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

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The production of neutral pions in 158·A GeV ^{208}Pb+^{208}Pb collisions has been studied in the WA98 experiment at the CERN SPS. Transverse momentum spectra are studied for the range $0.3\,\mathrm{GeV}/c \leq m_T - m_0 \leq 4.0\,\mathrm{GeV}/c$. 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 which is most naturally explained by assuming an equilibrated system.

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Ultra-relativistic heavy-ion collisions produce dense matter which is expected to be in the form of a deconfined phase of quarks and gluons at sufficiently high energy densities. The transverse momentum spectra of produced pions can provide information on both the initial and final state properties of the hot hadronic matter. 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 while the low p_T region would dominantly reflect the freeze-out 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 non-trivially 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 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 158·A 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 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 reactions ($\sigma_{min.bias} \approx 6300\,\mathrm{mb}$) are divided into eight centrality classes using the transverse energy E_T measured in the MIRAC calorimeter. In total, $\approx 9.6 \cdot 10^6$ 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 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 non-target interactions for peripheral collisions. The systematic error on the absolute yield is $\approx 10\%$ and increases sharply below $p_T = 0.4\,\mathrm{GeV}/c$. 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 $p_T = 4\,\mathrm{GeV}/c$. 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 perturbative QCD 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.[1] The pQCD calculation shows a very good agreement in the

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[1]The results shown have been corrected for a small numerical

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 ten at large p_T [4].

An alternative picture of the ultra-relativistic heavy ion reaction assumes that the mean-free path of the produced particles in the overlap region is sufficiently small that a thermal or hydrodynamical interpretation may be applied. The excited matter is characterized by thermal variables, such as temperature and collective velocities, which evolve over time. Hydrodynamical descriptions (see e.g. [12]) with properly adjusted parameters can describe the momentum spectra reasonably well. This is, however, beyond the scope of this paper – a detailed investigation of hydrodynamical descriptions of the momentum spectra will be given in a forthcoming publication.

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 ultra-relativistic nucleus-nucleus collisions 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

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

(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 158·A GeV ^{208}Pb+Pb collisions. For comparison, $\langle p_T(p_T^{min})\rangle$ values for 200·A GeV S+Au [9] and from a parametrization of pp data [13] are also included. N_{part} is extracted by

error by the author of [7] and have changed by $\approx 10-30\%$ compared to the publication.

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 mean transverse momentum appears to attain a limiting value of ≈ 280 MeV/c. Venus 4.12 [11] calculations show a qualitatively similar behaviour, although the values of $\langle p_T(p_T^{min})\rangle$ are somewhat lower than the experimental data. The simple implementation of rescattering which is used in this model seems to be strong enough to lead to a saturation for semi-peripheral 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 figure 1).

Alternatively, exponential fits to the spectra over the range 0.7 GeV/$c^2 \leq m_T - m_0 \leq 1.9$ GeV/c^2 have been performed. Although they do not adequately describe the spectra, even in this limited transverse mass range, they provide another measure of the spectral shape. The fitted inverse slopes show a similar saturation effect [13].

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 behaviour is very different from the observations in pp or p$\bar{p}$ collisions. For very high energy $\langle p_T \rangle$ 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 anti-correlation 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 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 behaviour 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 parameterized as $Ed^3N/dp^3 \propto N_{part}^{\alpha(p_T)} \cdot \sigma_0(p_T)$. The results for $N_{part} > 30$ 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 $N_{part}^{4/3}$ 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 semi-peripheral Pb+Pb collisions with pp the exponent α varies over the entire p_T interval, confirming the very different spectral shapes.

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 $N_{part}^{1.3}$, 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.

[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. B **118**, 138 (1982).

[4] D.K. Srivastava and K. Geiger, Phys. Rev. C **56**, 2718 (1997).

[5] WA98 Collaboration, M. Aggarwal et al., Nucl. Phys. A **610**, 200c (1996).

[6] WA98 Collaboration, T. Peitzmann et al., Quark Matter '97, Proceedings of the 13th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Tsukuba, Japan.

[7] X.-N. Wang, 1998, preprint hep-ph/9804384 and private communication.

[8] WA98 Collaboration, *Proposal for a large acceptance hadron and photon spectrometer*, 1991, Preprint CERN/SPSLC 91-17, SPSLC/P260

[9] WA80 Collaboration, R. Albrecht et al., nucl-ex/9805007, accepted for publication in Eur. Phys. J. C.

[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. A **610**, 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).

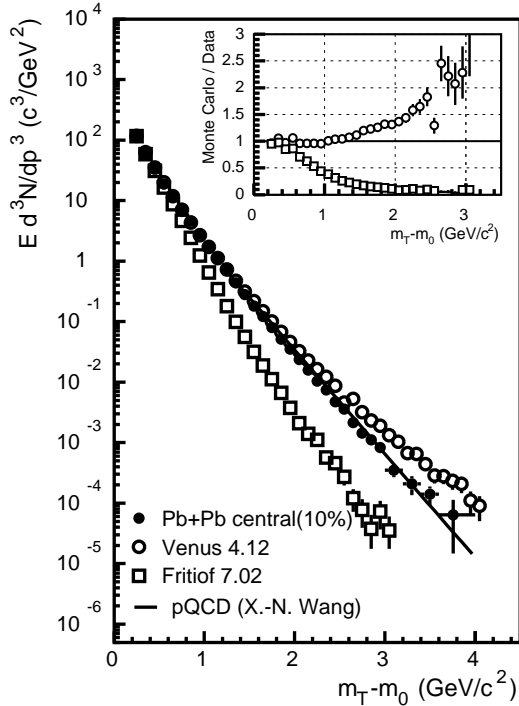[21] T. Kafka et al., Phys. Rev. D **16**, 1261 (1977).

FIG. 1. Transverse mass spectra of neutral pions in central collisions of 158 AGeV 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.
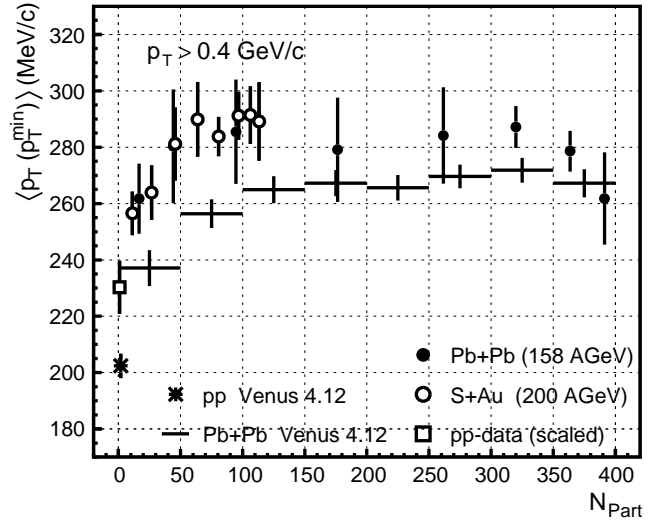

FIG. 2. Truncated mean transverse momentum $\langle p_T(p_T^{min})\rangle$ of π^0 mesons as defined by Eq. 1 plotted as a function of the average number of participants N_{part}. The solid circles correspond to the 8 E_T based centrality selections for Pb+Pb. The open square shows $\langle p_T(p_T^{min})\rangle$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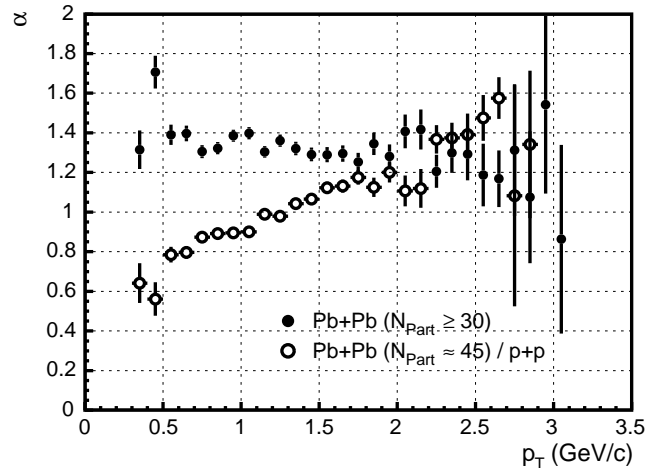

FIG. 3. The exponent $\alpha(p_T)$ of the dependence of the π^0 yield on the average number of participants N_{part} plotted as a function of the transverse momentum for 158 AGeV Pb+Pb. The solid circles are calculated based on the centrality selections with $N_{part} \geq 30$. The open circles are calculated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