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Rapidity and centrality dependence of photon and neutral pion transverse momentum distributions in 200 A·GeV ^{16}O+Au reactions

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Abstract

We report on a detailed investigation of γ and π^0 transverse momentum distributions measured in 200 A·GeV ^{16}O+Au reactions. The data cover the transverse momentum region from 0.4 GeV/c to about 3.5 GeV/c and the rapidity region $1.5 \leq y \leq 2.1$. The variation of the slopes of the $p_\perp$ spectra and the dependence of the averaged transverse momentum on centrality and rapidity is studied and compared to predictions of the VENUS 3.07 string model including rescattering effects.

Nuclear reactions at energies $E_{\mathrm{Lab}} > 10$ $A{\cdot}$GeV have been studied intensively both at BNL and CERN over the past years [1]. The goal is to investigate nuclear matter under conditions of extreme densities and temperatures, and to look for signals of the predicted phase transition from hadronic matter to the quark-gluon plasma (QGP). Unfortunately, most of these signals need to be distinguished from a large background created by hadronic processes. A thorough understanding of the general reaction mechanism and particle production is, therefore, an important prerequisite in any search for the QGP. In particular, one has to learn about the interaction of produced particles with their high density nuclear environment, as well as among produced particles themselves.

Information about the dynamics of the collision can be gained by investigating the spectra of photons and light mesons. Of special interest is the dependence of these spectra on the impact parameter and on the rapidity. Data from the first experiments with 60 and 200 $A{\cdot}$GeV heavy ions at the CERN–SPS have revealed differences from an extrapolation of nucleon-nucleon to nucleus-nucleus collisions [2]. For example, a backward shift of the centroid of the $dE_{\mathrm{T}}/d\eta$- and $dN_{\mathrm{ch}}/d\eta$-distributions for increasing target mass has been observed [3, 4] which is stronger than predicted by models based on a purely kinematic picture involving the number of projectile and target participants derived from geometrical considerations [3]. This is related to more dramatic discrepancies observed in the target rapidity region, where the yield of protons largely exceeds the model predictions [5] and where pion interferometry measurements show indications of two different source components for heavy targets [6]. The concepts proposed to explain these observations involve rescattering of secondaries. Such processes should primarily affect the target region.

Around midrapidity additional observables were identified to exhibit characteristic differences to model calculations. Especially transverse momentum distributions of produced particles show an increasing inverse slope with increasing target mass [7]. To investigate possible explanations for those deviations we have performed a systematic study of the $p_{\perp}$-spectra of photons and neutral pions by measuring the centrality and rapidity dependence, as well as by comparing the experimental distributions to predictions of an event generator which contains rescattering of secondaries in a general manner.

The data presented in this letter have been taken with the WA80 detector setup [8] at the CERN–SPS accelerator during the oxygen run in 1986. Using the finely granulated lead-glass calorimeter SAPHIR [9] in combination with the charged particle veto derived from the Streamer Tube Arrays [10], photons could be discriminated from other reaction products in the rapidity region $1.5 \leq y \leq 2.1$. In a second step of the analysis neutral pions have been reconstructed by calculating the invariant mass of all possible photon-pair combinations. Details about the particle identification method and the evaluation of the detection efficiency and the corrections for the geometrical acceptance have been published elsewhere [11, 12, 7].

Global event characterization has been achieved by measuring the forward energy flow, E_{F} ($\eta \geq 6$) in the zero degree calorimeter (ZDC) [13]. Central (peripheral) events are defined as those depositing less than 30% (between 40% and 88%) of the projectile energy in the area of the zero degree calorimeter. In a geometrical picture these cuts correspond to a full (partial) overlap between projectile and target nucleus. A much finer binning of event classes is applied in the second part of the analysis, where we subdivide the ZDC spectrum into nine bins of different centrality.

In Fig. 1 we show the measured transverse momentum distributions of photons and neutral pions both for peripheral and central events. The inclusive photon spectra cover the $p_\perp$-range from 400 MeV/c to 3800 MeV/c and the neutral pion spectra from 400 MeV/c to 3400 MeV/c. These data consist of roughly 0.4 million peripheral and 1.7 million central events, which is the full statistics collected during the above mentioned run. A notable feature of the data is the significant increase in the inverse slope of the spectra in going from peripheral to central events [14]. All four diagrams are overlayed with results from a string model calculation, which will be discussed below.

The observed variation in the slopes of the transverse momentum spectra for photons can be analyzed in an alternative way by calculating the *truncated mean transverse momentum*

$$\langle p_\perp \rangle_{\gamma,C} = \frac{\int_C^\infty p_\perp \frac{dN}{dp_\perp} dp_\perp}{\int_C^\infty \frac{dN}{dp_\perp} dp_\perp} - C$$

above a cutoff parameter C [7]. In the case of a pure exponential distribution the calculation of the truncated mean leads to exactly the same result as the extraction of the inverse slope parameter from the distribution. Deviations from an exponential behaviour can be studied by varying the cutoff parameter C, which gives the possibility to analyze the properties of high $p_\perp$ data in a model independent way [14]. As we want to concentrate in the present analysis on the properties of the medium to high $p_\perp$ part of the spectra, the cutoff parameter has been chosen to be $C = 400$ MeV/c.

In Fig. 2 $\langle p_\perp \rangle_{\gamma,400}$ is shown as function of the forward energy E_F. This plot reveals a significant increase in the mean transverse momentum of nearly 20% when going from the most peripheral to the most central events. Also shown are the predictions of two different event generators, which will be discussed below.

At present there exist at least three classes of models proposed to explain the observed behaviour of the $p_\perp$ and $\langle p_\perp \rangle_{\gamma,400}$ spectra. These are a hydrodynamical model incorporating nuclear flow [15], a non-equilibrium thermodynamics picture [16], and the concept of rescattering of produced particles [17, 18].

In the following we concentrate on investigating a rescattering explanation as implemented in the VENUS 3.07 model [18]. The generated events were subjected to a filter which simulates the experimental setup and trigger conditions and allows the results to be directly be compared to the experimental data. Predictions of VENUS have been compared already to target fragmentation data [19, 20] and can now be confronted to other observables in the mid-rapidity region.

Phenomenologically, rescattering is expected to have two major consequences on the transverse momentum spectra:

1. The scattering of e.g. produced pions off target spectator nucleons causes a backward shift of the mesons, thereby increasing their transverse momentum.
2. Inelastic processes may produce additional mesons. This would increase dominantly the yield of low $p_\perp$ particles.

While inelastic processes (2) would tend to reduce the $\langle p_\perp \rangle$, our analysis of the high $p_\perp$-part of the spectra is probably not sensitive to this effect, but should mainly probe the kinematic shift of the mesons (1).

The rescattering mechanism incorporated in the VENUS code considers the baryons of the incoming projectile and of the target as agglomerations of strings with three quarks each. When the first collision takes place, quarks are exchanged between projectile and target baryons according to a *string-flip* mechanism. The produced secondaries and the remaining baryons then propagate through space-time as linear strings. If such reaction products or any other particles left over after the first step of the NN-interaction again come closer than the so-called reinteraction radius, they interact and form an intermediate resonance which lives for a while and decays again. Different reinteraction radii are chosen for 2-quark (meson-like) and for 3-quark (baryon-like) strings [18]. Rescattering processes are known to result in a large increase of the baryon yield in the target region due to interactions of produced particles with target spectators.

Motivated by the inside-outside cascade picture, other rescattering models (like e.g. the MCFM-code [17]) contain a formation time parameter. In those models produced particles are not allowed to reinteract immediately. Only after a certain formation time do the particles obtain their physical properties and become allowed to interact. As the formation time in the laboratory system is momentum dependent, rescattering of high $p_\perp$ particles will be suppressed. Such models, contrary to the VENUS approach, will therefore show only minor effects in the context presented here. Both models, however, may reduce the effective cross-sections for produced secondaries, the two parameters being the interaction radius and the formation time, respectively. Evidently, both models are crude idealizations: The formation time concept assumes a vanishing cross-section for a certain time, but also the two interaction radii cannot properly account for the very different, momentum-dependent cross-sections of the various processes. Other string models, like FRITIOF 1.6 [21], do not incorporate any reinteraction mechanism of produced particles and will therefore be quoted only for comparison.

In order to compare to our experimental data we calculated two samples of about 110,000 VENUS events. For one data sample the two rescattering radii are set to the default values proposed by the authors of Ref. [18]. For the other, the radii are set to zero, which yields a data sample without rescattering.

As described above, Fig. 1 shows photon and neutral pion transverse momentum spectra for peripheral and central events. Overlayed to all four data samples we have plotted the result of VENUS calculations with and without reinteraction, respectively. All data and simulations are in units of the absolute cross-section.

VENUS including rescattering reproduces the measured photon $p_\perp$-distributions both for the peripheral and central events with minor deviations in the very low and very high $p_\perp$ region. The behaviour of VENUS without reinteraction resembles very much the behaviour of the FRITIOF 1.6 model. Neither of these two models reproduces the absolute value of the slope or the centrality dependence. FRITIOF 1.6 results are not shown here, but can be found in Ref. [7, 22].

Qualitatively, the behaviour found for the photon spectra is seen also in the $p_\perp$-spectra of reconstructed π^0s. For peripheral collisions only small deviations are found between the two model predictions and the experimental data, i.e. the rescattering mechanism is of minor importance only. Selecting central collisions results in a flattening of the experimental spectra which is only reproduced by the simulation with the rescattering mechanism activated. However, the model now tends to overestimate the cross section at very high values of $p_\perp$, which is a common trend observed in all four spectra of Fig. 1.

From the analysis of the target fragmentation region data, VENUS was found to underestimate the production rates of baryons in this region [19] by a significant amount. However, in that analysis the measured proton yields could be reproduced by enlarging the baryon-like rescattering radius of VENUS by about 20% from its default value. It is thus interesting to apply the modified rescattering strength also to the mid-rapidity data. In this case, however, no significant change in the photon or π^0 $p_\perp$-distributions was observed with the modified values.

Considering the centrality dependence of the truncated mean transverse momentum (cf. Fig. 2) one finds that the observed rise in going from peripheral to central events is roughly reproduced by VENUS with rescattering switched on. Only small deviations of the absolute values between the predictions and the measured data are observed. VENUS without rescattering as well as FRITIOF 1.6 predict a more or less constant behaviour for this quantity throughout the whole centrality range which is in contradiction to the experiment.

Additional information can be gained by examining the rapidity dependence of the truncated mean transverse momentum as shown in Fig. 3. We find a rise in the $\langle p_\perp \rangle_{\gamma,400}$ by about 15% when approaching mid-rapidity by increasing y from 1.5 to 2.1. Details about measuring the angular dependence are described in [14]. The data have not been corrected for the influence of high particle densities at the more forward laboratory angles. A preliminary analysis shows that the necessary correction for the particle density would enhance the measured y-dependence of the truncated mean transverse momentum [14]. This will be studied in detail in a forthcoming publication.

Similar rapidity dependencies of $\langle p_T \rangle$ or slopes of the spectra have been observed for charged particles from 200 A·GeV O + Au collisions [23], as well as for negative pions from 14.6 A·GeV Si + Au collisions [24], but are not reproduced by the presently used event generator. Both VENUS data samples, with and without rescattering, fail to describe the angular effect of the truncated mean transverse momentum; the model predicts no variation of $\langle p_\perp \rangle_{\gamma,C}$ over the rapidity region covered by the experiment. Also included in Fig. 3 is the rapidity dependence as expected from an isotropic fireball model. (The curve has been normalized to the data point at $\theta_{\rm lab} = 14.5^0$.) This model in fact predicts an increase, which is somewhat steeper than the one measured. One should keep in mind, however, that an isotropic fireball model does not describe global features of these reactions like e.g. the width of $dN/d\eta$-distributions.

The qualitative difference reflects the different underlying scenarios of the two models, namely full stopping, which results in a fireball located at a common center of mass, and partial transparency, which provides us with strings stretched out over a large range of longitudinal phase space. The rapidity dependence of $\langle p_\perp \rangle$ is therefore directly related to the amount of stopping, which is larger in the data compared to the string models. The rapidity dependence of the mean transverse momentum should also be taken into account when comparing photon or pion distributions measured in different rapidity regions in the same experiment or between different experiments.

In summary, we observe a flattening of the photon and neutral pion $p_\perp$-spectra in central events relative to peripheral ones. More specifically, a gradual increase in the truncated mean transverse momentum of photons by about 30 MeV/c is found when going from peripheral to central reactions. Compared to string models like FRITIOF 1.6 or VENUS 3.07 without rescattering, the predictions of VENUS 3.07 including rescattering show a much better agreement with the data. Qualitatively, the flattening of the high $p_\perp$-part of the spectrum can be explained by such a rescattering mechanism.

In addition, a significant rapidity dependence of the photon truncated mean transverse momentum in the experimentally covered region $1.5 \leq y \leq 2.1$ is observed. None of the existing string models, including VENUS 3.07 with rescattering, can reproduce these data. Although VENUS constitutes an improvement compared to previous models, the rescattering mechanism is still too crude, and more realistic assumptions are needed. The comparison to the simple fireball model illustrates that e.g. hydrodynamic models may provide a way to explain the rapidity dependence. The data presented here will allow detailed tests of more refined models.

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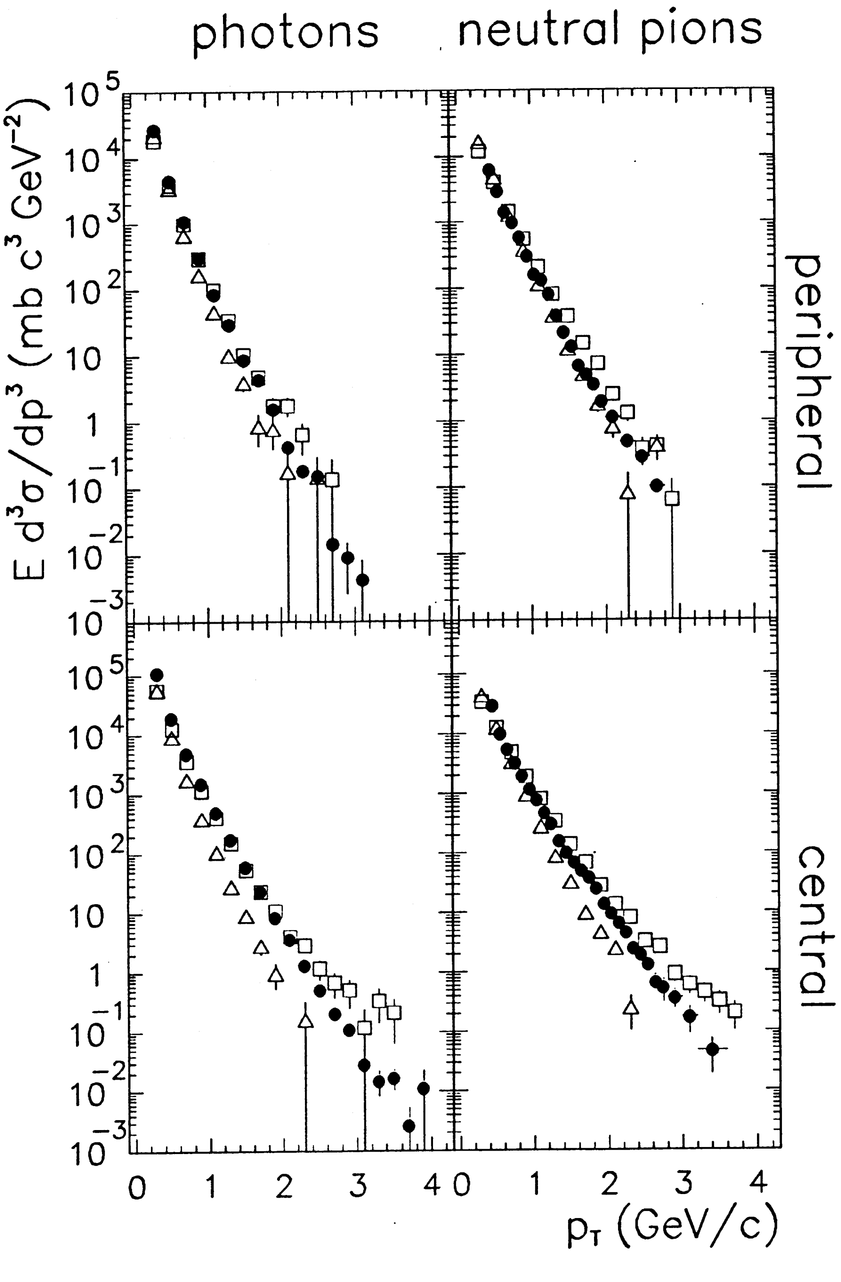

Figure 1: Peripheral and central π^0 and γ $p_\perp$ spectra from 200A·GeV ^{16}O+Au events. The filled circles denote experimental data, the open squares (triangles) VENUS 3.07 predictions with (without) rescattering.

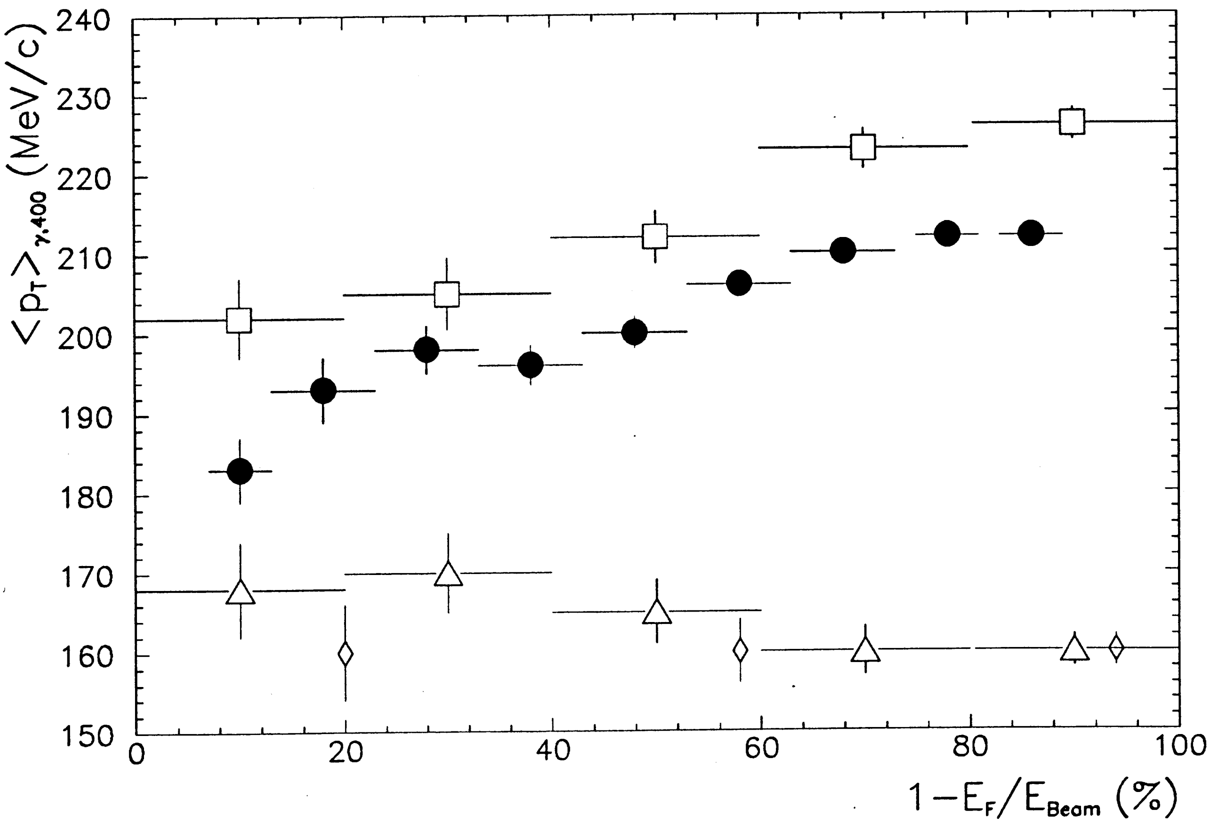

Figure 2: $\langle p_\perp \rangle_{\gamma,400}$ as a function of the centrality of 200A·GeV ^{16}O+Au reactions. The scale on the abscissa shows the centrality as $1 - E_{\rm F}/E_{\rm Beam}$. Thus an increasing value corresponds to increasing centrality. The circles denote experimental data, the open squares (triangles) are VENUS 3.07 predictions with (without) rescattering. The diamonds refer to FRITIOF 1.6 simulations.

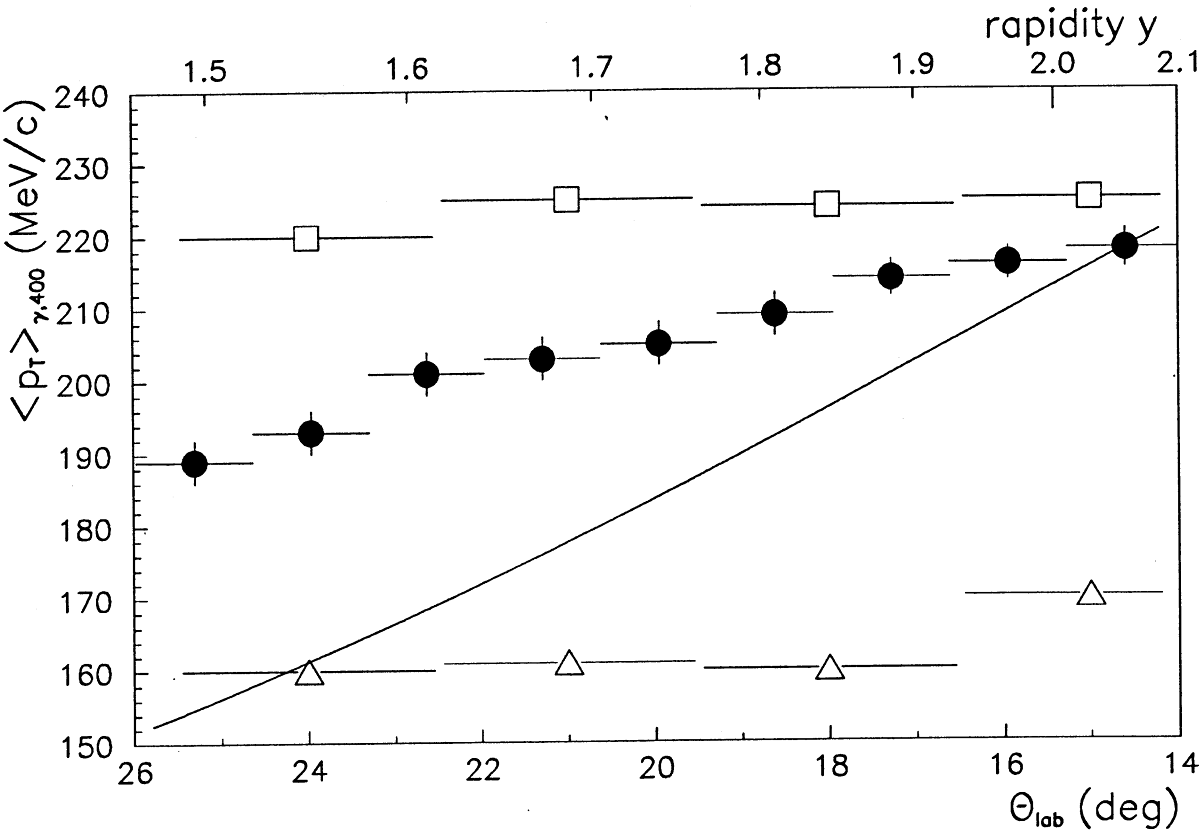

Figure 3: $\langle p_\perp \rangle_{\gamma,400}$ as a function of the rapidity y and of the laboratory angle θ_{lab} for 200A·GeV ^{16}O+Au collisions. The circles denote experimental data and the open squares (triangles) VENUS 3.07 simulations with (without) rescattering. Shown is also the prediction of an isotropic fireball model for massless particles (line plot) according to the relation $\langle p_\perp \rangle_{\gamma,400}(y) \propto 1/\cosh(y_{\mathrm{cm}} - y)$.