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Chapter 1

PARTICLE PRODUCTION IN 158-A GEV $^{208}\text{Pb} + ^{208}\text{Pb}$ COLLISIONS

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Abstract The production of neutral pions in 158-A GeV $^{208}\text{Pb} + ^{208}\text{Pb}$ collisions has been studied in the WA98 experiment. The centrality dependence of the neutral pion production 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 more than about 50 participants. The transverse mass spectrum is analyzed in terms of a

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thermal model with hydrodynamic expansion. The high accuracy and large kinematic coverage of the measurement constrains the extracted freeze-out parameters, and provides information on the freeze-out velocity profile.

Keywords: Quark Gluon Plasma, Heavy-ion collisions, Neutral pions, Particle production, Nuclear dependence, Thermalization, Freeze-out.

1. INTRODUCTION

Ultra-relativistic heavy-ion collisions provide the means to produce dense matter which at sufficiently high energy densities may undergo a phase transition from normal hadronic matter to a deconfined phase of quarks and gluons creating a Quark-Gluon Plasma (QGP). A primary goal of the ultra-relativistic heavy-ion programme is thus to identify and characterize the QGP phase transition. The classic means to search for a phase transition in condensed matter physics is to measure the heat capacity of the matter as a function of temperature, and to search for a discontinuous change in the heat capacity indicating a sudden change in the number of available degrees of freedom available to the system in the new phase. In the case of heavy-ion collisions one would like to perform the analogous measurement, which is to measure the temperature of the system as a function of the deposited energy, or energy density. Information about the temperature can be extracted from the spectral distributions of the emitted particles, while the energy density attained by the system is reflected in the amount of transverse energy or particle production. Indeed, one of the earliest signatures of QGP formation, proposed by Van Hove [1], 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 QGP phase transition had been supplied.

For these reasons it is of interest to study the centrality dependence of the particle 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 par-

ticle multiplicity or transverse energy, they should be most evident on the momentum distribution of the produced particles.

The transverse momentum spectra of produced pions can provide information on both the initial and final state properties of the hot 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 [2]) 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 scatterings and energy loss [3]. 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. In this paper we investigate in detail the centrality dependence of the neutral pion spectral shape and yields for 158-A GeV $^{208}\text{Pb}+^{208}\text{Pb}$ collisions as measured by the WA98 experiment and discuss the implications for a thermal description. Some of the results presented have been published elsewhere [4, 5].

2. THE WA98 EXPERIMENT

The CERN experiment WA98 [6] consists of large acceptance photon and hadron spectrometers together with several other large acceptance devices which allow various global measurements on an event-by-event basis. 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 minimum bias distribution ($\sigma_{min.bias} \approx 6300$ mb) is divided into various centrality classes using the transverse energy E_T measured in the MIRAC calorimeter. The impact parameter 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, N_{part} , is calculated from nuclear geometry using the extracted impact parameter. The results presented here were obtained from an analysis of the data taken with Pb beams in 1995 and 1996. In total, $\approx 9.6 \cdot 10^6$ reactions have been analyzed.

Figure 1.1 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 [8] and VENUS 4.12 [9] Monte Carlo programs. Predictions of a pQCD calculation [10] are included as a solid line. The inset shows the ratios of the results of the Monte Carlo codes to the experimental data.

3. π^0 PRODUCTION

The general π^0 analysis procedure is similar to that used in the WA80 experiment and described in [7]. 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 $p_T = 0.4 \text{ GeV}/c$. 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 $p_T = 4 \text{ GeV}/c$.

The measured neutral pion spectrum from central Pb+Pb reactions (10% of the minimum bias cross section) as a function of $m_T - m_0$ is shown in Fig. 1.1. The data are compared to predictions of the string model Monte Carlo generators FRITIOF 7.02 [8] and VENUS 4.12 [9].

As already observed in S+Au reactions [7], 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 [10], are able to describe the preliminary WA98 data at intermediate and high p_T . This prediction is included in Fig. 1.1 as a solid line. 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 [10]. 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 [11].

Figure 1.2 Truncated mean transverse momentum $\langle p_T(p_T^{min}) \rangle$ of π^0 mesons as defined by Eq. 1.1 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 [12], the open circles the results for S+Au collisions at 200 AGeV [7].

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

$$\langle p_T(p_T^{min}) \rangle = \left(\int_{p_T^{min}}^{\infty} p_T \frac{dN}{dp_T} dp_T \right) / \left(\int_{p_T^{min}}^{\infty} \frac{dN}{dp_T} dp_T \right) - p_T^{min}. \quad (1.1)$$

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.

Figure 1.2 shows $\langle p_T(p_T^{min}) \rangle$ as a function of the average number of participants N_{part} for 158-A GeV $^{208}\text{Pb}+\text{Pb}$ collisions. For comparison, $\langle p_T(p_T^{min}) \rangle$ values for 200-A GeV S+Au [7] and from a parametrization of pp data [12] are also included. 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 50 the mean transverse momentum appears to attain a limiting value of ≈ 280 MeV/c. VENUS 4.12 [9] calculations show a qualitatively similar behaviour, although the values of $\langle p_T(p_T^{min}) \rangle$ are somewhat lower than the experimental data.

Initial state multiple scattering, as suggested as explanation for the Cronin effect [2], 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.

Figure 1.3 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 a fit to 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.

More detailed information about the centrality dependence of the pion spectral shape and yield is shown in Fig. 1.3 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.

4. THERMAL FREEZEOUT

A successful thermal interpretation of relativistic heavy ion collisions must provide an accurate description of the pion spectra since pions provide the "thermal bath" of the late stages the collision. The WA98 π^0 data provide important constraints due to their accuracy and coverage in transverse mass.

The measured neutral pion cross section from central Pb+Pb reactions as a function of $m_T - m_0$ is shown in Fig. 1.1. The data have been fit with a hydrodynamical model [13] which includes transverse flow and resonance decays. This computer program calculates the direct production and the contributions from the most important resonances having two- or three-body decays including pions (ρ , K_S^0 , K^* , Δ , $\Sigma + \Lambda$, η , ω , η'). The code, originally intended for charged pions, has been adapted to predict neutral pion production. The model uses a gaussian transverse spatial density profile truncated at 4σ . The transverse flow rapidity is assumed to be a linear function of the radius. For all results presented here, a baryonic chemical potential of $\mu_B = 200$ MeV has been used. The results are not very sensitive, however, to the choice of μ_B for the $m_T - m_0$ region considered here.

This model provides an excellent description of the neutral pion spectra with a temperature $T = 185$ MeV and an average flow velocity of $\langle\beta_T\rangle = 0.213$. These values are very similar to the parameters obtained with similar fits to neutral pion spectra in central reactions of $^{32}\text{S}+\text{Au}$ [7]. The 2σ lower limit on the temperature is $T^{low} = 171$ MeV and the corresponding upper limit on the flow velocity is $\langle\beta_T^{upp}\rangle = 0.253$.

The high statistical accuracy and large transverse mass coverage of the present π^0 measurement reveals the concave curvature of the π^0 spectrum over a large m_T range, which constrains the parameters significantly. This is further demonstrated by studying the local slope at each m_T . The local (inverse) slope is given by

$$T_{local}^{-1} = - \left(E \frac{d^3\sigma}{dp^3} \right)^{-1} \frac{d}{dm_T} \left(E \frac{d^3\sigma}{dp^3} \right). \quad (1.2)$$

Figure 1.4 The local inverse slope of the transverse mass spectrum of neutral pions in central collisions of 158 AGeV Pb+Pb. The measured results (solid points) are compared to the hydrodynamical model best fit result (solid line; $T = 185$ MeV and $\langle\beta_T\rangle = 0.213$) and to the other results given in table 1.1.

The local slope results are plotted in Fig. 1.4. Each individual value of T_{local} has been extracted from 3 adjacent data points of Fig. 1.1. The data are compared to the hydrodynamical model best fit results, as well as fits in which the transverse flow velocities have been fixed to larger values comparable to those obtained by Refs. [14] and NA49 [15] (sets 2 and 3). The corresponding fit parameters are given in Table 1.1. The comparison demonstrates that while the large transverse flow velocity fits can provide a reasonable description of the data up to transverse masses of about 1 GeV, they significantly overpredict the local slopes at large transverse mass. While application of the hydrodynamical model at large transverse mass is questionable, the model cannot overpredict the measured yield. The observed overprediction therefore rules out the assumption of large transverse flow velocities, or points to a deficiency in the model assumptions used in these fits.

The curvature in the π^0 spectrum at large transverse mass is a result of the distribution of transverse velocities. Although the spectrum is not directly sensitive to the spatial distribution of particle emission, within this model it is dependent indirectly on the spatial distribution due to the assumption that the transverse rapidity increases linearly with radius. The large curvature at large transverse mass is due to high velocity contributions which result from the tail of the assumed gaussian density profile [16]. Figure 1.5 shows the transverse source velocity distributions $dN/dy(\beta)$ for the different parameter sets. The curves labelled 1-3 correspond to the calculations in figure 1.4 using a

Figure 1.5 Unnormalized multiplicity distributions as a function of the transverse source velocity for the parameter sets given in table 1.1.

gaussian spatial profile. In addition, velocity profiles are shown for a uniform density profile (set 4) and for a Woods-Saxon distribution:

$$\rho(r) = \frac{1}{1 + \exp[(r - r_0)/\Delta]} \quad (1.3)$$

with $\Delta/r_0 = 0.02$ (set 5). These are included in figures 1.4 and 1.5. It is seen that the uniform density assumption truncates the high velocity tail resulting in less curvature in the pion spectrum, while the Woods-Saxon has a more diffuse edge at high β .

Table 1.1 Parameters for different hydrodynamical model fits to the neutral pion spectrum shown in figures 1.4 and 1.5. The temperature T , average and RMS transverse flow velocity $\langle\beta_T\rangle$ and β_{RMS} are given together with the effective temperature $T_{eff} = T/\sqrt{(1 - \langle\beta_T\rangle)/(1 + \langle\beta_T\rangle)}$.

Set	spatial profile	T (MeV)	$\langle\beta_T\rangle$	β_{RMS}	T_{eff} (MeV)	χ^2/dof
1	Gauss	185 \pm 4	0.213 \pm 0.020	0.107	230	25.9/18
2	Gauss	75 \pm 1	0.469	0.199	125	386/19
3	Gauss	49 \pm 1	0.527	0.213	88	578/19
4	Uniform	178 \pm 13	0.274 \pm 0.046	0.093	235	33.3/18
5	WS	146 $^{+21}_{-16}$	0.365 $^{+0.056}_{-0.069}$	0.137	214	26.7/18

While the gaussian and uniform density assumptions have very different velocity profiles, it is interesting that both can provide acceptable fits to the pion spectrum with best fit results with similar $\langle\beta_T\rangle$ and T parameters, which give similar effective temperatures, and which have

similar velocity widths, β_{RMS} , as shown in Table 1.1. Compared to the gaussian profile result, the best fit result using the uniform profile gives a lower temperature of 178 MeV and would lead to weaker limits of $\langle\beta_T^{upp}\rangle = 0.42$ and $T^{low} = 134$ MeV. However, using the Woods-Saxon profile similar limits cannot be obtained. The best fit using data for $m_T - m_0 > 2 \text{ GeV}/c^2$ only as upper limits is obtained with $T = 129$ MeV and $\langle\beta_T\rangle = 0.42$.

The data presented here can be well described with high thermal freeze-out temperatures similar to temperatures which have been extracted for chemical freeze-out [17] and small transverse flow velocities. On the other hand, if the larger velocities obtained in other analyses which have considered limited particle spectra together with HBT results [14, 15, 18] persist, the present data obviously provide important information on the shape of the freeze-out velocity distribution.

5. 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 50 participating nucleons, the shape of the transverse momentum spectrum becomes invariant over the interval $0.5 < p_T < 3 \text{ GeV}/c$. 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.

We have argued that hydrodynamical models which attempt to extract the thermal freeze-out parameters of relativistic heavy ion collisions must provide an accurate description of the pion spectra, since pions most directly reflect the thermal environment in the late stage of the collision. In particular, models, or parameter sets, which overpredict the observed pion yields, even at large transverse mass, can immediately be ruled out. We have demonstrated that the high accuracy neutral pion spectra with large transverse mass coverage can constrain the thermal freeze-out parameters and model assumptions. Within the context of the hydrodynamical model of Ref. [13], only special choices of the velocity profile allow freeze-out parameters similar to those extracted from other recent analyses which consider also HBT results [14, 15, 18]. Other pro-

files favor large thermal freeze-out temperatures consistent with chemical freeze-out temperatures determined for the same system [17].

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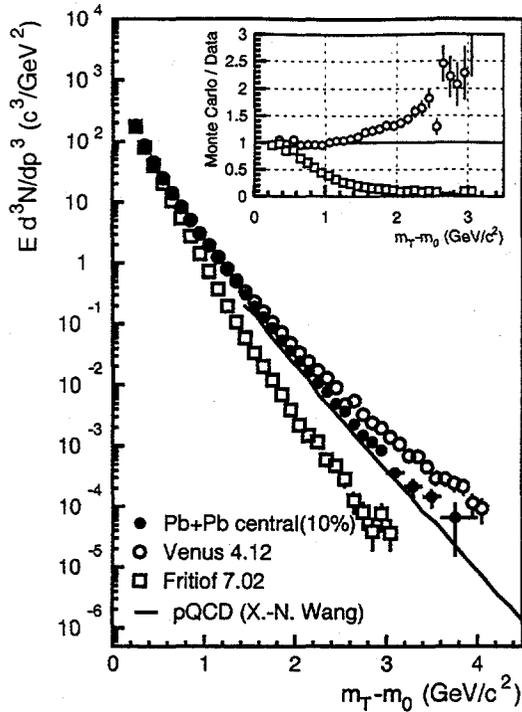


FIG. 1. Transverse mass spectra of neutral pions in central collisions of 158 AGeV Pb+Pb. Invariant yields per event are compared to calculations using the FRITIOF 7.02 [?] and VENUS 4.12 [?] Monte Carlo programs. Predictions of a pQCD calculation [?] are included as a solid line. The inset shows the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

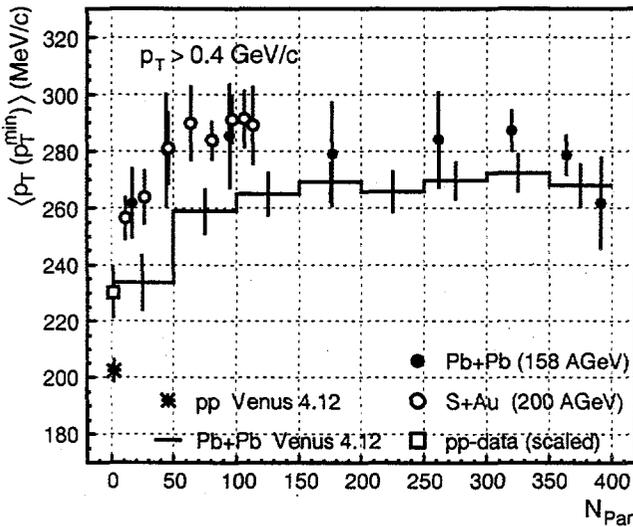


FIG. 2. Truncated mean transverse momentum $\langle p_T(p_T^{min}) \rangle$ of π^0 mesons as defined by Eq. ?? plotted as a function of the average number of participants N_{part} . The solid circles correspond to the $8 E_T$ based centrality selections for Pb+Pb. The open square shows $\langle p_T(p_T^{min})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

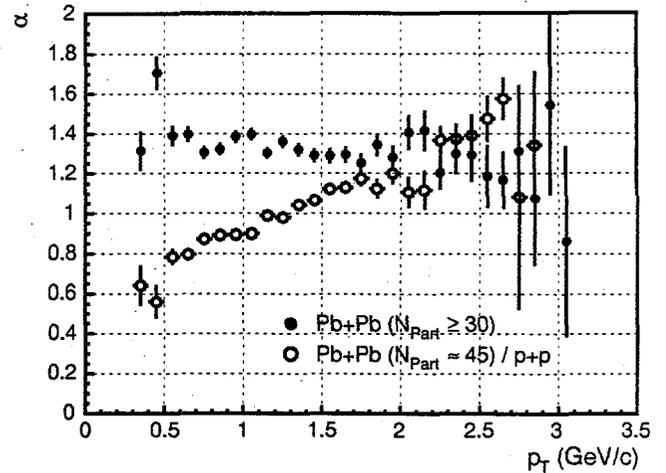


FIG. 3. The exponent $\alpha(p_T)$ of the dependence of the π^0 yield on the average number of participants N_{part} plotted as a function of the transverse momentum for 158 AGeV Pb+Pb. The solid circles are calculated based on a fit to the centrality selections with $N_{part} \ge 30$. The open circles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

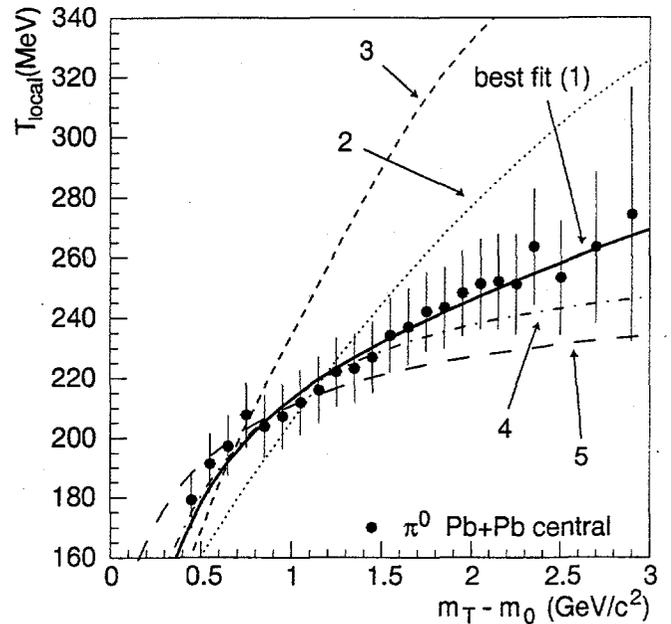


FIG. 4. The local inverse slope of the transverse mass spectrum of neutral pions in central collisions of 158 AGeV Pb+Pb. The measured results (solid points) are compared to the hydrodynamical model best fit result (solid line; $T = 185$ MeV and $\langle \beta_T \rangle = 0.213$) and to the other results given in table ??.

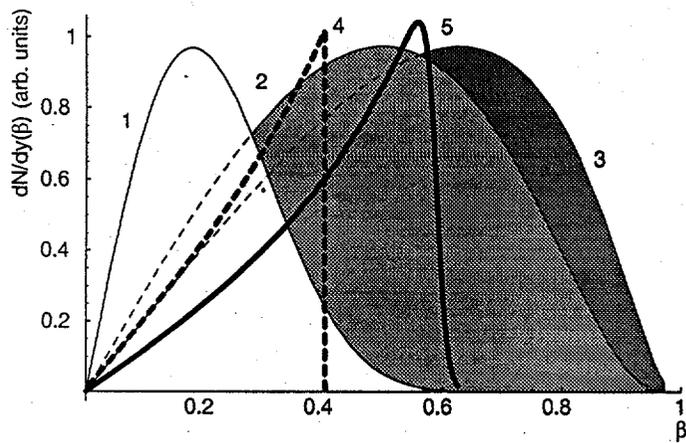


FIG. 5. Unnormalized multiplicity distributions as a function of the transverse source velocity for the parameter sets given in table ??.