

SPECTRA OF PRODUCED PARTICLES
AT CERN SPS HEAVY-ION COLLISIONS
FROM A PARTON CASCADE MODEL

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Abstract

We evaluate the spectra of produced particles (pions, kaons, antiprotons) from partonic cascades which may develop in the wake of heavy-ion collisions at CERN SPS energies and which may hadronize by formation of clusters which decay into hadrons. Using the experimental data obtained by NA35 and NA44 collaborations for S+S and Pb+Pb collisions, we conclude that the Monte Carlo implementation of the recently developed parton-cascade/cluster-hadronization model provides a reasonable description of the distributions of the particles produced in such collisions. While the rapidity distribution of the mid-rapidity protons is described reasonably well, their transverse momentum distribution falls too rapidly compared to the experimental values, implying a significant effect of final state scattering among the produced hadrons neglected so far.

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With the advent of heavy-ion beams and experiments at the CERN SPS, it seems for the first time to be possible to create strongly interacting matter at such high density that a thermal state of colored partons, deconfined over a macroscopic volume, may be formed and live sufficiently long to leave traces on the hadronic final state. The presence of such an exotic high-density parton state, a quark-gluon-plasma (QGP), should be mirrored in characteristic features of particle production. Specifically, the changing characteristics of particle production in dense and hot matter should teach us about the partonic components in the system and the QCD dynamics being responsible for a QGP formation. The study of the evolution of particle production is therefore the prime tool to identify the observables which signal the presence of a QGP, since this ephemeral state of exotic matter is expected to lead to a copious production of secondaries including photons, dileptons, and heavy mesons, all of which may carry some information about the nature of the highly compressed QCD matter.

A large body of data has already accumulated about the spectra of particles produced in such collisions at SPS energies. It is well known that a large part of these spectra can be explained quite well using either *thermal models*, or *hydrodynamic models*, or one of the several models based on *string phenomenology*. What does the success of these models imply and what does it portend for the search of a QGP? What information can we reliably obtain about the early stages of the evolution from these studies?

Thermal models, in principle deal with the situation which prevails just before the particles freeze-out when they are assumed to be in thermal and some degree of chemical equilibrium. This along with a parametrized transverse velocity profile then provides the description of the particle spectra (see e.g., Ref. [1]). Note however that, a complete thermodynamic equilibrium will also mean a complete loss of memory of the initial state, which we have to infer by extrapolating the densities and temperatures backwards in time, familiar in cosmological studies. The inferences drawn will lose their meaning if a complete thermodynamic equilibrium is *not maintained* during the entire history of evolution. It is not quite clear that this assumption is strictly valid.

Hydrodynamic models start at the other end of the history of evolution. They start with the assumption of some initial density, temperature, pressure, and an equation of state and study the evolution of the system under the assumption of thermodynamic equilibrium, as well as, the applicability of hydrodynamics. At very high energies one may obtain [2] the initial conditions from, e.g, a self screened parton cascade model or the HIJING model. At SPS energies they are often obtained (see e.g., Ref.[3] and references therein) from Bjorken's estimate [4] which relates the final transverse energy (or particle multiplicity) of the system with the energy density at any time τ by assuming a boost-invariant hydrodynamic expansion. One necessarily has to make an assumption about the time beyond which the hydrodynamic description (and assumption of an isentropic evolution) gets valid. There is no strong reason to believe that the assumption of boost invariance is valid either (see e.g. Ref.[5, 6]).

The popular models using the *string-phenomenology* [7, 8, 9, 10] have had a considerable success in describing the main features of the data. This success has in fact been of a great help in designing experiments at SPS energies, through simulations. In the basic string picture a nucleus-nucleus collision is viewed as a superposition of independent nucleon-nucleon scatterings, involving a small rapidity loss (of the order of one unit), where the wounded nucleons draw

color flux tubes (strings) between each other, and these strings subsequently fragment by $q\bar{q}$ production within a typical proper time of $\simeq 1 fm$. The production of particles and transverse energy is thus associated with non-perturbative, phenomenological string dynamics. When the string density becomes large and the strings begin to overlap, they cannot be treated as individual entities that fragment independently, and thus additional concepts such as string fusion to ‘color ropes’ or ‘string droplets’ have been invented to accommodate high-density effects in heavy-ion collisions at CERN SPS energy and above. Yet, from the theoretical point of view, these purely phenomenological concepts are somewhat unsatisfactory, since they only serve to mimic the underlying QCD dynamics, rather than addressing the problem from the fundamental degrees of freedom, that is quarks and gluons.

Distinct from the above approaches is the *QCD parton cascade picture* [11] which is founded on the firmly established framework of field theory, perturbative QCD and the renormalization group. Here a nucleus-nucleus collision is visualized as the interpenetration of clouds of quasireal quarks and gluons bound inside the initial nuclei [12]. At CERN SPS energy and above, the materialization of these partons through multiple short-range scatterings between partons (minijet production) together with associated QCD radiation (gluon bremsstrahlung) can be very frequent, leading to multiple internetted parton cascades, and hence to a copious production of particles and transverse energy. The short-distance character of these partonic interactions implies that perturbative QCD with its fundamental quark and gluon degrees of freedom can and must be used, at least during the early and most dissipative stage of the first few fm , where a description in terms of long-distance excitations such as strings or hadronic resonances appears questionable.

In view of the above, we feel that a recent study [13] where a Monte Carlo implementation (VNI [14]) of the parton-cascade / cluster hadronization model [15, 16] was found to provide reasonably accurate description of Pb+Pb collisions at SPS energies is of considerable interest. The explicit space-time description of the motion of the individual partons helps us to describe the collision in its entirety and frees us from the shackles of the assumptions about the initial conditions or evolution of the system required in thermal and hydrodynamic models. This is also more appealing as the inputs to the model are experimentally determined structure functions and well established methods of perturbative QCD. The hadronization model [16] employed in the treatment has been successfully tested in e^+e^- , ep and pp ($p\bar{p}$) collisions. The crucial parameter in the model, the so-called p_0 , which marks the boundary between soft and hard physics- by treating scatterings with $p_T > p_0$ via perturbative QCD and those with $p_T < p_0$ in a phenomenological fashion ¹ is obtained by a fit to pp ($p\bar{p}$) collisions at $\sqrt{s} = 10 - 1800$ GeV, and is fixed once for all [15]. To be precise, p_0 is assumed to depend on the total collision energy \sqrt{s} as well as the mass of the nuclear collision system, and is parametrized [14] as $p_0(\sqrt{s}, A, B) = (a/4) \cdot (E_h/GeV)^b$, where $a = 2$ GeV, $b = 0.27$, and $E_h = 2\sqrt{s}/(A + B)$ with A (B) the mass number of beam (target) nucleus.

It is important to establish the power as well as the short-comings of this approach by testing it for a variety of systems, and particles. In the present work we apply the treatment to

¹We actually switch off the soft-scatterings, as we found them of little consequence for energy and momentum transfer or particle production.

representative data for S+S collisions obtained by NA35 experiment and also to recent data on Pb+Pb and S+S collisions published by the NA44 collaboration.

We find that the spectra of produced particles like pions, kaons, and antiprotons are very well described by our treatment. While the rapidity distribution of protons is reasonably described, the transverse momentum distribution of protons falls too rapidly as compared to the experimental results. This once again underlines the need for final state interaction among hadrons, neglected at the moment. We would like to add that for Pb+Pb collisions the final state interaction among hadrons produced from VNI was found to substantially alter (and improve) the spectra for protons [17].

As the model has been repeatedly discussed and very well documented [15, 14, 13] we proceed directly to the discussion of our results.

The rapidity distribution of the transverse energy deposited by the hadrons in central collision of sulfur nuclei at 200 GeV/ nucleon lab-momentum is shown in Fig. 1. Our results are in excellent agreement with the NA35 estimate (see Table 10 Ref. [18]) for this value. We also see that the hard component, which encompasses hadrons which have at least one parton which underwent a hard scattering accounts for more than half of the transverse energy at central rapidities, though it drops rapidly as we move away from the central region. There the beam remnants which are formed from partons which did not interact at all provide a major contribution.

The rapidity distribution of negative hadrons for central collisions is shown in Fig. 2. It is evident that the model provides a very good description to the NA35 data [19]. In all the calculations shown hereafter, we have chosen the impact parameter range to reflect the centrality of the collision measured by the percentage of the minimum bias cross-section covered in the experiment. The transverse momentum distribution of the negative hadrons for most central collisions are shown in Fig. 3 and they are also well described by the model. Note that the model reproduces the correct normalization of the data. The rapidity and momentum distribution of kaons obtained by NA35 [20] collaboration are shown in Figs. 4. The good description for these strange mesons obtained for S+S collision here along with those for Pb+Pb collisions in Ref. [13] offer a natural explanation for increased production of strangeness in such collisions through flavour creation and flavour excitation inherent in a parton cascade approach. Recalling that as yet we have not included final state interaction among hadrons, these results imply that most of the strangeness is already produced by the time the partons hadronize.

The NA44 collaboration has recently presented fresh data [21] on the momentum distribution of π^+ , K^+ , and protons near central rapidity for S+S collisions. Our calculations are seen to reproduce the spectra for π^+ and K^+ , however the predictions for protons are seen to fall too rapidly compared to the experimental data (Fig. 5). As the NA44 data lack absolute normalization, we have normalized our predictions at $M_{T-} \text{ mass} = 0.3 \text{ GeV}$.

The same trend for protons is seen from NA35 data (Fig. 6) where the rapidity distribution is found to be reasonable within the experimental errors whereas the transverse momentum distribution is seen to drop far too rapidly. We estimate that the slope of our prediction is lower by about 30% compared to the experimental data.

Applying our model to the recently published data of the NA44 collaboration for positive and

negative pions, kaons, and protons for Pb+Pb collision [21], we find overall reasonable agreement (Fig. 7) for all the momentum distributions except for the protons. (Note again that as these data lack absolute normalization, we have normalized our predictions at $M_T - \text{mass} = 0.3 \text{ GeV}$.) It is really interesting to note that the distribution for antiprotons which are produced in the collision are better described by the model.

The disagreement for the transverse momentum distribution for protons seen earlier for S+S collisions is further confirmed from a comparison with the mid-rapidity protons measured by NA44 group for Pb+Pb collisions at SPS energies [22]. We again see that (Fig. 8) whereas the rapidity distribution is in reasonable agreement with the experimental measurements, the transverse momentum distribution is seen (here multiplied by a factor of 5) to drop far too rapidly. We estimate that our slope for protons is too low by about 50%. The increasing discrepancy for the proton transverse momentum distribution as we go from S+S to Pb+Pb collisions reflects the increasing importance of final state interaction for bigger systems.

In summary, we have analyzed the hadronic spectra for S+S and Pb+Pb collisions at SPS energies, using the parton cascade model supplemented by a cluster hadronization scheme developed recently. The rapidity and transverse momentum distribution of pions, kaons and antiprotons are described fairly well by the model. Also the rapidity spectra of the mid-rapidity protons are described decently, however, the transverse momentum distribution obtained here is seen to fall too rapidly, compared to the experimental measurements. The inclusion of final state interaction among the produced hadrons, neglected so far in the model, is expected to remove the remaining discrepancy as well [17].

These results along with the findings reported earlier [13] strongly suggest that the initial stages in relativistic heavy ion collisions at SPS energies can indeed be described in terms of parton degrees of freedom with their interactions treated in terms of perturbative QCD.

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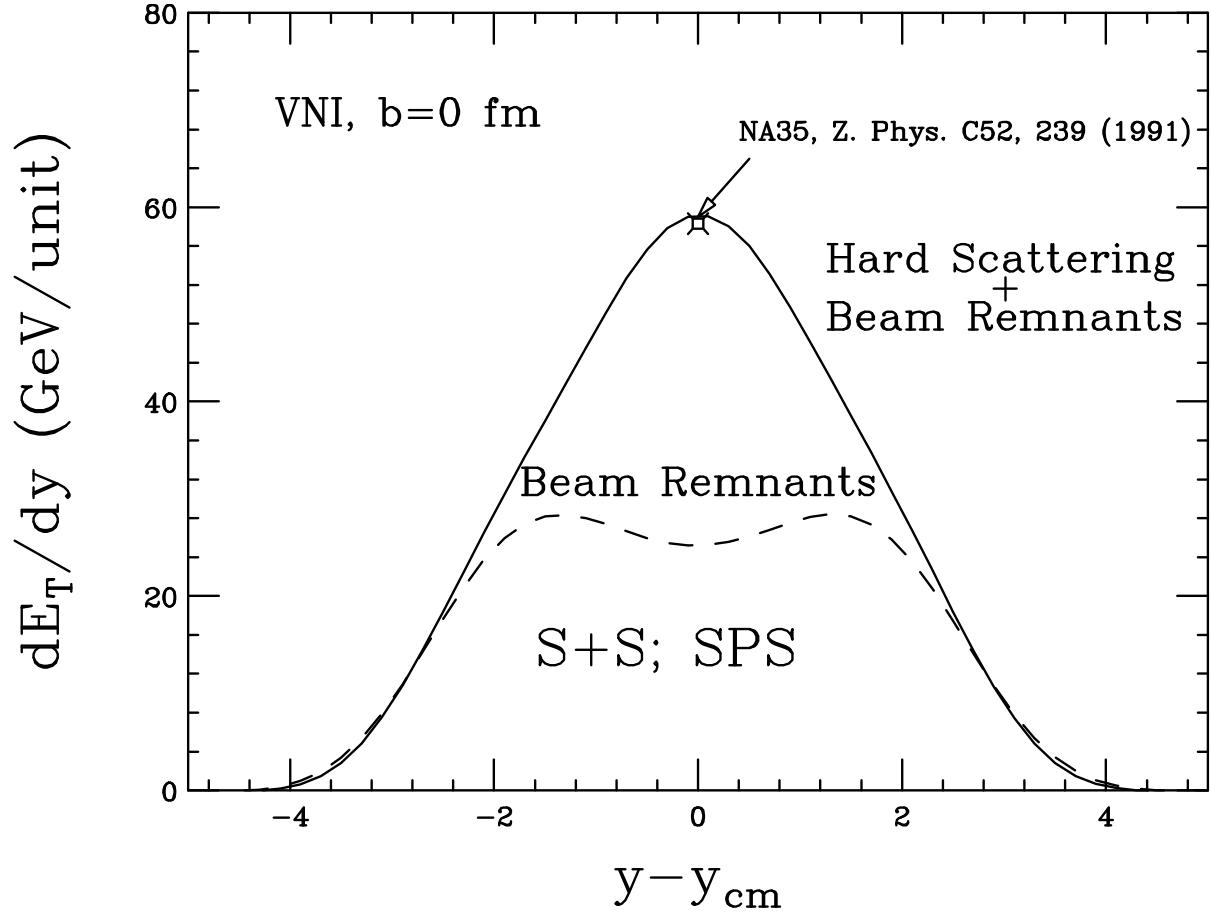


Figure 1: Transverse energy distribution in central collision of sulfur nuclei at CERN SPS. The dashed curve gives the contribution of only the remnant partons, which have not undergone scattering, while the solid curve shows the sum of contributions from parton cascade *and* the fragmentation of beam remnants.

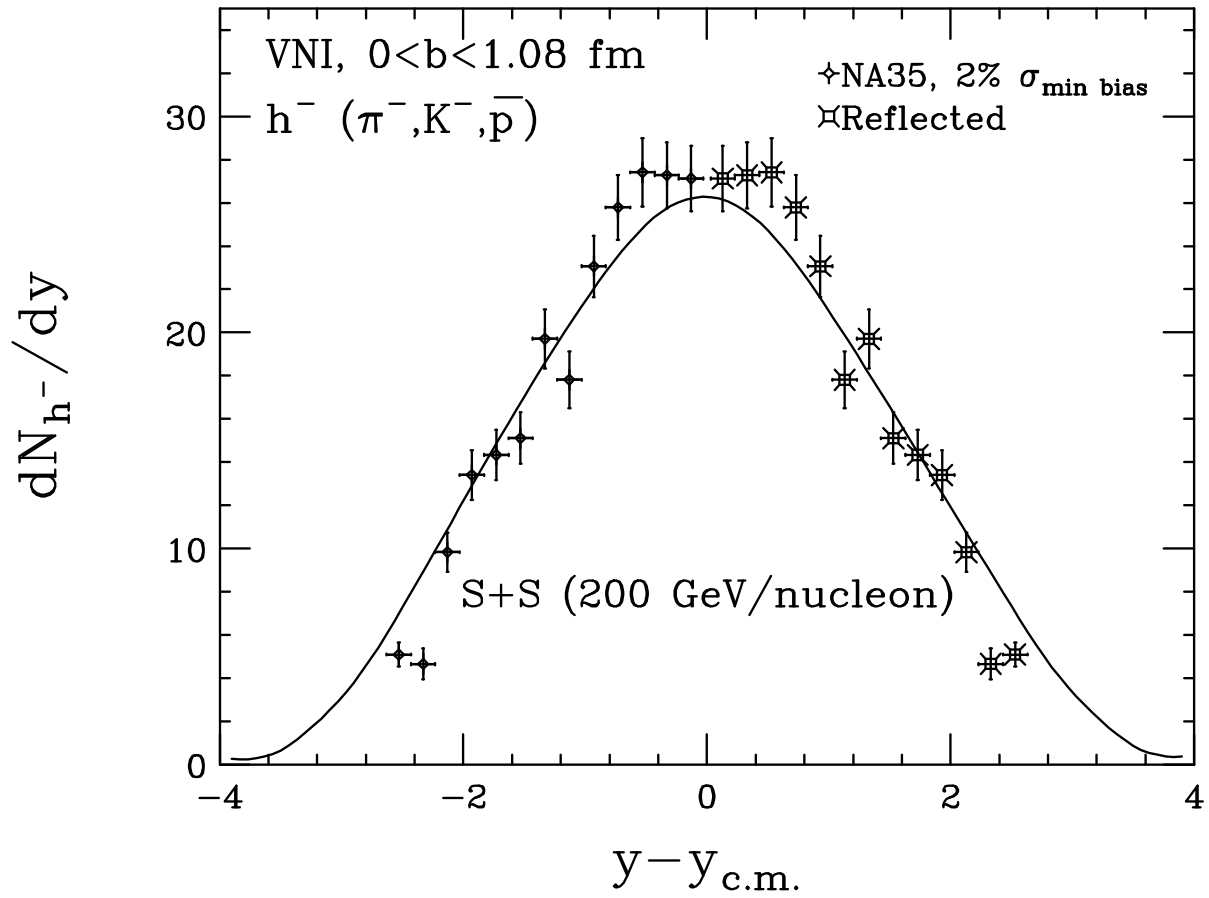


Figure 2: The rapidity distribution of negative hadrons for most central collisions of sulfur nuclei at CERN SPS.

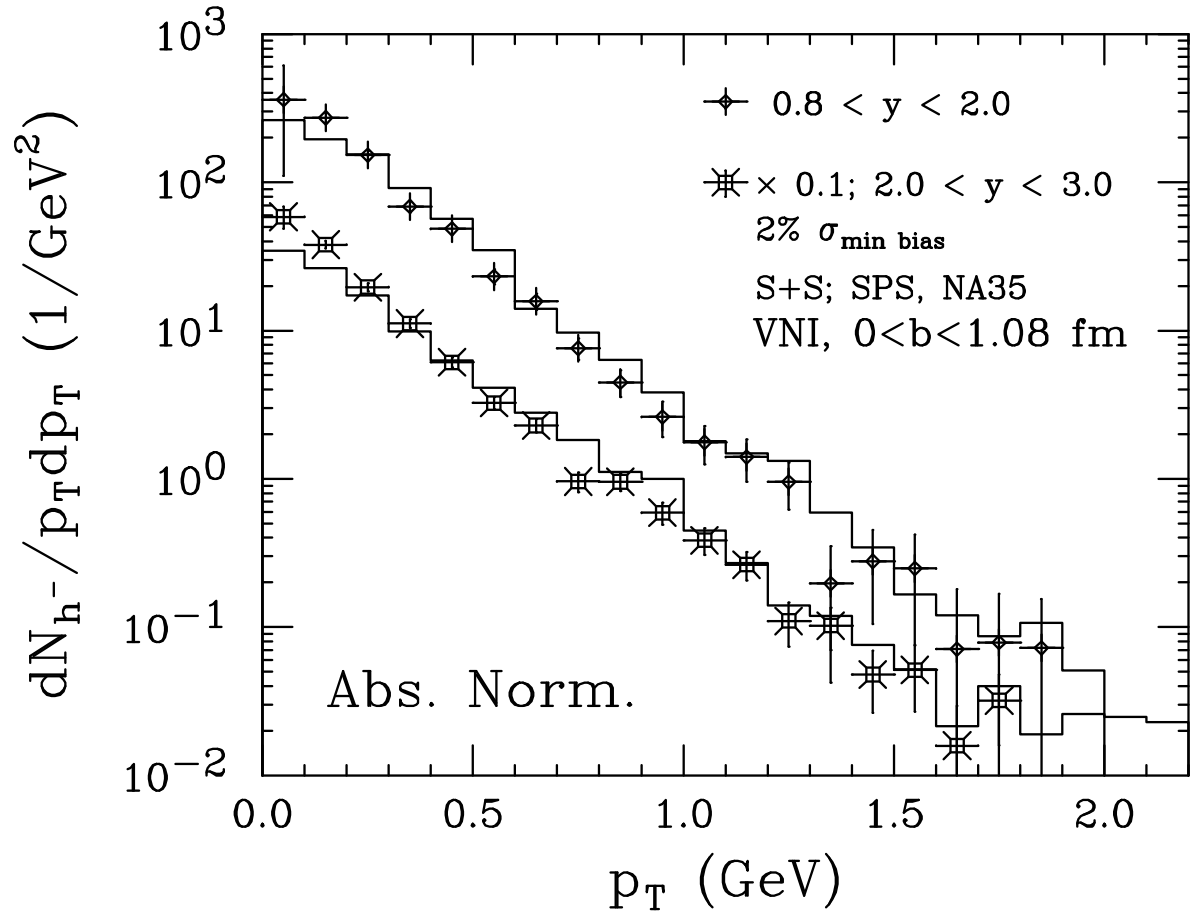


Figure 3: The transverse momentum distribution of negatively charged hadrons (π^- , K^- , and \bar{p}) in central collisions of sulfur nuclei at CERN SPS. No normalization factor has been used.

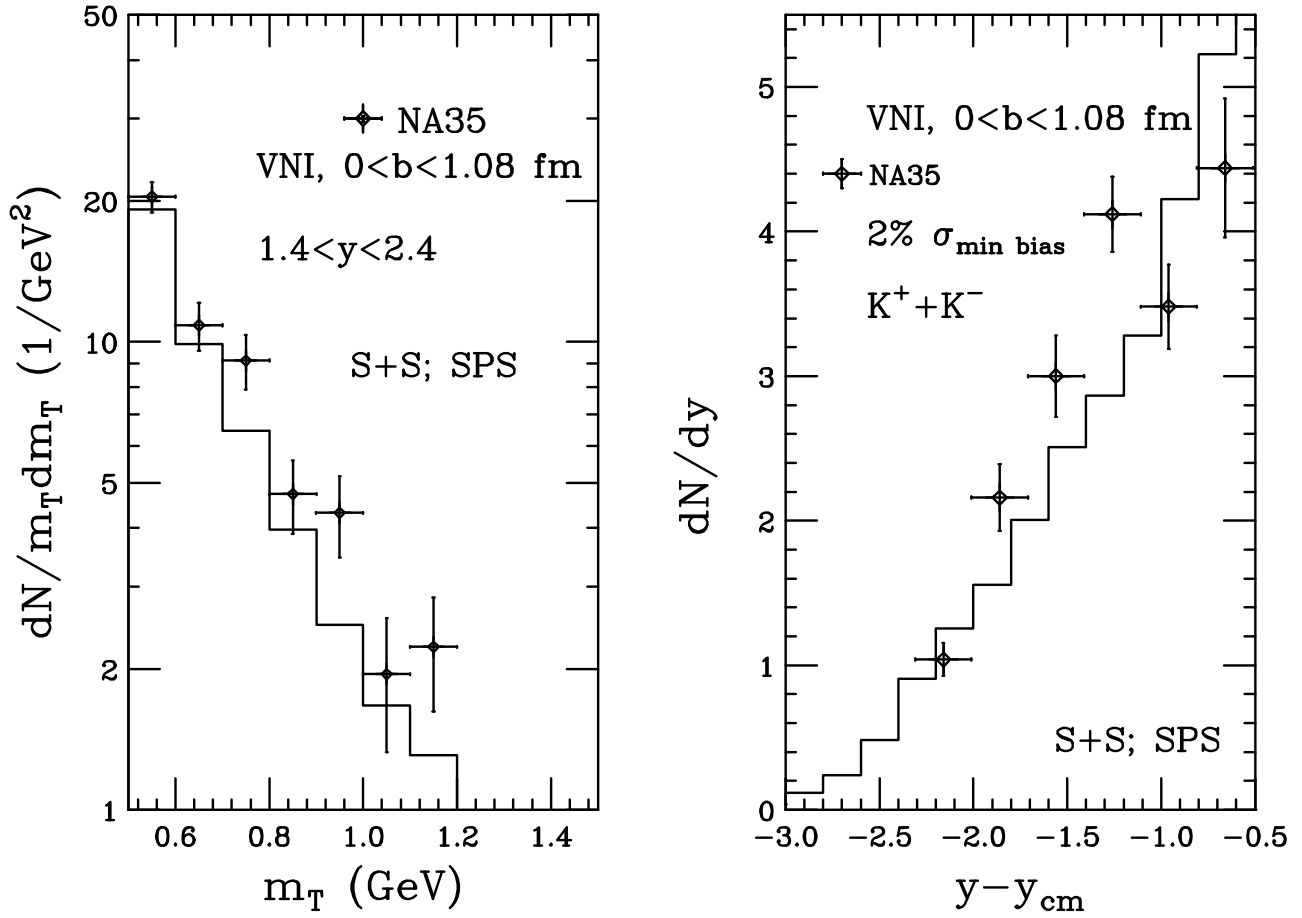


Figure 4: The transverse momentum and rapidity distribution of kaons from central collision of sulfur nuclei at CERN SPS. No normalization factor has been used.

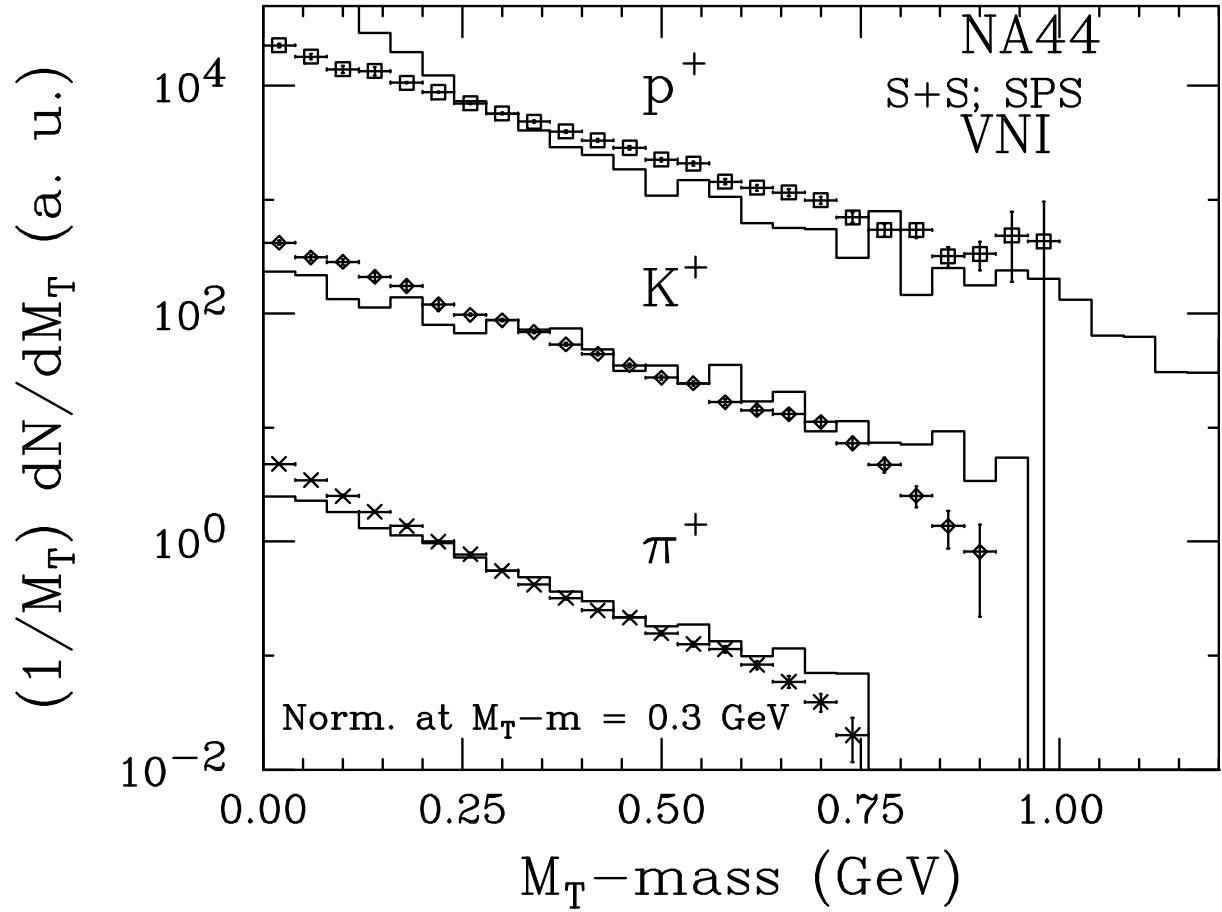


Figure 5: The transverse momentum distribution of positively charged hadrons (π^+ , K^+ , and p^+) from central collisions of sulfur nuclei at CERN SPS. As the data lack absolute normalization, the predictions have been normalized to the data at $M_T - \text{mass} = 0.3$ GeV. The data correspond to 10% most central collisions and thus we have chosen the impact parameter range as $0 < b < 2.4$ fm.

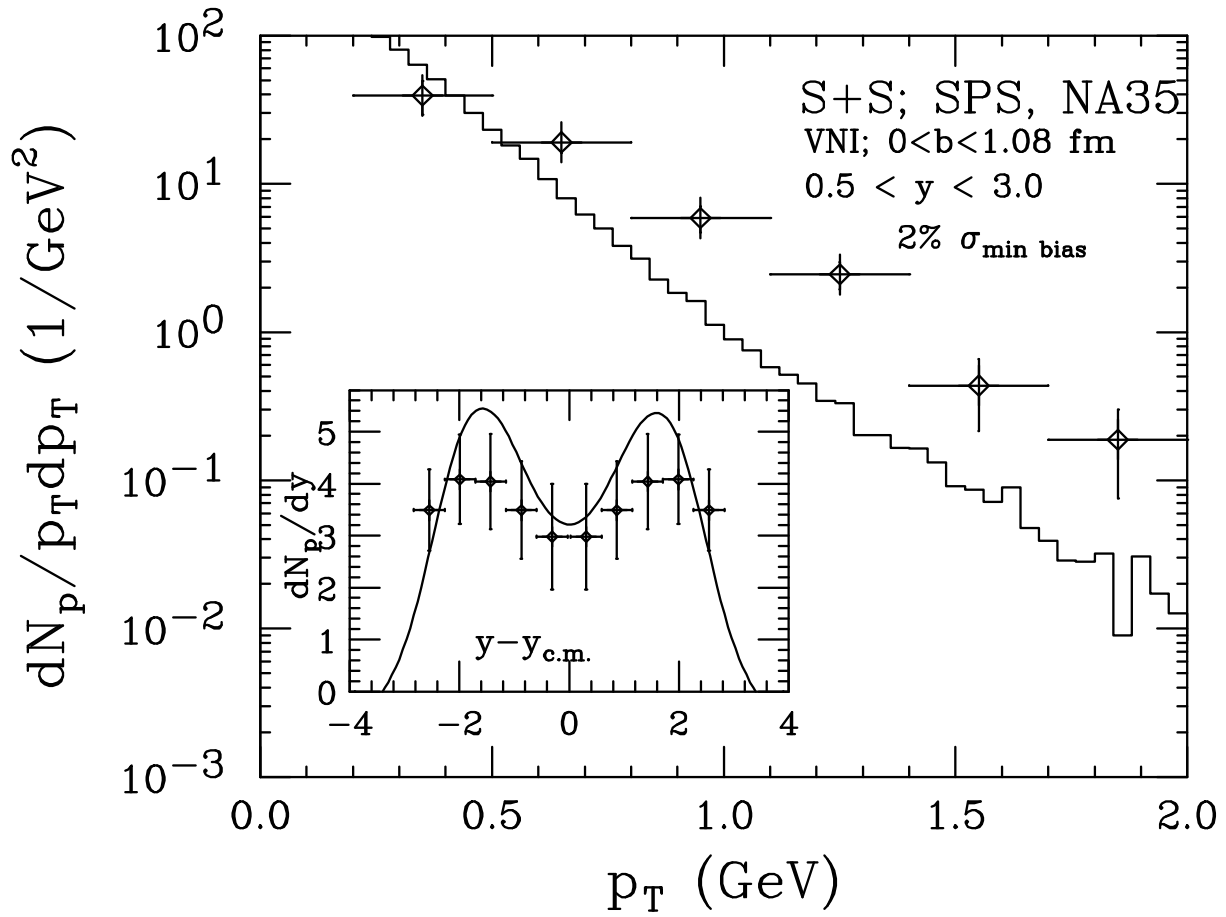


Figure 6: The rapidity and transverse momentum distribution of protons from central collision of sulfur nuclei at CERN SPS.

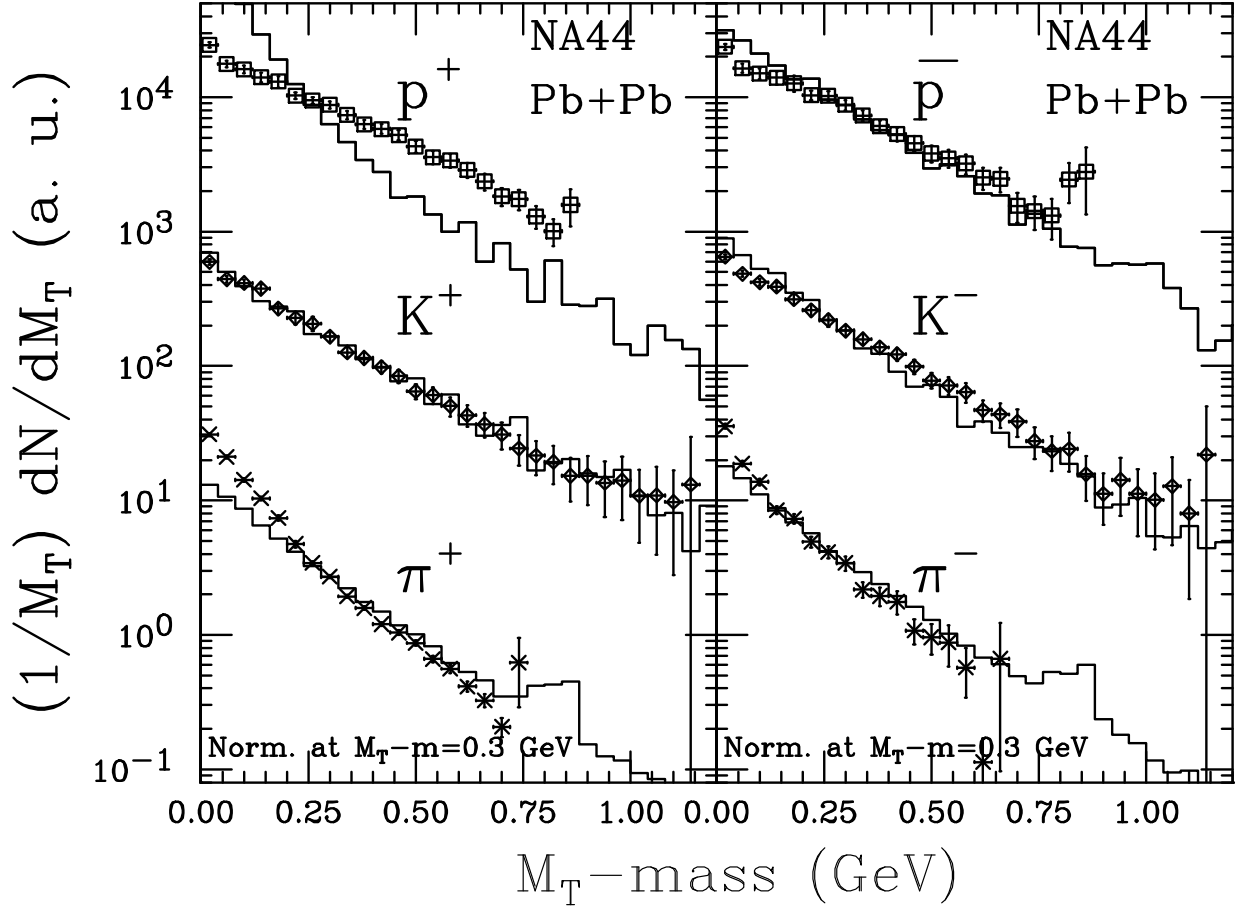


Figure 7: The transverse momentum distribution of positively and negatively charge hadrons, (π , K , and p) from central collisions of lead nuclei at CERN SPS. As the data lack absolute normalization, the predictions have been normalized to the data at $M_T - \text{mass} = 0.3$ GeV. The data correspond to 6.4% most central collisions and thus we have chosen impact parameter in the range $0 < b < 3.6$ fm.

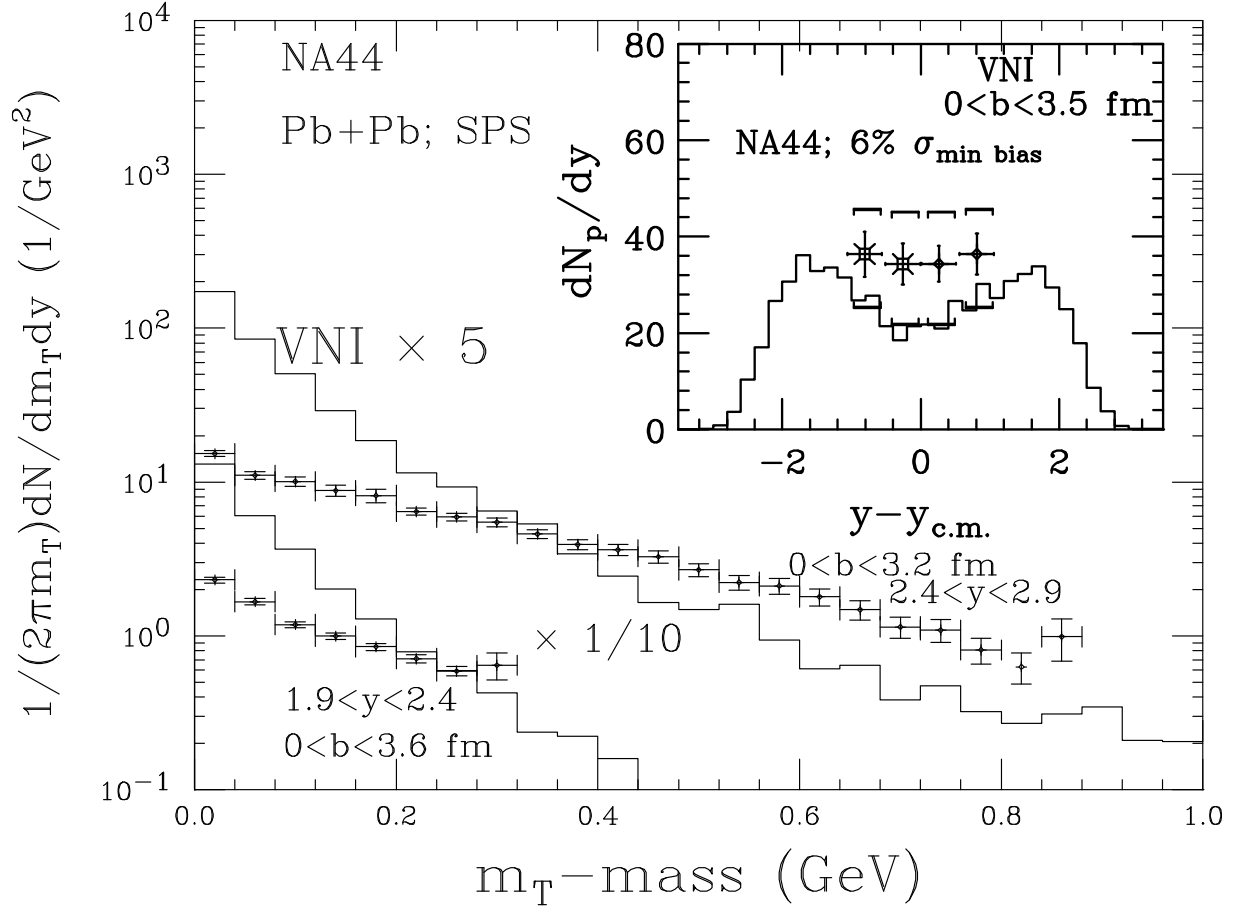


Figure 8: The rapidity and transverse momentum distribution of protons from central collision of lead nuclei at CERN SPS. The predictions for the transverse momentum distribution have been multiplied by a factor of 5 for a better presentation. The horizontal square brackets denote the systematic errors.