigate the conclusions of Kharzeev and Satz [26], namely that a purely hadronic explanation of the J/ψ suppression seen by NA50 is not possible. Certainly, the energy and number densities for both baryons and mesons achieved in the present simulations (LUCIFER II) are high enough $\sim 4-5$ GeV$/(fm)^3$ and last for sufficiently long times for Pb+Pb at 158 GeV/c, to perhaps expect unusual high density behaviour. The striking new results of NA50 [24] must then be taken very seriously.

5. ACKNOWLEDGEMENTS

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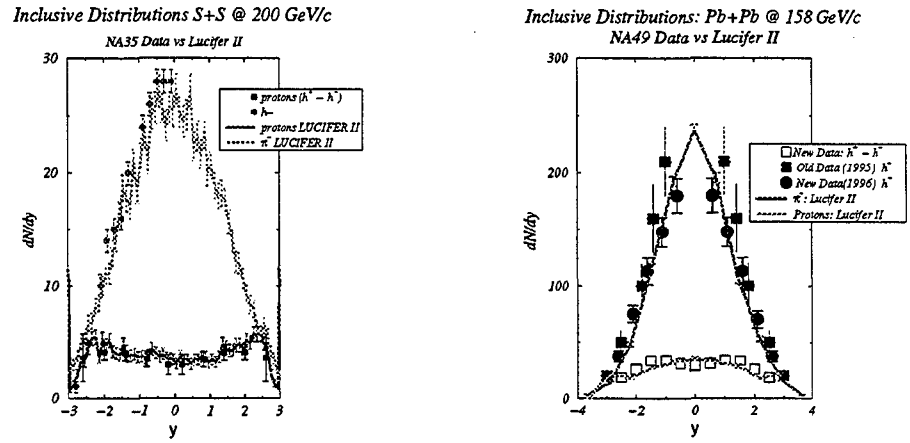
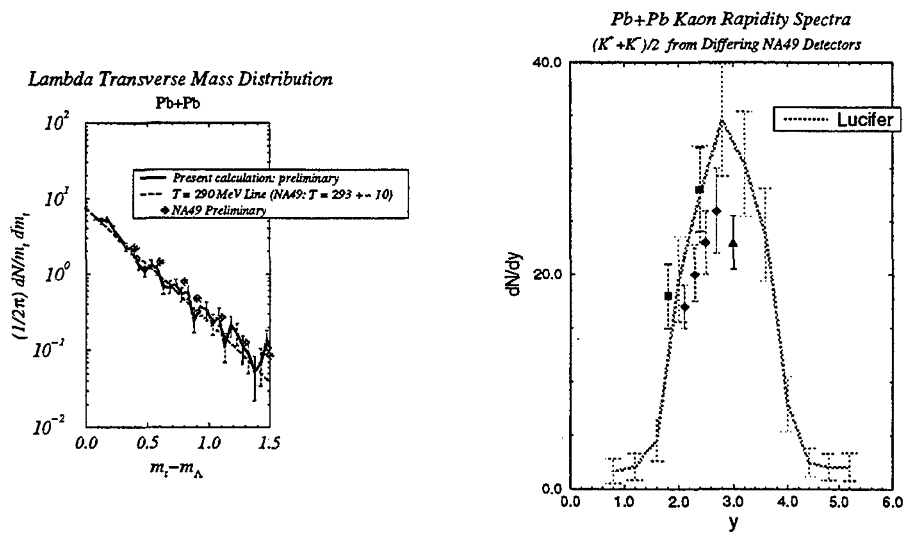


(a) (b)

Figure 4. Rapidity distributions for π^- and protons (a) compared to NA35 S+S data and (b) compared to preliminary NA49 Pb+Pb data. In both experiments the measurement of π^-'s is obtained from corrected h^- and for protons from h^+ - h^-.



(a) (b)

Figure 5. (a) Comparison of calculated transverse momentum distribution for Λ and also (b) of $K^+ + K^-$ production, to preliminary NA49 Pb+Pb data at SPS energies.

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