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Reexamining lepton pairs at ultrarelativistic energies

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We confirm the importance of standard medium effects (hadronic rescattering) in heavy-ion collisions by using a perturbative-QCD-motivated hadronic model to investigate the dilepton spectra from Pb+Au collisions at 158 GeV/nucleon. These same effects, namely, prompt $\pi\rho \rightarrow \pi e^+e^-$, have been studied in several CERN SPS systems [J. Murray, W. Bauer, and K. Haglin, Phys. Rev. C **57**, 882 (1998)]. The results presented here are consistent with previous studies stating that this type of rescattering effect explains a portion of the ''excess'' lepton pairs seen by the CERES experiment, but not the entire effect. [S0556-2813(99)00607-X]

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In future heavy-ion programs, considerable effort will be spent on gaining information about the space-time history of the collision. This information becomes increasingly important if a phase transition to quark-gluon degrees of freedom occurs during the reaction. In order to have an understanding of this transition, as well as being able to determine its existence, it is necessary to find signals that will remain intact during all stages of the collision. Although hadrons are abundant in the final state, they are only truly sensitive to the system dynamics after hadronization occurs. In addition, the resulting hadronic environment will participate in multiple interactions before reaching the detector. Therefore, reconstructing any information that hadrons might contain about the initial stages of the collision would be a daunting task.

This is the reason electromagnetic signals, such as dileptons and direct photons, have gained in popularity. These probes, due to a large mean free path in hadronic matter, appear in the detector after almost no interaction with the medium. This property makes electromagnetic signals ideal for studying the early stages of a heavy-ion collision where this type of phase transition might occur. This is why understanding these probes in current heavy-ion experiments is essential. In order to shed some light on the higher temperature and density experiments where ''new'' physics should occur, one must fully understand how electromagnetic signals behave in lower temperature and density systems.

With this in mind, we revisit dilepton data taken by the CERES Collaboration [1]. As in the S+Au lepton pair measurements, the invariant mass spectra of dileptons from a Pb projectile, with an energy of 158 GeV/nucleon, incident on a Au target reported an excess of dileptons over the Collaboration's ''cocktail'' predictions [1]. Since purely conventional explanations for the excess seem to be insufficient [2], the nature of the enhancement suggests several possibilities. Among the most prominent are studies into medium modifications resulting in a shifted ρ mass [3,4] and consequences arising from modifications in the $\pi^+\pi^- \rightarrow e^+e^-$ reaction [5,4]. The study in this paper will be restricted to a more conventional approach [6–8] using nonresonant scattering of pions and ρ's to partially explain the enhancement of electron-positron pairs.

To describe the initial stages of an ultrarelativistic heavy-ion collision, it is necessary to use parton degrees of freedom. Consequently, there are efforts underway to construct so-called parton cascades [9,10]. These models are based on perturbative QCD (pQCD) and are therefore attractive candidates for a spacetime transport theory in this energy regime. However, we have shown that there are severe problems with causality violations [11] and with the time ordering of soft-gluon emission [12].

Therefore, under these circumstances, a much simpler approach might provide more reliable results: geometrical folding of the results of event generators for the elementary processes. This prescription is followed, for example, in HIJING [13]. The simulation used in this study is similar to HIJING. It employs pQCD and parton distribution functions to characterize the individual nucleon-nucleon collisions and uses Glauber-type geometry [14] to determine the scaling. The kinematics of the nucleon-nucleon collisions are handled by PYTHIA and JETSET [15], high energy event generators using pQCD matrix elements as well as the Lund fragmentation scheme. We refer the reader to our previous work for a more detailed description of the model [8].

Dileptons from pseudoscalars (π^0, η, η') and vectors (ω, ρ^0, ϕ) produced in the primary scattering phase are not enough to account for the hadron-induced data measured by the CERES Collaboration. Therefore, in addition to this type of lepton pairs, our model also incorporates secondary scattering of hadronic resonances. All pions and ρ's formed during the primary collisions of nucleons will have a chance to scatter amongst themselves before decaying. The reactions we consider are of two types, one which produces a resonance that decays to dileptons and the other which goes to dileptons directly.

Of the first type, $\pi^+\pi^- \rightarrow \rho^0 \rightarrow e^+e^-$ and $\pi^0\rho^\pm \rightarrow a_1^\pm \rightarrow \pi^\pm e^+e^-$ have been included. Of the second type, $\pi^0\rho^\pm$

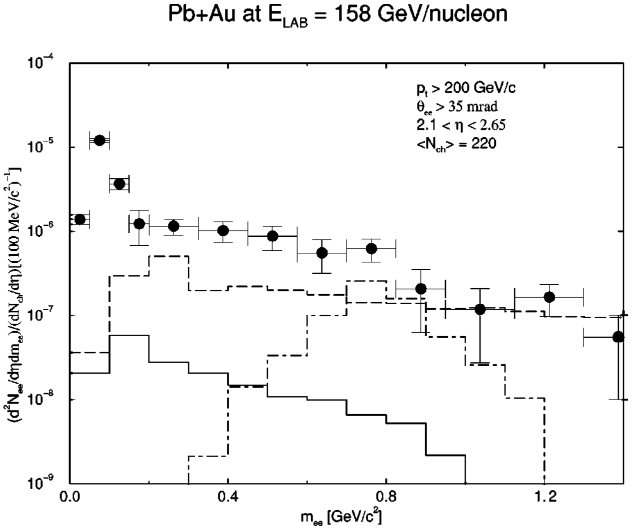

FIG. 1. Dilepton invariant mass contributions from each secondary scattering process considered: $\pi\pi \to e^+e^-$ (dot-dashed line), $\pi\rho \to a_1 \to \pi e + e^-$ (solid line), and $\pi\rho \to \pi e^+e-$ (dashed line) as compared with CERES data for Pb+Au collisions.

$\to \pi^{\pm}e^+e^-$ has been included and the other isospin channels ($\pi^{\pm}\rho^0 \to \pi^{\pm}e^+e^-, \pi^{\mp}\rho^{\pm} \to \pi^0e^+e^-$) are assumed to be of the same magnitude. To accomplish these types of scattering, pions and ρ's must of course appear in the final state of the model described in the previous section. As the default, JETSET automatically decays all hadronic resonances, but it also contains provisions to prohibit them. We thus allow pions and ρ's to scatter when conditions are favorable. Technically, the steps involved in secondary scattering are similar to those for primary (nucleon-nucleon) scattering.

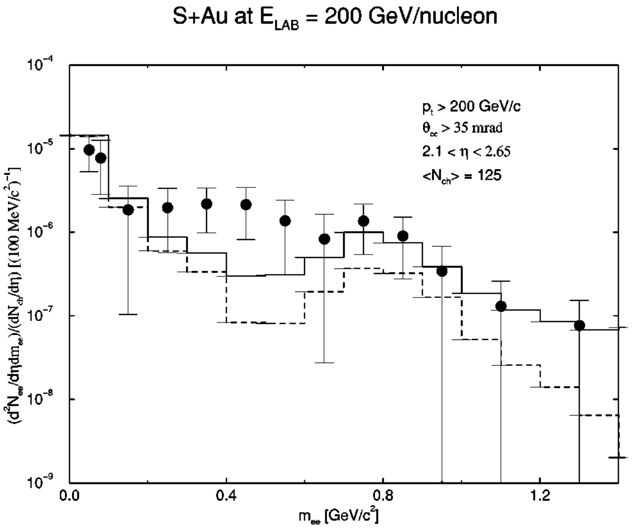

FIG. 2. Total dilepton invariant mass distributions: primary meson decays alone (dashed line) and primary meson decays with secondary scattering (solid line) as compared with CERES data for S+Au collisions.

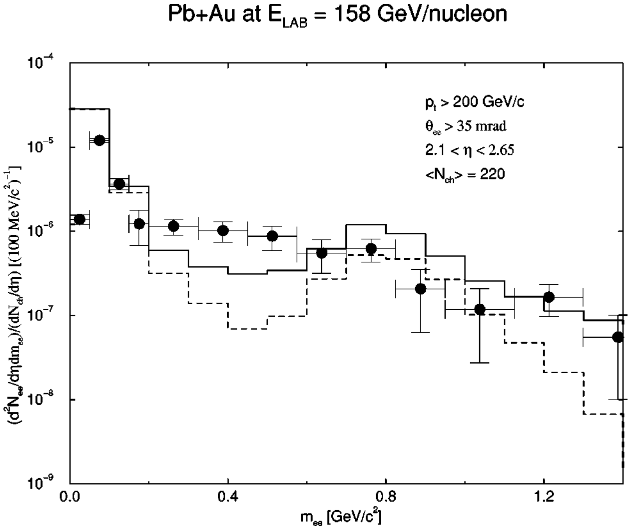

FIG. 3. Total dilepton invariant mass distributions: primary meson decays alone (dashed line) and primary meson decays with secondary scattering (solid line) as compared with CERES data for Pb+Au collisions.

Since the S+Au dilepton study was published [8], several additions have been made to the simulation. Previously, the only pions and ρ's that were allowed to secondary scatter came from the string fragmentation stage of the simulation. Pions and ρ's resulting from a hadronic decay chain were prevented from rescattering. These particles are now allowed to scatter and contribute to the dilepton spectra. Since our calculation includes dileptons from $\pi^+\pi^-$ resonant production as well as $\pi\rho$ scattering, adjustments should be made to compensate for possible double counting. Charged pions that annihilate to form a lepton pair cannot also scatter with a neutral ρ to form a lepton pair and a pion. This effect has been accounted for in our results. It should be noted that any effects arising from the lifetime of pions and ρ's have not been accounted for, as it is possible for the pions and ρ's to decay inside the reaction zone before having a chance to interact. In the final addition made to our simulation, we allow the original projectile nucleons that did not participate in the primary scattering stage to scatter with pions in the secondary (intermediate) stage. These unscattered projectile nucleons could contribute significantly to the overall multiplicity, provided that they exist in sufficient numbers. Based on the largest region of excess in the lepton pair spectra, we focused on the production of the η meson by this mechanism. This type of rescattering is handled entirely by PYTHIA.

The total dilepton yield from our model is the sum of lepton pairs from primary plus secondary scattering. The invariant mass distributions of the dileptons from all contributions will be discussed in the last section.

A reasonable candidate for a successful model description of ultrarelativistic heavy-ion collisions must at minimum be able to reproduce the rapidity distributions and transverse spectra of pions produced in the collisions. We have performed these tests with our model and compared the results to available experimental data at CERN [8]. We will not repeat this analysis here, but only state the results: the total number of produced pions is reproduced to better than a factor of 2; the shape of the rapidity distribution shows the correct degree of stopping; the slope of the transverse momenta is reproduced. It should be noted that our model was also tested against the proton-induced interactions ($p+\mathrm{Be}$ and $p+\mathrm{Au}$) at CERN [8]. In both cases, our simulation reproduced the lepton pair data by only considering the primary decays of pseudoscalar and vector mesons. It is also reassuring that the dilepton spectra from these decays in our model were consistent with the cocktail predictions made by the CERES Collaboration for all systems: $p+\mathrm{Be}$, $p+\mathrm{Au}$, S+Au, and Pb+Au.

The contributions from the individual channels described in the previous section are shown in Ref. [8] for the S+Au data and in Fig. 1 for the Pb+Au data. In both cases, the $\pi\rho$ direct channel contributes the most significantly to the overall spectra. With the inclusion of all secondary scattering channels, the invariant mass distributions of dileptons are shown in Fig. 2 for S+Au and Fig. 3 for Pb+Au. Both systems have a marked increase in lepton-pair production between an invariant mass of 200 and 500 MeV as well as a noticeable increase in the higher mass region when compared with the spectra without secondary scattering included. The bulk of the increase is attributed to nonresonant $\pi\ \rho$ scattering, not pseudoscalar and vector meson production by secondary scattering of projectile nucleons with pions. The latter effect is minimal, as on average only about 20 (5) projectile nucleons rescatter with pions in the Pb- (S-) induced collisions. The proton-induced reactions do not show any significant increase in dilepton production with secondary scattering included. It is not surprising that secondary scattering becomes important in the nucleus-nucleus systems, as a denser nuclear medium is created during these collisions as compared to the proton-induced collisions.

When comparing the differences between our calculations and the experimental results for the S+Au dilepton spectrum to those found in Pb+Au, one finds that our calculations are much closer to experiment for the heavier projectile. During the next CERN run, CERES should be able to conclusively determine whether or not conventional explanations are also insufficient for describing the Pb data. In any event, conventional methods, such as the rescattering studied in this paper, cannot currently account for the entire excess of electron-positron pairs found in either the S+Au or Pb+Au systems. Despite this fact, the estimates made in these studies indicate that a true understanding of the dilepton mass spectra at CERN SPS should include the rescattering effects investigated here.

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