

Pion Interferometry: Recent results from SPS

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Abstract

Recent HBT results from the CERES experiment at the SPS are reviewed. Emphasis is put on the centrality and beam energy dependence, and the results are put into perspective with results at lower and higher beam energies. The rather weak beam energy dependence of the HBT radii may be understood in terms of a transition from baryon to pion dominated freeze-out. The observed short lifetimes and emission durations are presently in contradiction to results from model calculations.

1 Introduction

While single particle momentum distributions give only indirect insight to the space-time evolution of the system created in high energy heavy ion collisions, the lifetime and the spatial extent of the pion source as well as the existence of collective velocity fields at the time of thermal freezeout can be probed by the study of Bose-Einstein momentum correlations of identical pions via HBT interferometry [1]. The width of the correlation peak at vanishing relative momenta reflects the so-called length of homogeneity of the pion emitting source. Only in static sources can the length of homogeneity, in the following also called 'source radius', be interpreted as the true geometrical size of the system. In a dynamic system, the occurrence of space-momentum correlations of the emitted particles due to collective expansion generally leads to a reduction of the observed source radii, depending on the strength of the expansion and the thermal velocity of the pions $\sqrt{T_f/m_t}$ at thermal freeze-out [2]. A differential analysis of the HBT correlations in bins of the pair transverse momentum $k_t = \frac{1}{2}|p_{t,1} + p_{t,2}|$ thus provides valuable information about the properties of the collective expansion of the system [3].

To obtain most detailed information about the space-time evolution the three-momentum difference vector \vec{q} of two like-sign pions is decomposed into components, $\vec{q} = (q_{\text{long}}, q_{\text{side}}, q_{\text{out}})$. Following Bertsch and Pratt [4], q_{long} is the momentum difference along the beam direction, calculated in the longitudinal

rest frame (LCMS) of the pair, q_{out} is parallel to the pair transverse momentum \vec{k}_t and q_{side} is perpendicular to q_{long} and q_{out} .

The correlation function is defined as the ratio $C_2(\vec{q})=A_2(\vec{q})/B_2(\vec{q})$ where the 'signal' $A_2(\vec{q})$ is the probability to find a pair with momentum difference \vec{q} in a given event and the 'background' $B_2(\vec{q})$ is the corresponding mixed-event distribution.

The normalized correlation functions are fit by a Gaussian:

$$C_2(\vec{q}) = 1 + \lambda \exp(-R_{\text{long}}^2 q_{\text{long}}^2 - R_{\text{side}}^2 q_{\text{side}}^2 - R_{\text{out}}^2 q_{\text{out}}^2 - 2R_{\text{outlong}}^2 q_{\text{out}} q_{\text{long}}), \quad (1)$$

with R_{long} , R_{side} , R_{out} being the Gaussian source radii and λ the correlation strength. The cross-term R_{outlong}^2 appears as a consequence of space-time correlations in non-boost-invariant systems.

2 Results from SPS

Pion HBT interferometry analyses have been performed by a number of experiments at SPS [5, 6, 7, 8]. A systematic study of the centrality dependence of HBT radii around midrapidity from Pb+Au collisions at all three presently available SPS energies, 40, 80, and 158 AGeV, was recently presented by the CERES collaboration [9]. Details of their analysis can be found in [10].

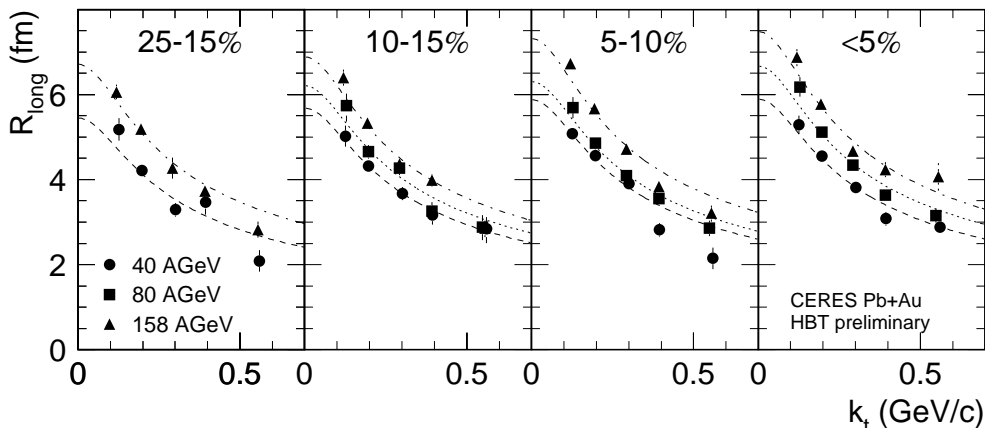


Fig. 1: R_{long} vs. k_t [10]. The lines represent fits to the data (see text).

The k_t -dependence of the longitudinal source parameter R_{long} is shown in Fig. 1 for the three different beam energies and as function of the centrality of the collision. Similar to previous studies, a strong decrease of R_{long} with k_t is observed, characteristic for a strong collective longitudinal expansion,

where the length of homogeneity is entirely saturated by the thermal length scale $\sim \sqrt{T_f/m_t}$. For the case of longitudinal boost-invariance, R_{long} can be connected to the lifetime τ_s of the system, the time elapsed between the onset of expansion and kinetic freeze-out by $R_{\text{long}} = \tau_s (T_f/m_t)^{1/2}$ [2].

The slight but systematic overall increase of R_{long} with centrality and beam energy is reflected in a correspondingly longer lifetime when applying the above expression to the data and assuming $T_f = 120$ MeV (see fits in Fig. 1). The observed lifetimes at the SPS are 6-8 fm/c.

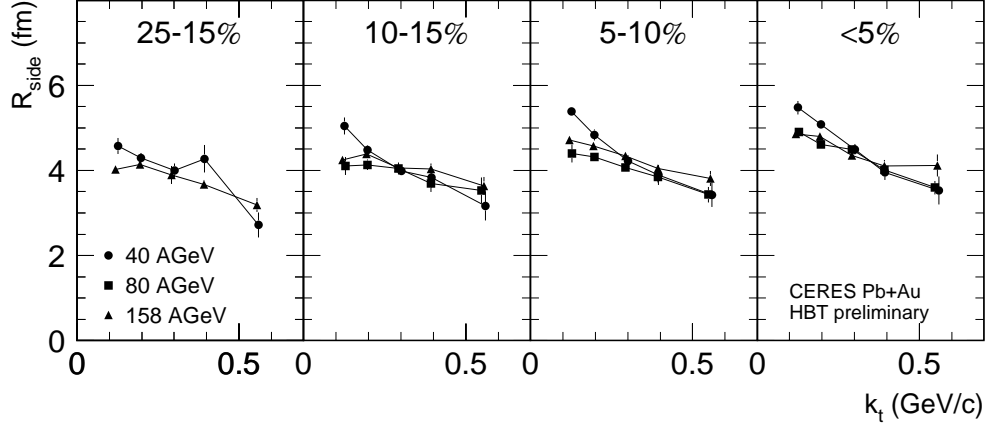


Fig. 2: R_{side} vs. k_t [10].

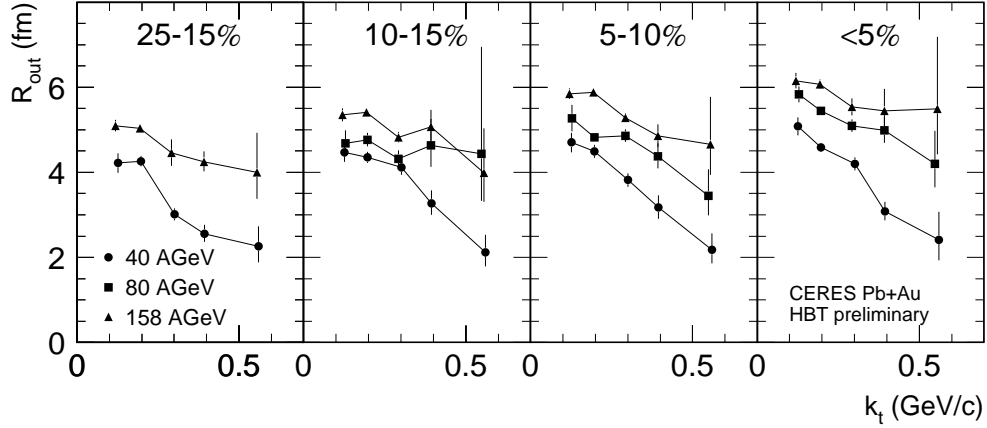


Fig. 3: R_{out} vs. k_t [10].

The transverse source parameter R_{side} is closely related to the *true* geometrical transverse extension of the system at freeze-out. Consequently, a weaker k_t -dependence is observed for R_{side} (Fig. 2), indicating the presence of radial flow. A slight but systematic increase of R_{side} with centrality is measured at all

beam energies, as expected from simple collision geometry. The beam energy dependence is surprising: largest R_{side} and the strongest k_t -dependence are observed at the lowest energy. This led previously to the conclusion that radial flow may reach a maximum at the lower SPS energies [11]. We will discuss below that the extraction of the radial flow velocity from the k_t -dependence of R_{side} at the lower SPS energies might be questionable. At 158 AGeV, a radial flow velocity of about $0.5c$ was obtained from the analysis of single particle m_t -spectra and $R_{\text{side}}(k_t)$ [5, 12].

Many authors have discussed that a strong first order phase transition with a large latent heat can lead to a retardation of hadronization during the mixed phase and consequently to a long duration of pion emission [4, 13, 14, 15, 16]. This should be observable via a strong increase of the outward source parameter R_{out} with respect to R_{side} . However, no long-lived source has been observed so far. At SPS, R_{out} (Fig. 3) is similar to R_{side} , indicating a short pion emission duration and a sudden freeze-out.

3 Beam energy dependence

A large amount of pion interferometry data have been published by experiments at AGS, SPS, and RHIC. This allows for a systematic study of the source parameters over a wide range of beam energies. It has been argued that the *HBT null effect* [17], the absence of any beam energy dependence, in particular when going to RHIC, is the actual surprising result from HBT interferometry.

In Fig. 4 are shown the k_t -dependences of R_{long} , R_{side} , and R_{out} in central Pb(Aa)+Pb(Au) collisions at different beam energies [18, 10, 19]. Indeed, no dramatic variation of any of the source parameters can be observed. However, a closer inspection reveals some interesting features. R_{long} is approximately constant from AGS to the lower SPS energies, but develops a significant increase within the SPS regime and towards RHIC, indicating a smooth increase of the lifetime.

Most interesting is the behaviour of R_{side} : It is gradually *decreasing* at small k_t up to top SPS energy, connected with a continuous *flattening* of the k_t -dependence. At RHIC, R_{side} is again larger than at SPS while the shape is not yet well measured, at least the $\pi^-\pi^-$ sample looks rather flat. Naively, the flattening indicates a *decrease* of the radial flow velocity as function of beam energy, in contradiction to the present understanding [20].

R_{out} shows a rather weak energy dependence, possibly indicating a shallow minimum at the lower SPS energy.

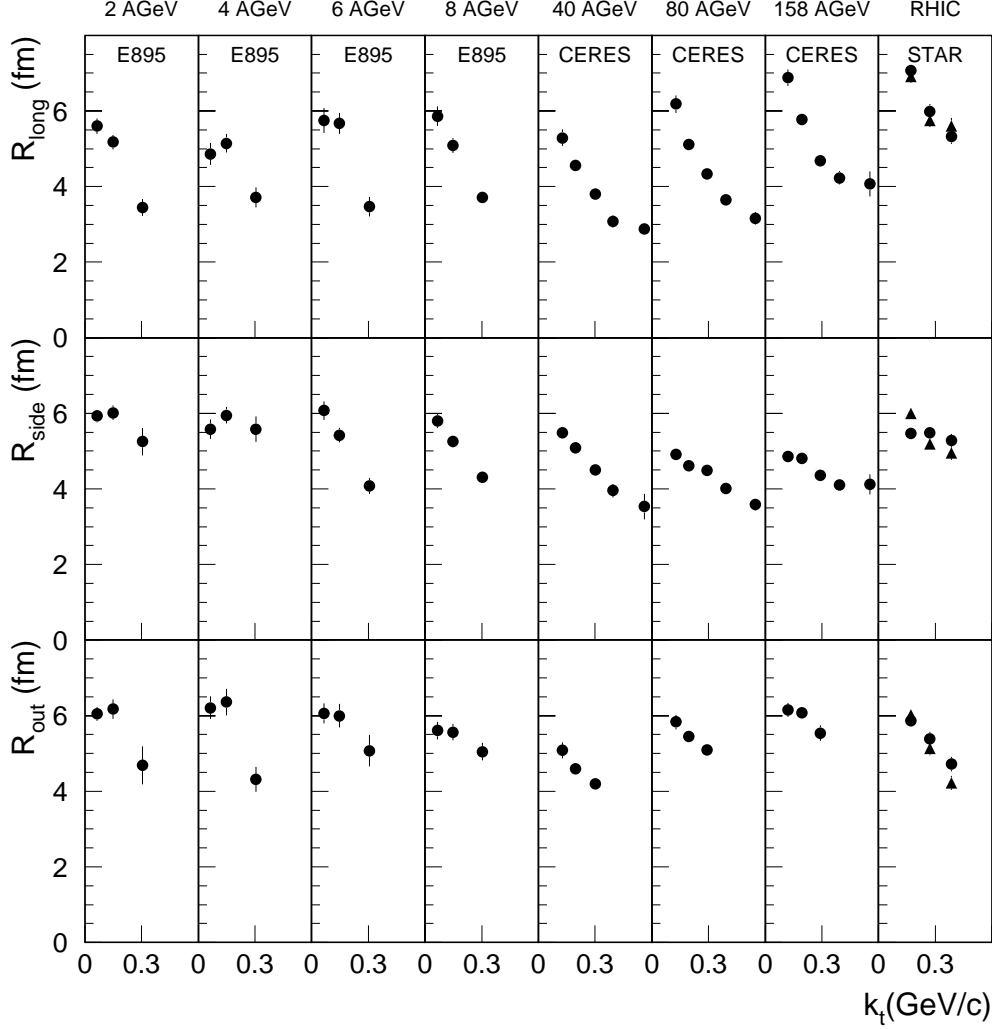


Fig. 4: k_t -dependence of HBT radii around midrapidity in central Pb(Au)+Pb(Au) collisions at different beam energies. The data are from [18, 10, 19].

A straight-forward investigation of the freeze-out properties can be performed by relating the measured source parameters to an effective freeze-out volume, $V_f = 2\pi R_{\text{long}} R_{\text{side}}^2$. Assuming freeze-out at constant density [21], we expect V_f to scale linearly with the charged particle multiplicity. Fig. 5 shows V_f as function of the number of participants at 40, 80, and 158 AGeV. A linear scaling with N_{part} is indeed observed at all three energies, consistent with the assumption of a constant freeze-out density, since the number of charged particles was found to scale close to linear with N_{part} at SPS [22].

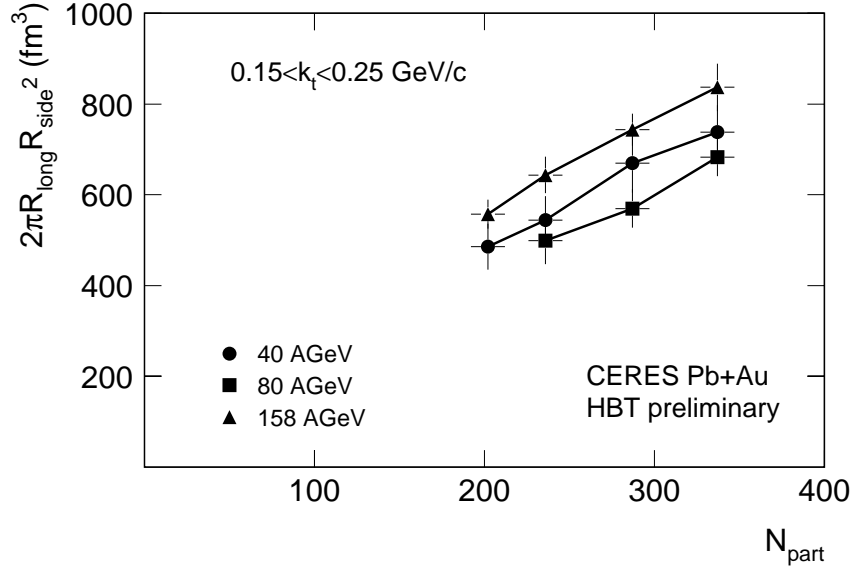


Fig. 5: V_f as function of N_{part} at different SPS energies [10].

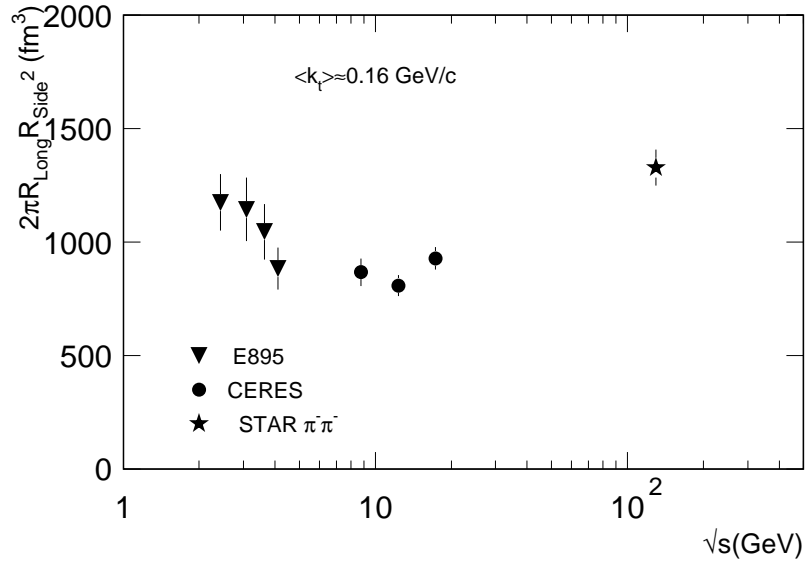


Fig. 6: V_f in central Pb(Au)+Pb(Au) collisions as function of \sqrt{s} (see text). E895 points are at $\langle k_t \rangle = 0.15$ GeV/c [18], STAR is at $\langle k_t \rangle = 0.17$ GeV/c [19], CERES points are the average of their bins at $\langle k_t \rangle = 0.12$ and $\langle k_t \rangle = 0.2$ GeV/c [10].

But the beam energy dependence is surprising: There is no clear hierarchy visible in Fig. 5 as expected from the increase of multiplicity by about 50% between 40 AGeV and 158 AGeV; the smallest V_f are observed at 80 AGeV. Obviously, the freeze-out volume scales with multiplicity as long as multiplicity

is controlled via centrality, but it does not scale accordingly as multiplicity changes with beam energy.

The comparison of V_f at different beam energies from AGS to RHIC sheds some light on this: The freeze-out volume V_f is gradually decreasing within the AGS energy range, reaches a minimum at SPS and then increases towards RHIC, as demonstrated in Fig. 6.

Clearly, a simple relation between multiplicity and freeze-out volume cannot hold. On the other hand, it is plausible to assume that at low energies pions interact mainly with nucleons, while at high energies pion-pion scattering dominates. Is the transition from nucleon to pion dominated freeze-out characterized by a minimum in V_f at SPS?

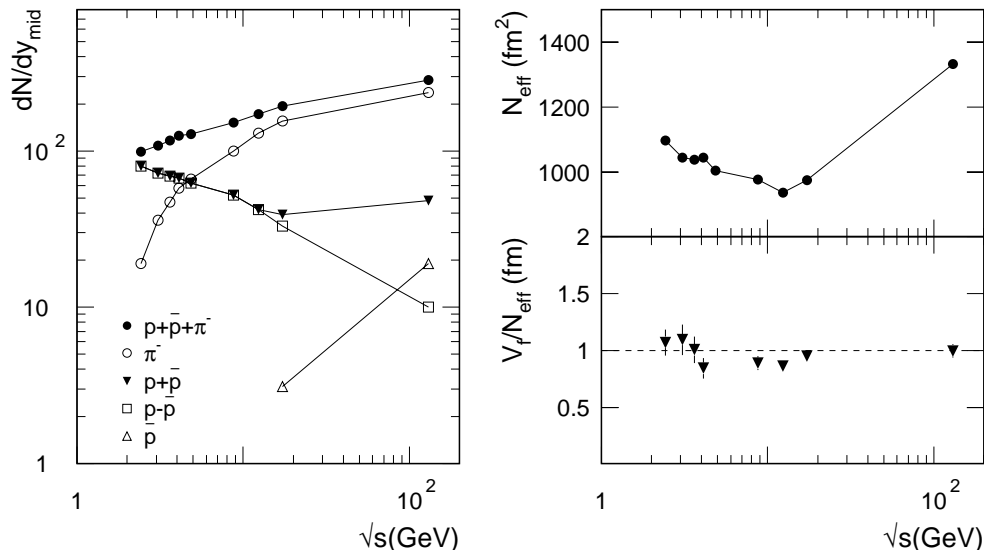


Fig. 7: Left: Midrapidity yields of different particles vs. \sqrt{s} . Upper right: cross section weighted sum of particle yields (see text). Lower right: ratio V_f/N_{eff} vs. \sqrt{s} .

In Fig. 7 (left) the midrapidity density of pions [23, 24, 25, 26] and protons [27, 28, 11, 29, 30, 31] in central Pb(Au)+Pb(Au) collisions is shown as function of \sqrt{s} . The pion yield increases monotonically with beam energy. The *total* proton ($p+\bar{p}$) yield at midrapidity drops from AGS to SPS and stays approximately constant between SPS and RHIC because the decreasing number of net protons is compensated by $p-\bar{p}$ production. The sum of pions and protons, however, is still a monotonic function of \sqrt{s} .

At this point, the different cross sections $\sigma_{\pi\pi}$ and $\sigma_{\pi N}$ have to be considered. In Fig. 7 (upper right) the cross section weighted sum of pions and protons $N_{eff}=2 \cdot N_{p+\bar{p}} \cdot \sigma_{\pi N} + 3 \cdot N_{\pi^-} \cdot \sigma_{\pi\pi}$ is shown ¹. For the cross sections $\sigma_{\pi\pi}=10$ mb

¹Note that there are a few simplifications: the protons are multiplied by 2 to account for

and $\sigma_{\pi N}=65$ mb are assumed. Indeed, the cross section weighted sum of pions and nucleons at midrapidity is *non*-monotonic and exhibits a minimum at SPS. As a consequence, the ratio V_f/N_{eff} , which has the dimension of a length, is approximately constant (Fig. 7, lower right). This result suggests $V_f/N_{\text{eff}}\approx 1$ fm as a universal freeze-out condition.

In this picture, the relatively weak beam energy dependence of HBT source parameters can be understood as an interplay between the decreasing (and eventually levelling off) $(p+\bar{p})$ yield and the increasing pion multiplicity at midrapidity, if their different cross sections with pions are taken into account. It is interesting to obtain a detailed understanding of the role of protons for pion freeze-out at low energies. The strong momentum dependence of the $\sigma_{\pi N}$ cross section may affect the k_t -dependence of R_{side} at low beam energies and cause the flattening of the k_t -dependence with increasing beam energy, as the importance of protons ceases. At the lower SPS energies, where protons are still important, the interpretation of the k_t -dependence of R_{side} in terms of radial flow may be questionable, and possibly breaks down at AGS.

4 Discussion

Single particle spectra and azimuthal anisotropies at SPS and RHIC have been well reproduced by state-of-the-art hydro+cascade calculations [32, 33, 34]. However, they fail to reproduce the measured HBT parameters, in particular the lifetime of the system is grossly overestimated.

In these models, the early plasma phase is described by hydrodynamics assuming an ideal plasma EOS with a first order phase transition and a mixed phase with an adjustable latent heat. At the end of the mixed phase, hadrons are created assuming a thermal phase space population superimposed by the collective velocity field created by the plasma pressure. After hadronization, hadrons are rescattered using a hadronic cascade code.

In [35] the response of the hydro+cascade calculation to different choices of the latent heat is well documented. From this investigation, it becomes obvious that the choice of a relatively large latent heat of 0.8 GeV/fm³, needed to describe the SPS single particle data, is mainly driven by the observed mass dependence of the inverse slope parameters. Smaller latent heat produces larger flow velocities *before* hadronization and therefore too hard spectra, in particular for the multi-strange baryons which do not follow the linear scaling behaviour observed for π , K, p [36]. On the other hand, a small latent heat

the neutrons, which is not completely correct for the lowest beam energies. Also the role of light nuclei and other produced particles is neglected.

would lead to an early acceleration of the matter and therefore to a faster dilution and shorter lifetime, in particular of the hadronic phase, which is suggested by the HBT measurements.

This leads to a closer inspection of the data as represented in Fig. 8 (left). For some of the particle species, the observed inverse slope parameter scales linearly with the particle mass, consistent with the assumption of a common flow velocity. There are, however, a number of exceptions which do not follow this rule (ϕ , Ξ , Ω). This was explained by their small cross sections with the surrounding matter, hence they are expected to participate less in the collective motion.

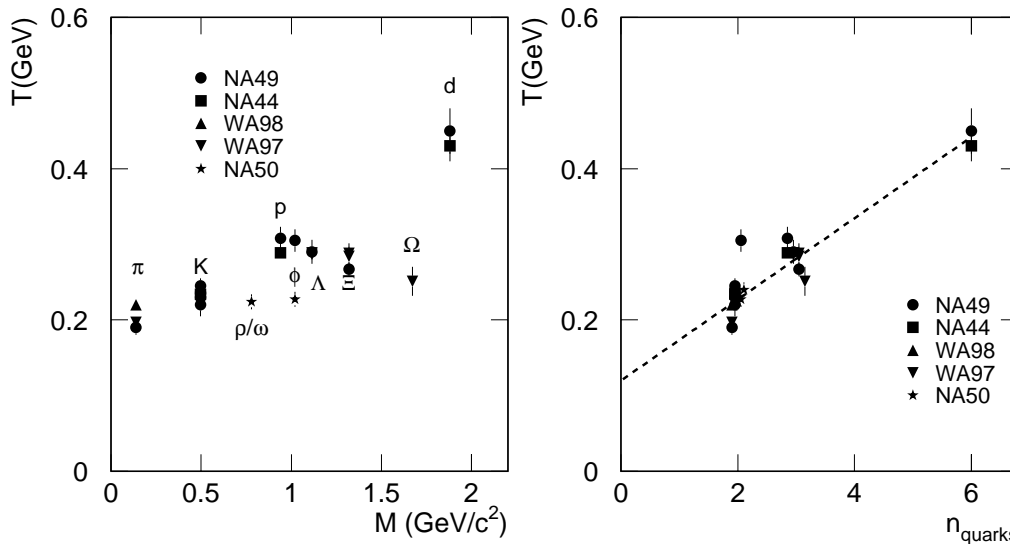


Fig. 8: Left: Inverse slope parameter vs. mass of hadrons at SPS. Right: Inverse slope parameter vs. number of constituent quarks.

On the other hand, it is evident that the data separate into two groups: All mesons have similar slopes, and the same is true for baryons. One may therefore as well correlate the inverse slope with the number of constituent quarks inside the hadron, rather than with the hadron mass (Fig. 8, right). Also here a scaling behaviour can be observed, and almost all particles are consistent with this trend. Note that the large inverse slope of the ϕ observed by NA49 [37] is experimentally still under debate, since there is also a measurement by NA50 [38], giving a much smaller number.

The physical picture which arises from this representation is different from the common interpretation: collective motion has completely developed *before* hadronization, with constituent quarks being the flowing objects. Hadrons are formed by coalescence of constituent quarks, preferentially if they are close

in phase space, thereby adding their momenta. When hadrons acquire mass, momentum is conserved which leaves the momentum spectra unchanged. In this picture, the data are consistent with a kinetic freeze-out temperature of 0.12 GeV, a collective quark flow velocity of $\sqrt{1/3}$ and an effective quark mass of 0.33 GeV: $T=0.12 + \frac{1}{2} \frac{1}{3} \cdot 0.33 \cdot n_{\text{quarks}}$ (dashed line in Fig. 8, right). Most of the explosive power of the system would be assigned to the early, pre-hadronic phase of the collision, thereby qualitatively explaining the short lifetimes observed by HBT. It also suggests that the hadronic mass scale is no more relevant in the early phase of the collision, as naively expected for a deconfined partonic system.

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