Centrality Dependence of Neutral Pion Production in 158A GeV ^{208}Pb + ^{208}Pb Collisions

M. M. Aggarwal,[1] A. Agnihotri,[2] Z. Ahammed,[3] A. L. S. Angelis,[4] V. Antonenko,[5] V. Arefiev,[6] V. Astakhov,[6] V. Avdeitchikov,[6] T. C. Awes,[7] P. V. K. S. Baba,[8] S. K. Badyal,[8] A. Baldine,[6] L. Barabach,[6] C. Barlag,[9] S. Bathe,[9] B. Batiounia,[6] T. Bernier,[10] K. B. Bhalla,[2] V. S. Bhatia,[1] C. Blume,[9] R. Bock,[11] E.-M. Bohne,[9] Z. K. Böröcz,[9] D. Bucher,[9] A. Buijs,[12] H. Büsching,[9] L. Carlen,[13] V. Chalyshev,[6] S. Chattopadhyay,[3] R. Cherbatchev,[5] T. Chujo,[14] A. Claussen,[9] A. C. Das,[3] M. P. Decowski,[18] V. Djordjadze,[6] P. Donni,[4] I. Doubovik,[5] M. R. Dutta Majumdar,[3] K. El Chenawi,[13] S. Eliseev,[15] K. Enosawa,[14] P. Foka,[4] S. Fokin,[5] V. Frolov,[6] M. S. Ganti,[3] S. Garpman,[13] O. Gavrishchuk,[6] F. J. M. Geurts,[12] T. K. Ghosh,[16] R. Glasow,[9] S. K. Gupta,[2] B. Guskov,[6] H. A. Gustafsson,[13] H. H. Gutbrod,[10] R. Higuchi,[14] I. Hrivnacova,[15] M. Ippolitov,[5] H. Kalechofsky,[4] R. Kamermans,[12] K.-H. Kampert,[9] K. Karadjev,[5] K. Karpio,[17] S. Kato,[14] S. Kees,[9] H. Kim,[7] B. W. Kolb,[11] I. Kosarev,[6] I. Koutcheryaev,[5] T. Krümpel,[9] A. Kugler,[15] P. Kulinich,[18] M. Kurata,[14] K. Kurita,[14] N. Kuzmin,[6] I. Langbein,[11] A. Lebedev,[5] Y. Y. Lee,[11] H. Löhner,[16] L. Luquin,[10] D. P. Mahapatra,[19] V. Manko,[5] M. Martin,[4] A. Maximov,[6] R. Mehdiyev,[6] G. Mgebrichvili,[5] Y. Miake,[14] D. Mikhalev,[6] G. C. Mishra,[19] Y. Miyamoto,[14] D. Morrison,[20] D. S. Mukhopadhyay,[3] V. Myalkovski,[6] H. Naef,[4] B. K. Nandi,[19] S. K. Nayak,[10] T. K. Nayak,[3] S. Neumaier,[11] A. Nianine,[5] V. Nikitine,[6] S. Nikolaev,[6] P. Nilsson,[13] S. Nishimura,[14] P. Nomokonov,[6] J. Nystrand,[13] F. E. Obenshain,[20] A. Oskarsson,[13] I. Otterlund,[13] M. Pachr,[15] A. Parfenov,[6] S. Pavliouk,[6] T. Pietzmann,[9] V. Patracek,[15] W. Pinanaud,[10] F. Plasil,[7] M. L. Purschke,[11] B. Raeven,[12] J. Rak,[15] R. Raniwala,[2] S. Raniwala,[2] V. S. Ramamurthy,[19] N. K. Rao,[8] F. Retiere,[10] K. Reygers,[9] G. Roland,[18] L. Rosselet,[4] I. Roufanov,[6] C. Roy,[10] J. M. Rubio,[4] H. Sako,[14] S. S. Sambyal,[8] R. Santo,[9] S. Sato,[14] H. Schlagheck,[9] H.-R. Schmidt,[11] G. Shabratova,[6] I. Sibiriak,[5] T. Siemiarczuk,[17] D. Silvermyr,[13] B. C. Sinha,[3] N. Slavine,[6] K. Söderström,[13] N. Solomey,[4] S. P. Sørensen,[20] P. Stankus,[7] G. Stefanek,[17] P. Steinberg,[18] E. Stenlund,[13] D. Stüken,[9] M. Sumbera,[15] T. Svensson,[13] M. D. Trivedi,[3] A. Tsvetkov,[5] C. Twenhöfel,[12] L. Tykarski,[17] J. Urbahn,[11] N. v. Eijndhoven,[12] G. J. v. Nieuwenhuizen,[18] A. Vinogradov,[5] Y. P. Viyogi,[3] A. Vodopianov,[6] S. Vörös,[4] B. Wysłouch,[18] K. Yagi,[14] Y. Yokota,[14] and G. R. Young[7]

(WA98 Collaboration)

[1]*University of Panjab, Chandigarh 160014, India*
[2]*University of Rajasthan, Jaipur 302004, India*
[3]*Variable Energy Cyclotron Centre, Calcutta 700 064, India*
[4]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[5]*RRC (Kurchatov), RU-123182 Moscow, Russia*
[6]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[7]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6372*
[8]*University of Jammu, Jammu 180001, India*
[9]*University of Münster, D-48149 Münster, Germany*
[10]*SUBATECH, Ecole des Mines, Nantes, France*
[11]*Gesellschaft für Schwerionenforschung (GSI), D-64220 Darmstadt, Germany*
[12]*Universiteit Utrecht/NIKHEF, NL-3508 TA Utrecht, The Netherlands*
[13]*University of Lund, SE-221 00 Lund, Sweden*
[14]*University of Tsukuba, Ibaraki 305, Japan*
[15]*Nuclear Physics Institute, CZ-250 68 Rez, Czech Republic*
[16]*KVI, University of Groningen, NL-9747 AA Groningen, The Netherlands*
[17]*Institute for Nuclear Studies, 00-681 Warsaw, Poland*
[18]*MIT, Cambridge, Massachusetts 02139*
[19]*Institute of Physics, 751-005 Bhubaneswar, India*
[20]*University of Tennessee, Knoxville, Tennessee 37966*

(Received 26 June 1998)

The production of neutral pions in 158A GeV ^{208}Pb + ^{208}Pb collisions has been studied in the WA98 experiment at the CERN Super Proton Synchrotron (SPS). Transverse momentum spectra are studied for the range $0.3 \leq m_T - m_0 \leq 4.0$ GeV/c. The results for central collisions are compared to various models. The centrality dependence of the neutral pion spectral shape and yield is investigated. An invariance of the spectral shape and a simple scaling of the yield with the number of participating nucleons is observed for centralities with greater than about 30 participating nucleons. This is most naturally explained by assuming an equilibrated system. [S0031-9007(98)07532-2]

PACS numbers: 25.75.Dw

0031-9007/98/81(19)/4087(5)$15.00

Ultrarelativistic heavy-ion collisions produce dense matter which is expected to be in the form of a deconfined phase of quarks and gluons, or quark gluon plasma (QGP), at sufficiently high energy densities. The transverse momentum spectra of produced pions can provide information on both the initial and the final state properties of the hot hadronic matter. The low p_T pion production would dominantly reflect the temperature of the hadronic system at the freeze-out stage occurring late in the reaction. It is strongly influenced by rescattering among the final state hadrons. The high p_T pion production is expected to be dominated by hard scattering of the partons. In pA collisions the high p_T region is known to be enhanced (Cronin effect [1]) due to initial state scattering of the incident partons leading to a broadening of their incoming p_T. In AA collisions, many of the scattered partons must traverse the excited matter to escape and therefore may undergo additional rescatterings and energy loss [2]. In the case of significant parton rescattering, the parton distributions may approach thermal distributions with a temperature reflecting the initial state of the excited matter. The intermediate p_T region of the pion spectrum might then reflect this initial temperature. Indeed, one of the earliest signatures of QGP formation, proposed by Van Hove [3], was the observation of a saturation of the average transverse momentum with increasing energy (or entropy) density for systems excited just above the critical energy density. With increasing energy density, the initial temperature would not rise above the critical temperature until all of the latent heat of the QQP phase transition had been extracted.

For these reasons it is of interest to study the centrality dependence of the pion production. It is generally believed that the initial energy density increases with increasing centrality, due to the many overlapping interactions. Also, the volume of the excited matter increases with centrality, as well as the amount of rescattering. Since rescattering is the feature which distinguishes AA collisions nontrivially from pp collisions, and since significant rescattering is a prerequisite for thermalization, it is imperative to demonstrate an understanding of the centrality dependence of the AA results in order to understand the effects of rescattering. While those effects may be minor on extensive observables, like the particle multiplicity or transverse energy, they should be most evident on the momentum distribution of the produced particles. Recently it has been argued that a parton cascade description could successfully describe many of the features of central Pb + Pb collisions at the CERN Super Proton Synchrotron (SPS) energies [4]. Surprisingly, low momentum transfer soft parton collisions were found to have little influence on the final observables. Similarly, recent perturbative QCD calculations were able to reproduce the preliminary WA98 neutral pion result for central collisions [5,6] without need for the effects of parton energy loss or rescattering [7]. In this Letter we present neutral pion spectra for 158A GeV ^{208}Pb + ^{208}Pb collisions and investigate in detail the centrality dependence of the spectral shape and yield.

The CERN experiment WA98 [5,8] consists of large acceptance photon and hadron spectrometers together with several other large acceptance devices which allow one to measure various global variables on an event-by-event basis. The results presented here were obtained from an analysis of the data taken with Pb beams in 1995 and 1996. The minimum bias (min-bias) reactions ($\sigma_{\text{min-bias}} \approx 6300$ mb) are divided into eight centrality classes using the transverse energy E_T measured in the MIRAC calorimeter. In total, $\approx 9.6 \times 10^6$ reactions have been analyzed.

Neutral pions are reconstructed via their $\gamma\gamma$ decay branch using 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 $2.35 < \eta < 2.95$. The measurement of neutral pions, though difficult at low transverse momenta, is superior to those of charged pions at high momenta because of the improving energy resolution of the calorimetric measurement.

The general analysis procedure is similar to that used in the WA80 experiment and described in [9]. Hits in the lead-glass detector are combined in pairs to provide distributions of pair mass vs pair transverse momentum (or transverse mass) for all possible combinations. Subtraction of the combinatorial background is performed using mixed event distributions. The resulting momentum distributions are corrected for geometrical acceptance and reconstruction efficiency. The efficiency depends on the particle occupancy in the detector and therefore has been calculated independently for each centrality bin. The systematic error of the pion yields is mainly due to errors in the reconstruction efficiency for central collisions and to corrections for nontarget interactions for peripheral collisions. The systematic error on the absolute yield is $\approx 10\%$ and increases sharply below $p_T = 0.4$ GeV/c. An additional systematic error originates from the uncertainty of the momentum scale of 1%. The influence of this rises slowly for higher p_T and leads to an error of 15% at $p_T = 4$ GeV/c. A detailed discussion of the analysis procedure and the error contributions will be given in a forthcoming publication.

The measured neutral pion spectrum from central Pb + Pb reactions (10% of min-bias cross section) as a function of $m_T - m_0$ is shown in Fig. 1. The data are compared to predictions of the string model Monte Carlo generators FRITIOF 7.02 [10] and VENUS 4.12 [11]. As already observed in S + Au reactions [9], both generators fail to describe the data well at large m_T. The FRITIOF prediction is more than an order of magnitude lower at high m_T while VENUS significantly overpredicts the data. Alternatively, it has recently been shown that

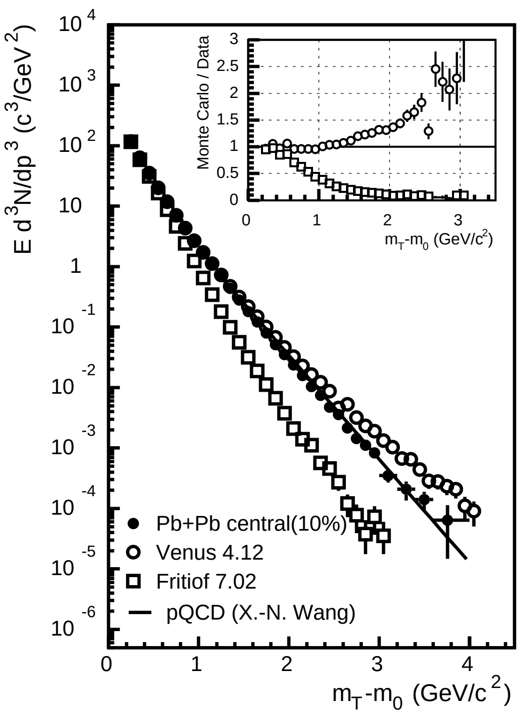

FIG. 1. Transverse mass spectra of neutral pions in central collisions of 158A GeV Pb + Pb. Invariant yields per event are compared to calculations using the FRITIOF 7.02 [10] and VENUS 4.12 [11] Monte Carlo programs. Predictions of a pQCD calculation [7] are included as a solid line. The inset shows the ratios of the results of the Monte Carlo codes to the experimental data.

perturbative QCD (pQCD) calculations, including initial state multiple scattering and intrinsic p_T [7], are able to describe the preliminary WA98 data at intermediate and high p_T. This prediction is included in Fig. 1 as a solid line. (The results shown have been corrected for a small numerical error by the author of [7] and have changed by ≈10%–30% compared to the publication.) The pQCD calculation shows a very good agreement in the high m_T region. This surprising agreement has been interpreted as an indication for unexpectedly small effects of parton energy loss [7]. On the other hand, the parton cascade Monte Carlo code, VNI, which provides a more detailed pQCD description, overpredicts the measured WA98 result by more than a factor of 10 at large p_T [4]. In an alternative picture, hydrodynamical descriptions (see, e.g., [12]) with properly adjusted parameters can describe the momentum spectra reasonably well.

In view of the above discussion and the difficulty to describe the details of the neutral pion spectrum, it is apparent that the theoretical description of ultrarelativistic nucleus-nucleus collisons remains uncertain. In order to demonstrate a consistent description of nuclear effects it is important to investigate the details of the pion production as a function of the system size. To study the centrality dependence of the spectral shape in a manner which is independent of model or fit function we have used the truncated mean transverse momentum $\langle p_T(p_T^{\min})\rangle$, where

$$\langle p_T(p_T^{\min})\rangle = \left(\int_{p_T^{\min}}^{\infty} p_T \frac{dN}{dp_T}\, dp_T \Big/ \int_{p_T^{\min}}^{\infty} \frac{dN}{dp_T}\, dp_T\right) - p_T^{\min}. \quad (1)$$

The lower cutoff $p_T^{\min} = 0.4$ GeV/c is introduced to avoid systematic errors from extrapolation to low p_T and has been chosen according to the lowest p_T of the present data where systematic uncertainties imposed by the necessary corrections are still small. In general, the value of $\langle p_T(p_T^{\min})\rangle$ differs from the true average p_T, except in the case of a purely exponential distribution $d\sigma/dp_T$. For a purely exponential invariant cross section, $d^2\sigma/dp_T^2$, $\langle p_T(p_T^{\min})\rangle$ decreases with increasing $p_T^{\min}$.

Figure 2 shows $\langle p_T(p_T^{\min})\rangle$ as a function of the average number of participants N_{part} for 158A GeV ^{208}Pb + Pb collisions. For comparison, $\langle p_T(p_T^{\min})\rangle$ values for 200A GeV S + Au [9] and from a parametrization of pp data [13] are also included. N_{part} is extracted by the assumption of a monotonic relation between impact parameter and transverse energy and using the resulting correspondence between measured cross section and impact parameter. The average number of participants is calculated from nuclear geometry using the extracted impact parameter. Together these data show the general trend of a rapid increase of $\langle p_T(p_T^{\min})\rangle$ compared to pp results for small system sizes. For N_{part} greater than about 30 the

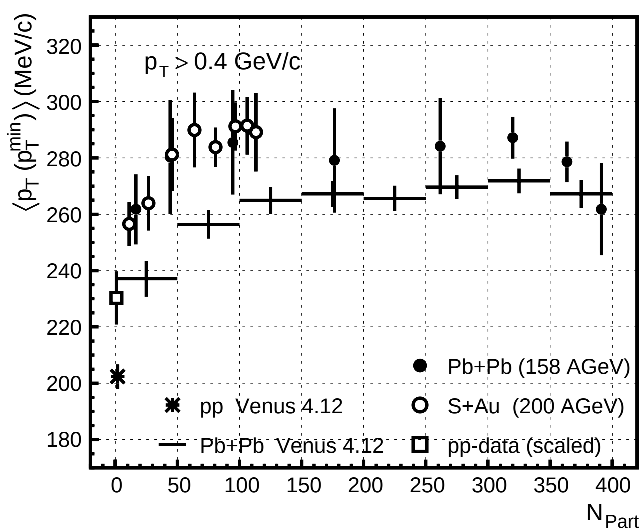

FIG. 2. Truncated mean transverse momentum $\langle p_T(p_T^{\min})\rangle$ of π^0 mesons as defined by Eq. (1) plotted as a function of the average number of participants N_{part}. The solid circles correspond to the 8 E_T based centrality selections for Pb + Pb. The open square shows $\langle p_T(p_T^{\min})\rangle$ extracted from a parametrization of pp data scaled to the same c.m. energy [13], the open circles the results for S + Au collisions at 200A GeV [9]. For comparison, results from VENUS 4.12 [11] are included as histograms for Pb + Pb collisions and as a star for pp. A cut parameter $p_T^{\min} = 0.4$ GeV/c was used.

mean transverse momentum appears to attain a limiting value of $\approx$280 MeV/c^2. [The variation of $\langle p_T(p_T^{\min})\rangle$ has been studied for values of $p_T^{\min} = 0.2\text{–}1.0$ GeV/c. The saturation is always observed; the statistical significance, however, decreases with increasing threshold.] VENUS 4.12 [11] calculations show a qualitatively similar behavior, but underpredict the present data, as well as the pp data. The simple implementation of rescattering which is used in this model seems to be strong enough to lead to a saturation for semiperipheral collisions as in the experimental data. One should, however, keep in mind that VENUS 4.12 does not correctly describe pion production at high p_T (see Fig. 1).

Earlier investigations of the dependence of $\langle p_T\rangle$ of pions on system size [9,14,15] at SPS energies have suggested such a saturation for large systems. The present study is the first investigation of the dependence with Pb ions at the SPS. Preliminary results from the AGS have indicated a weak increase in the average m_T of pions with the number of participants for Au + Au collisions [16].

It is important to note that the observed limiting behavior is very different from the observations in pp or $p\overline{p}$ collisions. For very high energies $\langle p_T\rangle$ rises with the pseudorapidity density of charged particles [17–20]. In that case, more violent parton scatterings presumably result in a harder spectrum of leading particles together with a greater multiplicity of fragmentation products. This would lead to the observed correlation between $\langle p_T\rangle$ and multiplicity. At lower $\sqrt{s}$, comparable to the data presented here, $\langle p_T\rangle$ decreases for increasing multiplicity [21], most likely due to energy conservation. In the case of nuclear reactions, this anticorrelation is lost due to the large number of binary collisions. Instead, the initial increase of $\langle p_T(p_T^{\min})\rangle$ with N_{part} is interpreted as a result of multiple scattering. Initial state multiple scattering, as suggested as an explanation for the Cronin effect [1], would imply a continuing increase of $\langle p_T(p_T^{\min})\rangle$ for more central collisions. Here, however, the surprising observation is that additional multiple scattering, implied by increasing N_{part}, does not alter the pion distributions. This is most easily understood as a consequence of final state rescattering and is, of course, the behavior expected for a thermalized system.

More detailed information about the centrality dependence of the pion spectral shape and yield is shown in Fig. 3 where the neutral pion yield per event has been parametrized as $Ed^3N/dp^3 \propto N_{\text{part}}^{\alpha(p_T)}\sigma_0(p_T)$. The results for $N_{\text{part}} > 30$ are well described by this scaling with an exponent $\alpha(p_T) \approx 1.3$, independent of p_T. Consistent with the previous discussion, the results indicate a constant spectral shape over the entire interval of measurement from $0.5 < p_T < 3$ GeV/c. The observed $N_{\text{part}}^{4/3}$ scaling for symmetric systems implies a scaling with the number of nucleon collisions, as confirmed by a similar analysis. However, this scaling does not extrapolate from the pp results. On the contrary, when comparing semiperipheral Pb + Pb collisions with pp the exponent α varies over the entire p_T interval, confirming the very different spectral shapes.

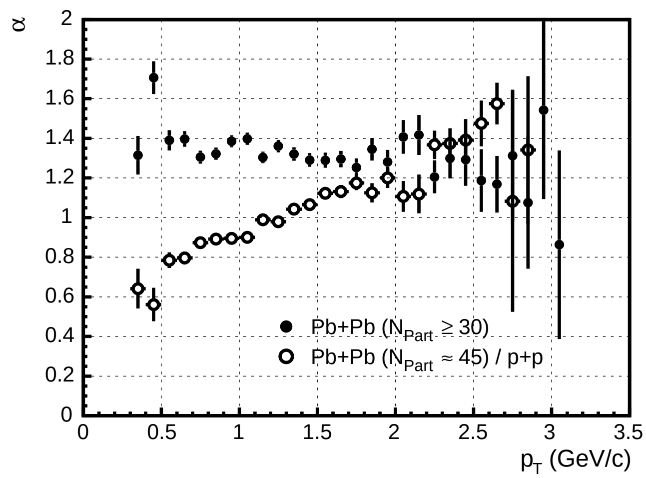

FIG. 3. The exponent $\alpha(p_T)$ of the dependence of the π^0 yield on the average number of participants N_{part} plotted as a function of the transverse momentum for 158A GeV Pb + Pb. The solid circles are calculated based on a fit to the centrality selections with $N_{\text{part}} \geq 30$. The open circles are calculated based on the ratio of the semiperipheral data ($N_{\text{part}} \approx 45$) to a parametrization of pp data.

In summary, we have analyzed the centrality dependence of high precision transverse momentum spectra of neutral pions from 158A GeV Pb + Pb collisions. The neutral pion spectra are observed to show increasing deviation from pp results with increasing centrality, indicating the importance of multiple scattering effects. However, for centralities with more than about 30 participating nucleons, the shape of the transverse momentum spectrum becomes invariant over the interval $0.5 < p_T < 3$ GeV/c. In this interval the pion yield scales like $N_{\text{part}}^{1.3}$, or like the number of nucleon collisions, for this range of centralities. Since the amount of rescattering increases with centrality, the invariance of the spectral shape with respect to the number of rescatterings, most naturally suggests a dominantly thermal emission process. It will be important to determine whether cascade models which reproduce the observed invariant spectral shape will support the interpretation as an "effective" thermalization due to significant rescattering.

We wish to express our gratitude to the CERN accelerator division for excellent performance of the SPS accelerator complex. We acknowledge with appreciation the effort of all engineers, technicians, and support staff who have participated in the construction of the experiment. This work was supported jointly by the German BMBF and DFG, the U.S. DOE, the Swedish NFR and FRN, the Dutch Stichting FOM, the Stiftung für Deutsch-Polnische Zusammenarbeit, the Grant Agency of the Czech Republic under Contract No. 202/95/0217, the Department of Atomic Energy, the Department of Science and

Technology, the Council of Scientific and Industrial Research and the University Grants Commission of the Government of India, the Indo-FRG Exchange Program, the PPE division of CERN, the Swiss National Fund, the International Science Foundation under Contract No. N8Y000, the INTAS under Contract No. INTAS-93-2773, ORISE, Research-in-Aid for Scientific Research (Specially Promoted Research & International Scientific Research) of the Ministry of Education, Science and Culture, the University of Tsukuba Special Research Projects, and the JSPS Research Fellowships for Young Scientists. ORNL is managed by Lockheed Martin Energy Research Corporation under Contract No. DE-AC05-96OR22464 with the U.S. Department of Energy. The MIT group has been supported by the U.S. Department of Energy under the cooperative agreement DE-FC02-94ER40818.

[1] D. Antreasyan *et al.*, Phys. Rev. D **19**, 764 (1979).
[2] X.-N. Wang and M. Gyulassy, Phys. Rev. Lett. **68**, 1480 (1992).
[3] L. Van Hove, Phys. Lett. **118B**, 138 (1982).
[4] D. K. Srivastava and K. Geiger, Phys. Rev. C **56**, 2718 (1997).
[5] WA98 Collaboration, M. Aggarwal *et al.*, Nucl. Phys. **A610**, 200c (1996).
[6] WA98 Collaboration, T. Peitzmann *et al.*, in *Quark Matter '97, Proceedings of the 13th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Tsukuba, Japan* (to be published).
[7] X.-N. Wang, e-print hep-ph/9804384, 1998; (private communication).
[8] WA98 Collaboration, Report No. CERN/SPSLC 91-17, SPSLC/P260, 1991.
[9] WA80 Collaboration, R. Albrecht *et al.*, Eur. Phys. J. C **5**, 255–267 (1998).
[10] B. Andersson, G. Gustafson, and H. Pi, Z. Phys. C **57**, 485 (1993).
[11] K. Werner, Phys. Rep. **232**, 87 (1993).
[12] U. A. Wiedemann and U. Heinz, Phys. Rev. C **56**, 3265 (1997).
[13] C. Blume, Doctoral thesis, University of Münster, Germany, 1998.
[14] WA80 Collaboration, R. Albrecht *et al.*, Phys. Lett. B **201**, 390 (1987).
[15] HELIOS Collaboration, T. Åkesson *et al.*, Z. Phys. C **46**, 361 (1990).
[16] E866 Collaboration, L. Ahle *et al.*, Nucl. Phys. **A610**, 139c (1996).
[17] SFM Collaboration, A. Breakstone *et al.*, Phys. Lett. B **183**, 227 (1987).
[18] UA1 Collaboration, G. Arnison *et al.*, Phys. Lett. **118B**, 167 (1982).
[19] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **61**, 1819 (1988).
[20] E735 Collaboration, T. Alexopoulos *et al.*, Phys. Lett. B **336**, 599 (1987).
[21] T. Kafka *et al.*, Phys. Rev. D **16**, 1261 (1977).