Direct Photons and Hard Scattering at the SPS

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A significant direct photon signal, compared to statistical and systematical errors, is seen at $p_T > 1.5$ GeV/c in central ^{208}Pb+^{208}Pb collisions at 158 A GeV. The results constitute the first observation of direct photons in ultrarelativistic heavy-ion collisions. The observed excess exceeds expectations based on pA measurements at similar $\sqrt{s}$ and pQCD predictions. The result indicates modification of the parton distributions, as may result from rescattering of the partons (k_T broadening) and will be significant for diagnosis of quark gluon plasma formation. The centrality dependence of the transverse mass distribution of neutral pions demonstrates a nuclear enhancement due to rescattering (Cronin effect). However, the enhancement is weaker than expected for the most central collisions.

The observation of a new phase of strongly interacting matter, the quark gluon plasma (QGP), is one of the most important goals of current nuclear physics research. Photons (both real and virtual) were one of the earliest proposed signatures for QGP formation [1,2]. Real photons are dominantly produced by scatterings of charged particles during the collision. Once produced, they interact with the surrounding matter only electromagnetically resulting in a long mean free path. They are therefore likely to escape from the system directly after production without further interaction, unlike hadrons. Thus, photons carry information on their emitting sources from throughout the entire collision history, including the initial hot and dense phase.

Following early estimates of photon emission rates [3–6], Kapusta et al. [7] made detailed comparisons of the emissivity of the QGP and a hadron gas as two contrasting scenarios. It was demonstrated that the thermal emission rates of a hadron gas and a QGP were very similar and dependent essentially only on the temperature T. This led the authors to conclude that direct photons are a good thermometer for strongly interacting matter, but would not in themselves allow to distinguish between the two scenarios.

Recently, it was shown by Aurenche et al. [8] that photon production rates in the QGP when calculated up to two loop diagrams, are considerably greater than the earlier lowest order estimates (although these calculations are still under investigation - see the contribution of Aurenche in these proceedings). A new higher order process of $q\overline{q}$ annihilation with rescattering was found to dominate the photon emission rate from quark matter at high photon energies. Following this result, Srivastava [9] has reinvestigated the predicted photon production in heavy-ion collisions and shown that at sufficiently high initial temperatures the photon yield from quark matter may significantly exceed the contribution from the hadronic matter to provide a direct probe of the quark matter phase.

A large number of measurements of prompt photon production at high transverse momentum ($p_T > 3\,\mathrm{GeV/c}$) exist for proton-proton, proton-antiproton, and proton-nucleus collisions (see e.g. [10]). To a great extent, especially at higher $\sqrt{s}$, these data can be successfully described by perturbative QCD calculations and provide an important foundation from which to study photon production in nucleus-nucleus collisions. First attempts to observe direct photon production in ultrarelativistic heavy-ion collisions with oxygen and sulphur beams found no significant excess [11–14]. The WA80 collaboration [14] provided the most interesting result with a p_T dependent upper limit on the direct photon production in S+Au collisions at $200A$GeV. This result was subsequently used by several authors to rule out a simple version of the hadron gas scenario [15–18] and has been interpreted to set an upper limit on the initial temperature of $T_i = 250\,\mathrm{MeV}$ [19].

The first observation of direct photon production in ultrarelativistic heavy-ion collisions was recently reported [20]. The results are from the CERN experiment WA98 which consists of large acceptance photon and hadron spectrometers. In addition, several other large acceptance devices allow to measure various global variables on an event-by-event basis for event characterization. Photons are measured with the WA98 lead-glass photon detector, LEDA, which consisted of 10,080 individual modules with photomultiplier readout. The detector was located at a distance of 21.5 m from the target and covered the pseudorapidity interval $2.35 < \eta < 2.95$ ($y_{cm} = 2.9$). The particle identification was supplemented by a charged particle veto detector in front of LEDA.

The extraction of direct photons in the high multiplicity environment of heavy-ion collisions must be performed on a statistical basis by comparison of the measured inclusive photon spectra to the background expected from hadronic decays. Individual photons cannot be tagged as isolated direct photons in these reactions due to the high multiplicities. To obtain the direct photon spectrum the following steps are performed (for a detailed description of the detectors and the analysis procedure see [21]): First, the raw photon spectra are accumulated after application of the photon identification criteria (such as transverse shower size) to the showers observed in the LEDA. The raw photon spectra are then corrected for contamination by charged and neutral hadrons, for conversions, for the identification efficiency, and acceptance. The efficiency includes all effects of the detector response such as distortions by shower overlap, dead and bad modules, and energy resolution. Neutral pions are reconstructed via their $\gamma\gamma$ decay branch. Invariant mass spectra are accumulated for all photon pairs for each pair p_T bin. The photon-pair combinatorial background is estimated by event-mixing and then subtracted from the real-pair spectra. The yield in the π^0 mass peak is extracted to obtain the raw neutral pion p_T spectra. These are then corrected for conversions, for the π^0 identification efficiency, and for geometrical acceptance. In addition, η mesons are extracted in a limited transverse momentum range with an analogous procedure.

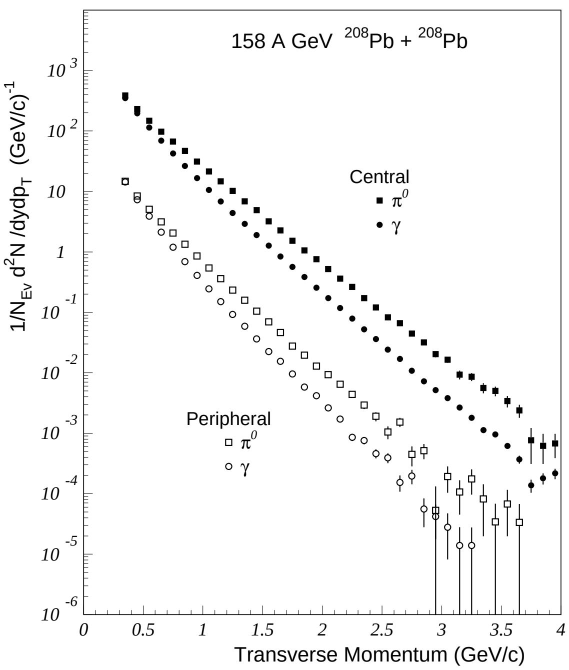

FIG. 1. The inclusive photon (circles) and π^0 (squares) transverse momentum distributions for peripheral (open points) and central (solid points) 158 A GeV ^{208}Pb+^{208}Pb collisions. The data have been corrected for efficiency and acceptance. Only statistical errors are shown.

The final measured inclusive photon spectra are then compared to the calculated background photon spectra to check for a possible photon excess beyond that from long-lived radiative decays. The background calculation is based on the measured π^0 spectra and the measured η/π^0-ratio. The spectral shapes of other hadrons having radiative decays are calculated assuming m_T-scaling [22] with yields relative to π^0's taken from the literature. It should be noted that the measured contribution (from π^0 and η) amounts to $\approx 97\%$ of the total photon background.

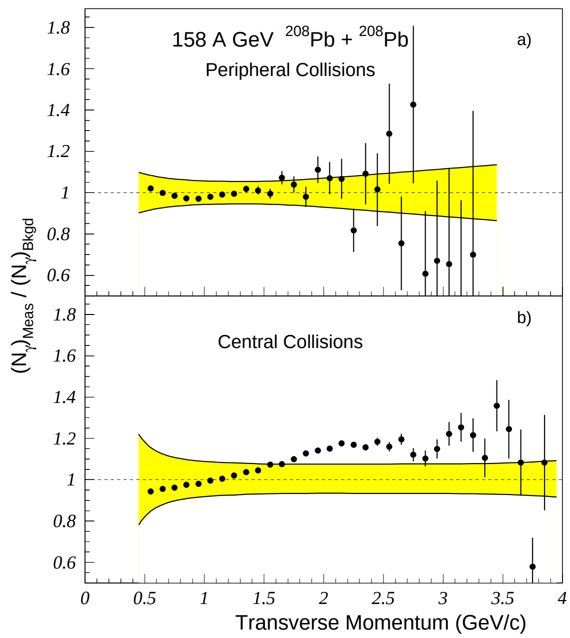

FIG. 2. The $\gamma_{\rm Meas}/\gamma_{\rm Bkgd}$ ratio as a function of transverse momentum for peripheral (part a)) and central (part b)) 158 A GeV ^{208}Pb+^{208}Pb collisions. The errors on the data points indicate the statistical errors only. The p_T-dependent systematical errors are indicated by the shaded bands.

Fig. 1 shows the fully corrected inclusive photon spectra for peripheral and central collisions. The spectra cover the p_T range of $0.3 - 4.0$ GeV/c (slightly less for peripheral collisions) and extend over six orders of magnitude. Fig. 1 also shows the distributions of neutral pions which extend over a similar momentum range with slightly larger statistical errors.

The ratio of measured photons to calculated background photons is displayed in Fig. 2 as a function of transverse momentum. The upper plot shows the ratio for peripheral collisions which is seen to be compatible with one, i.e. no indication of a direct photon excess is observed. The lower plot shows the same ratio for central collisions. It rises from a value of ≈ 1 at low p_T to exhibit an excess of about 20% at high p_T.

A careful study of possible systematical errors is crucial for the direct photon analysis. The various sources of systematical errors have been investigated and are discussed in detail in [21]. The largest contributions are from the γ and π^0 identification efficiencies and the uncertainties related to the η measurement. It should be emphasized that the inclusive photon and neutral meson (the basis for the background calculation) yields have been extracted from the same detector for exactly the same data sample. This decreases the sensitivity to many detector related errors and eliminates all errors associated with trigger bias or absolute yield normalization. The estimate of the systematical errors has been checked by performing the entire analysis with various photon selection criteria which change the efficiency and background corrections by factors of 2-3. The final results were verified to be consistent within the systematical errors for the different analysis cuts. The total p_T-dependent systematical errors are shown by the shaded regions in Fig. 2. A significant photon excess is clearly observed in central collisions for $p_T > 1.5\,\mathrm{GeV/c}$.

The final invariant direct photon yield per central collision is presented in Fig. 3. The statistical and asymmetric systematical errors of Fig. 2 are added in quadrature to obtain the total upper and lower errors shown in Fig. 3. An additional p_T-dependent error is included to account for that portion of the uncertainty in the energy scale which cancels in the ratios. In the case that the lower error is less than zero a downward arrow is shown with the tail of the arrow indicating the 90% confidence level upper limit ($\gamma_{Excess} + 1.28\,\sigma_{Upper}$).

No published prompt photon results exist for proton-induced reactions at the $\sqrt{s}$ of the WA98 measurement. Instead, prompt photon yields for proton-induced reactions on fixed targets at 200 GeV are shown in Fig. 3 for comparison. Results are shown from FNAL experiment E704 [23] for proton-proton reactions, and from FNAL experiment E629 [24] and CERN SPS experiment NA3 [25] for proton-carbon reactions. These results have been divided by the total pp inelastic cross section ($\sigma_{int} = 30$ mb) and by the mass number of the target to obtain the invariant direct photon yield per nucleon-nucleon collision. They have then been multiplied by the calculated average number of nucleon-nucleon collisions (660) for the central Pb+Pb event selection for comparison with the present measurements. This scaling is estimated to have an uncertainty of less than 10%. The proton-induced results have also been scaled from $\sqrt{s} = 19.4$ GeV to the lower $\sqrt{s} = 17.3$ GeV of the present measurement under the assumption that $Ed^3\sigma_\gamma/dp^3 = f(x_T)/s^2$, where $x_T = 2p_T/\sqrt{s}$ [26]. The $\sqrt{s}$-scaling effectively reduces the 19.4 GeV proton-induced results by about a factor of two. This comparison indicates that the observed direct photon production in central ^{208}Pb+^{208}Pb collisions has a shape similar to that expected for proton-induced reactions at the same $\sqrt{s}$ but a yield which is enhanced.

Wong and Wang [27] have investigated the effects of parton intrinsic k_T on photon production. Results of their calculations (scaled to central Pb+Pb collisions according to the number of binary collisions) are also shown in Fig. 3 with and without the effects of parton intrinsic k_T by the long-dashed and short-dashed curves, respectively. At this low incident energy, the parton intrinsic k_T is seen to significantly increase the predicted photon yield by a factor which increases from about 4 to about 8 with decreasing p_T. The predicted direct photon yield with intrinsic k_T included is in good agreement with the proton-induced results (from which the value of $\langle k_T^2 \rangle = 0.9$ (GeV/c)^2 was extracted). It is also in agreement with the shape of observed excess photon spectrum in central ^{208}Pb+^{208}Pb collisions, but underpredicts the observed yield by about a factor of 2.5. A possible explanation might be additional k_T broadening of the incoming partons due to soft scatterings prior to the hard scattering which produces the photon [28]. Recently, Dumitri et al. published [29] an analysis which indicated that an additional k_T broadening contribution of $\Delta k_T^2 \approx 1$ GeV^2/c^2 would allow to describe the central Pb+Pb data in the region above $p_T > 2.5$ GeV/c. However, the excess photon yield at intermediate p_T would not be accounted for in this prompt photon calculation.

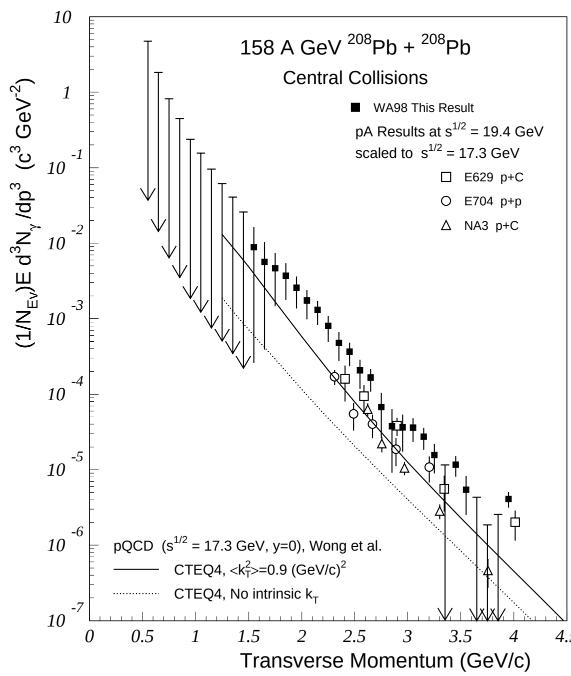

FIG. 3. The invariant direct photon multiplicity for central 158 A GeV ^{208}Pb+^{208}Pb collisions. The error bars indicate the combined statistical and systematical errors. Data points with downward arrows indicate unbounded 90% CL upper limits. Results of several direct photon measurements for proton-induced reactions have been scaled to central ^{208}Pb+^{208}Pb collisions for comparison.

Already from the measured shape of the transverse mass spectra of hadrons it is evident that heavy ion reactions are not merely a superposition of nucleon-nucleon collisions. In p+A collisions the flattening of the transverse mass spectra compared to p+p results (Cronin effect [30]) has been attributed to initial state multiple scattering of partons [31]. It the case of central ^{208}Pb+^{208}Pb collisions, it has been shown that the neutral pion spectra can be described well alternatively by perturbative QCD predictions [32], or by hydrodynamical model calculations [33]. The determination of the relative contribution of hard and soft processes in particle production is especially important in view of the interest in the energy loss of partons traversing dense matter [34,35], generally referred to as *jet quenching*, as a potential probe of quark gluon plasma. The observable effect of jet quenching is the suppression of particle production at high transverse momenta.

Information about the mechanism of particle production, and possible modifications of the spectra of produced particles can be obtained by a detailed comparison of the particle spectra for different reaction systems, or different centralities. At high transverse momenta one expects the pion multiplicity to increase in proportion to the number of binary nucleon-nucleon collisions, characteristic of a hard process. In fact, it is already well known from p+A collisions at beam energies of 200 - 400 GeV that the absolute yield of produced pions increases even more strongly than the increase in target mass - the well known Cronin effect [30].

To investigate the dependence of the pion yield on centrality in ^{208}Pb+^{208}Pb collisions the ratios of the measured pion transverse mass distributions for two different samples (labeled X and Y) normalized to the calculated number of binary collisions for that sample

$$R_{XY}(m_T) \equiv \frac{\left(E\frac{d^3N}{dp^3}(m_T)/N_{coll}\right)_X}{\left(E\frac{d^3N}{dp^3}(m_T)/N_{coll}\right)_Y} \qquad (0.1)$$

are shown in Figs. 4. The ratio of peripheral ^{208}Pb+^{208}Pb collisions to p+p shown in Fig. 4a increases strongly with increasing transverse mass, as expected due to the Cronin effect. A similar trend is observed when going from peripheral to medium-central data samples (Fig. 4b). In addition, the pion yield is seen to increase roughly proportional to the number of binary collisions even at rather low transverse masses. In going from medium-central to central (Fig. 4c) the trend is reversed: the ratio decreases with increasing transverse mass and the pion multiplicities increase more weakly than the number of collisions. The ratio of very central to central collisions shows an indication of a similar effect although not very significant.

Included in Fig. 4 are results of HIJING calculations (open circles) for the same centralities. They show a very different trend: For all but the most central case the ratios increase with increasing transverse mass, for high transverse masses the ratio is always larger than one. HIJING does not describe p+p data well at these energies while a reasonable description of central Pb+Pb collisions is obtained by an implementation of the Cronin effect via a soft transverse momentum kick model which results in a very strong A dependence, as was pointed out already in [37]. Thus the reasonable description of central Pb+Pb collisions by HIJING appears to be fortuitous. The authors of [37] stated that a better implementation of the Cronin effect should use an additional intrinsic k_T of the incoming partons and a likely weaker k_T broadening. Still, in any model of the Cronin effect one would expect the ratios of central to less central spectra, as shown in Fig. 4c, to be larger than one at high transverse mass. A more refined calculation including intrinsic k_T was performed in [38] using the same model as in [32]. The results are also shown in Fig. 4 as solid lines. As expected, the ratios show a weaker increase at high m_T compared to HIJING, but are all ≥ 1 and thus do not explain the centrality dependence, as seen in Fig. 4c.

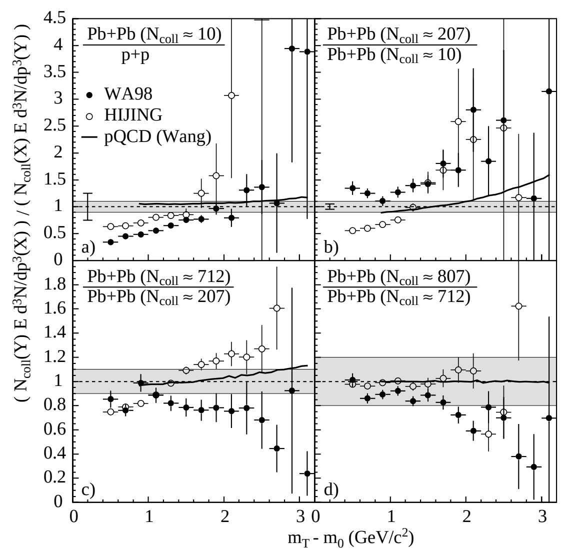

FIG. 4. Ratios of invariant mass distributions of neutral pions normalized to the number of binary collisions. The upper left plot (a) shows the ratio of distributions for peripheral Pb+Pb collisions to a parameterization of pp collisions. The other plots (b-d) show the ratio of more central sample to a more peripheral sample. The shaded regions show the estimated systematic error in the π^0 distribution. The additional error bar in (a) and (b) shows the normalization uncertainty due to the calculation of the number of collisions and the absolute cross section normalization relative to p+p.

With these observations in mind one can revisit the evolution of the particle yields with system size at given transverse mass. This is done in Fig. 5 where the neutral pion yield per binary collision:

$$R_{bin} \equiv E\frac{d^3N}{dp^3}/N_{coll} \qquad (0.2)$$

is shown as a function of the number of collisions for four different transverse mass intervals. In addition to Pb+Pb reactions the parameterization of p+p is included. At relatively low transverse mass the yield per collision decreases as expected from the scaling exponent $\alpha_c < 1$. With increasing transverse mass a rise of R_{bin} develops which is most prominent for the highest m_T. However, it is also clear that R_{bin} decreases significantly with N_{coll} for $N_{coll} > 200$.

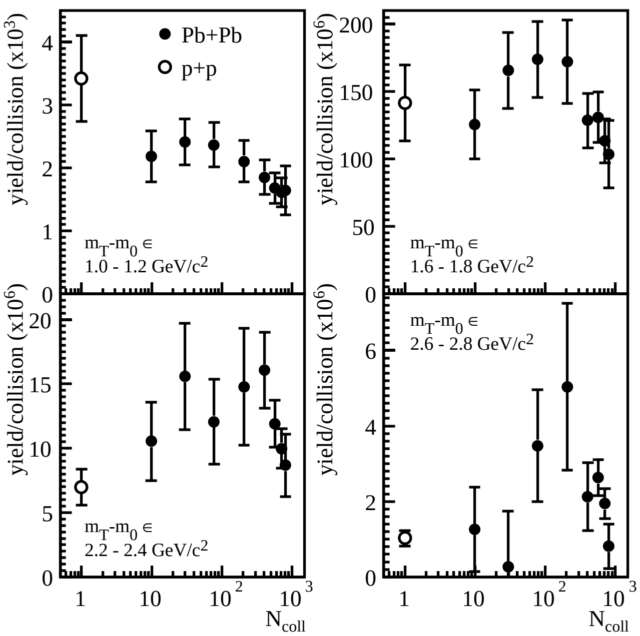

FIG. 5. Multiplicities of neutral pions normalized to the number of binary collisions N_{coll} as a function of N_{coll} for different ranges of transverse mass as indicated in the figures. The filled circles show the experimental results for Pb+Pb reactions, the open circles the parameterization for p+p reactions. The error bars contain statistical and systematic errors added in quadrature.

In summary, the first observation of direct photons in ultrarelativistic heavy-ion collisions has been presented. While peripheral Pb+Pb collisions exhibit no significant photon excess, the 10% most central reactions show a clear excess of direct photons in the range of p_T greater than about 1.5 GeV/c. The invariant direct photon multiplicity as a function of transverse momentum was presented for central ^{208}Pb+^{208}Pb collisions and compared to proton-induced results at similar incident energy. The comparison suggests excess direct photon production in central ^{208}Pb+^{208}Pb collisions beyond that expected from proton-induced reactions. The result suggests modification of the prompt photon production in nucleus-nucleus collisions, or additional contributions from pre-equilibrium or thermal photon emission.

Similarly, the neutral pion spectra show a behaviour which is not trivially expected from p-induced results. A possible explanation of this behaviour might be that the multiple scattering mechanisms which are expected to be responsible for the apparent k_T-broadening in p+A and peripheral Pb+Pb might be modified in central Pb+Pb collisions. This might be possible if both *initial* and *final* state scatterings are relevant for the enhancement, and the relative contributions are shifted more towards final state contributions in central collisions, reminiscent of a more and more thermalized system. Alternative explanations might involve suppression mechanisms independent of the nuclear enhancement in question, e.g. an onset of quenching via energy loss of produced particles (partons or hadrons) in central Pb+Pb collisions.

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[1] E.L. Feinberg, Nuovo Cimento **34** A, 391 (1976).
[2] E. Shuryak, Phys. Lett. B **78**, 150 (1978).
[3] K. Kajantie and H.I. Miettinen, Z. Phys. C **9**, 341 (1981).
[4] F. Halzen and H.C. Liu, Phys. Rev. D **25**, 1842 (1982).
[5] B. Sinha, Phys. Lett. B **128**, 91 (1983).
[6] L.D. McLerran and T. Toimela, Phys. Rev. D **31**, 545 (1985).
[7] J. Kapusta, P. Lichard, and D. Seibert, Phys. Rev. D **44**, 2774 (1991).
[8] P. Aurenche, F. Gelis, H. Zaraket, and R. Kobes, Phys. Rev. D **58**, 085003 (1998).
[9] D.K. Srivastava, Eur. Phys. J. C **10**, 487 (1999); and erratum, nucl-th/0103023.
[10] W. Vogelsang and M.R. Whalley, J. Phys. G: Nucl. Part. Phys. **23**, A1 (1997).
[11] HELIOS Collaboration, T. Åkesson et al., Z. Phys. C **46**, 369 (1990).
[12] WA80 Collaboration, R. Albrecht et al., Z. Phys. C **51**, 1 (1991).
[13] CERES Collaboration, R. Baur et al, Z. Phys. C **71**, 571 (1996).
[14] WA80 Collaboration, R. Albrecht et al., Phys. Rev. Lett. **76**, 3506 (1996).
[15] D.K. Srivastava and B. Sinha, Phys. Rev. Lett. **73**, 2421 (1994).
[16] N. Arbex, U. Ornik, M. Plümer, A. Timmermann, and R. M. Weiner, Phys. Lett. B **354**, 307 (1995).
[17] A. Dumitru, U. Katscher, J. A. Maruhn, H. Stöcker, W. Greiner, and D. H. Rischke, Phys. Rev. C **51**, 2166 (1995).
[18] J. J. Neumann, D. Siebert, and G. Fai, Phys. Rev. C **51**, 1460 (1995).
[19] J. Sollfrank et al., Phys. Rev. C **55**, 392 (1997).
[20] WA98 Collaboration, M.M. Aggarwal et al., Phys. Rev. Lett. **85**, 3595 (2000).
[21] WA98 Collaboration, M.M. Aggarwal et al, nucl-ex/0006007, submitted to Phys. Rev. C.
[22] M. Bourquin and J.-M. Gaillard, Nucl. Phys. B **114**, 334

(1976).
[23] E704 Collaboration, D.L. Adams et al., Phys. Lett. B **345**, 569 (1995).
[24] E629 Collaboration, M. McLaughlin et al., Phys. Rev. Lett. **51**, 971 (1983).
[25] NA3 Collaboration, J. Badier et al., Z. Phys. C **31**, 341 (1986).
[26] J.F. Owens, Rev. Mod. Phys. **59**, 465 (1987).
[27] C.Y. Wong and H. Wang, Phys. Rev. C **58**, 376 (1998).
[28] G. Papp, P. Levai, and G. Fai, Phys. Rev. C **61**, 021902 (2000).
[29] A. Dumitru et al., Phys. Rev. C **64**, 054909 (2001).
[30] D. Antreasyan et al., Phys. Rev. D **19**, 764 (1979).
[31] A. Krzywicki, Phys. Lett. B **85**, 407 (1979).
[32] X.-N. Wang, Phys. Rev. Lett. **81**, 2655 (1998).
[33] WA98 Collaboration, M.M. Aggarwal et al., Phys. Rev. Lett. **83**, 926 (1999).
[34] X.-N. Wang and M. Gyulassy, Phys. Rev. Lett. **68**, 1480 (1992).
[35] R. Baier, D. Schiff, and B.G. Zakharov, Ann. Rev. Nucl. Sci. **50**, 37 (2000).
[36] WA98 Collaboration, M.M. Aggarwal et al., submitted to Eur. Phys. J. C, preprint nucl-ex/0108006.
[37] M. Gyulassy and P. Levai, Phys. Lett. B **442**, 1 (1998).
[38] E. Wang and X.-N. Wang, prepring nucl-th/0104031.