CHARGED HADRON SPECTRA AND CORRELATIONS IN HEAVY ION COLLISIONS AT CERN: RESULTS FROM EXPERIMENT NA44

JEREMY DODD
Nevis Laboratories, Columbia University,
P.O. Box 137, Irvington, NY 10533, USA.
E-mail: dodd@nevis.columbia.edu

for the

NA44 COLLABORATION
H. Bøggild, J. Boissevain, J. Dodd, B. Erazmus, S. Esumi, C.W. Fabjan, D. Ferenc, D.E. Fields, A. Franz, J.J. Gaardhøje, O. Hansen, D. Hardtke, H. van Hecke, E.B. Holzer, T. Humanic, P. Hummel, B.V. Jacak, R. Jayanti, M. Kaneta, M. Kopytine, M. Leltchouk, T. Ljubicic, B. Lörstad, N. Maeda, A. Medvedev, M. Murray, S. Nishimura, H. Ohnishi, G. Paic, S.U. Pandey, F. Piuz, J. Pluta, V. Polychronakos, M. Potekhin, G. Poulard, A. Sakaguchi, J. Simon-Gillo, J. Schmidt-Sorensen, W. Sondheim, M. Spegel, T. Sugitate, J.P. Sullivan, Y. Sumi, W.J. Willis, K. Wolf, N. Xu, and D. Zachary.
NBI, LANL, Columbia, Nantes, Hiroshima, CERN,
Zagreb, OSU, Vienna, Lund, Texas A&M, BNL.

ABSTRACT

NA44 has measured single particle inclusive spectra and two-particle correlations of hadrons produced near midrapidity in a wide range of nuclear collisions from pBe to PbPb.
Transverse mass distributions of pions, kaons, protons, antiprotons and deuterons are presented. A clear increase in the inverse slope parameters of these spectra is observed for the heavier particles as the size of the collision system increases, which may signal the existence of transverse flow.
Two-pion and two-kaon correlations have been measured in both proton-nucleus and nucleus-nucleus collisions. High statistics data sets allow multidimensional fits of the two-particle correlation functions. The pion source parameters are large compared to the projectile radius, and larger than the kaon source parameters from the same system. We observe a common $1/\sqrt{m_T}$ dependence for pions and kaons, indicating the presence of collective expansion.
New results from the first Pb beam run at CERN are presented. Transverse mass distributions for pions, kaons and protons, and the proton yield at midrapidity are shown, along with two-pion correlations from PbPb collisions.

1. The NA44 Experiment

The NA44 detector is described in [1]. The spectrometer is optimised to measure single- and two-particle distributions of charged hadrons produced near midrapidity over a wide p_T range: $0.0 \leq p_T \leq 1.5$ GeV/c. This coverage is provided by operating the spectrometer in two angular settings, at 44 and 131 mrad with respect to the incident beam. Scintillator hodoscopes are used for tracking, and also provide time-of-flight information with $\sigma_{\rm TOF} < 100$ ps. The momentum resolution $\delta p/p$ is approximately 0.2%. Two threshold Cherenkov detectors in conjunction with the time-of-flight information provide particle identification. In all cases, particle contamination is less than 5%, and for most of the data presented here, it is less than 1%. An interaction (and centrality) trigger is provided by 2 rectangular scintillator paddles sitting downstream of the target and covering approximately $1.3 < \eta < 3.5$. Offline, a silicon pad multiplicity detector with 2π azimuthal coverage over the range $1.5 < \eta < 3.3$ is used for event characterisation.

For the Pb era, starting in November 1994, the detector was upgraded to provide improved tracking (new pad and strip chambers) and improved particle identification (two new Cherenkov counters).

2. Single Particle Spectra

Single particle inclusive spectra and particle yields provide information about the dynamics of heavy ion collisions. The degree of nuclear stopping, rescattering, and possible collective effects such as flow, can all be addressed, and the applicability of thermodynamical descriptions tested.

NA44 has measured single particle distributions for a variety of collision systems, from pBe to PbPb. For the pA data, events are triggered by requiring a track candidate in the spectrometer arm and at least one charged particle in the downstream scintillators. In the case of the AA data, an additional centrality requirement is made on the downstream scintillator: for the SS data, this corresponds to approximately the 10% most central interactions, while for SPb and PbPb, it is $\sim 15\%$.

Figure 1 shows the invariant cross-section for π^+, K^+, p and $\bar{p}$ as a function of $m_T - m$ ($m_T = \sqrt{p_T^2 + m^2}$) in central SPb collisions. In each case, the data are close to midrapidity ($y_{NN} \sim 3$). The distributions have been corrected for geometrical acceptance, momentum resolution, reconstruction efficiency and decays in flight (pions and kaons). The data can be reasonably well-described by exponentials in m_T: shown are the results of fits to a single exponential of the form $Ce^{-\frac{m_T}{T}}$. There is a clear increase of the inverse slope with particle mass. Extracting the inverse slope parameters from these fits yields values of 156$\pm$8 MeV for π^+, 206$\pm$6 MeV for K^+, 242$\pm$3 MeV for protons, and 215$\pm$6 MeV for antiprotons. The errors are statistical only. Systematic errors are under study and currently estimated to be less than 15%. Both the spectral shapes and inverse slopes are in good agreement with those predicted by the RQMD(1.08) event generator[2] (with ropes), for which events are generated with approximately the same impact parameter distribution as the data.

Figure 2 shows the inverse slopes as a function of collision system. For the pA data, no dependence on the size of the target nucleus is observed. By contrast, the inverse slopes for AA collisions increase with particle mass and system size, illustrating the

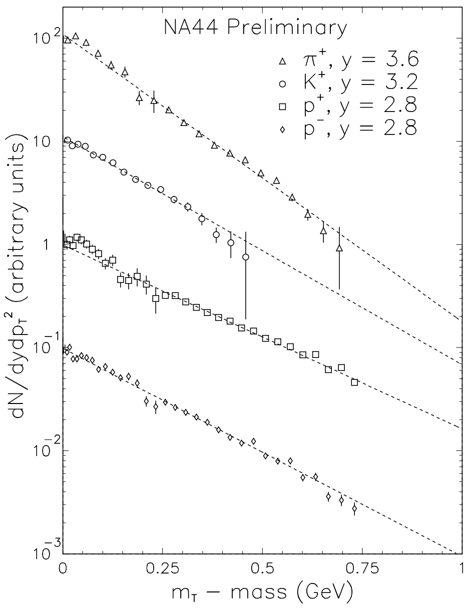

Figure 1: Invariant cross-section (arbitrary units) as a function of m_T - m for π^+, K^+, p and $\bar{p}$ in central SPb collisions. Errors are statistical only.

importance of rescattering in the heavy systems.

Results on deuteron and antideuteron production in NA44 have recently become available[3], allowing us to extend the study of transverse mass spectra to heavier particles. Figure 3 shows the deuteron spectrum measured in central SPb collisions, alongside those for π^+, K^+, and protons. An exponential fit to the data yields an inverse slope of 349±47 MeV (statistical error only). The increase of the inverse slope with particle mass noted above is clearly confirmed in the deuteron spectrum.

Such behaviour suggests that there may be significant transverse expansion in the nucleus-nucleus collisions. Given this trend, it is natural to study the data in the context of a thermal model. Schnedermann et al. have developed such a model[4] incorporating longitudinal and transverse flow. The computed transverse mass spectrum has the form:

$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T I_0 \left(\frac{p_T \sinh(\rho)}{T_{fo}}\right) K_1 \left(\frac{m_T \cosh(\rho)}{T_{fo}}\right) \tag{1}$$

where $\rho = \tanh^{-1}\beta_r$, $\beta_r(r) = \beta_s \left(\frac{r}{R}\right)^n$ with $n = 1$, and I_0, K_1 are modified Bessel functions. This then determines the shape of the m_T spectra in terms of two parameters: the freezeout temperature T_{fo} and the surface velocity β_s. Figure 3 shows the result of fitting the NA44 data to (1), yielding T_{fo} = 140 MeV and $\beta_s = 0.42c$. The data are consistent with the existence of transverse flow, however it must be noted that there are many different pairs (T_{fo}, β_s) which fit the data. A similar fit has been performed to the SS and PbPb data, which for T_{fo} = 140 MeV, yield $\beta_s = 0.4c$ and

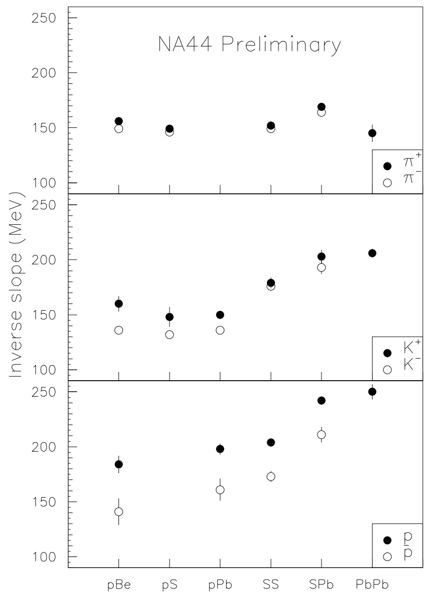

Figure 2: Inverse slopes as a function of collision system. Slopes are fit over the range $p_T < 800$ MeV/c. Systematic errors on the absolute values are $\pm$ 15%, relative errors within one particle type are smaller.

$0.5c$ respectively.

Interpreting the increased inverse slopes from the heavy systems as an indication of larger transverse flow raises the question of the degree of nuclear stopping, and hence the fraction of the initial kinetic energy which is converted into excitation of the system, in these collisions. Figure 4 shows the proton rapidity distribution (preliminary) in semi-central PbPb collisions, where the shaded circles are measured data, and open circles are the same data points reflected about $y_{mid} = 2.9$. We observe a large proton rapidity density around midrapidity, indicating that there is a high degree of stopping of the target and projectile nucleons in truly heavy ion collisions at these energies. The figure also shows predictions from the RQMD and Lund (FRITIOF)[5] models, calculated for the same centrality range as the data. Contributions to the proton yield from λ and other unstable particle decays are included in the RQMD calculations. Simulations indicate that at midrapidity, $67 \pm 9\%$ of protons from λ decay are accepted in the NA44 spectrometer. Within current errors, the data tend to favour the higher stopping prediction of RQMD, which is a result of multiple rescattering of secondary particles produced in the collision.

3. Two-Particle Correlations

Two-particle correlation functions are used to study the space-time extent of an emitting source. In the case of heavy ion collisions, such correlations are typically

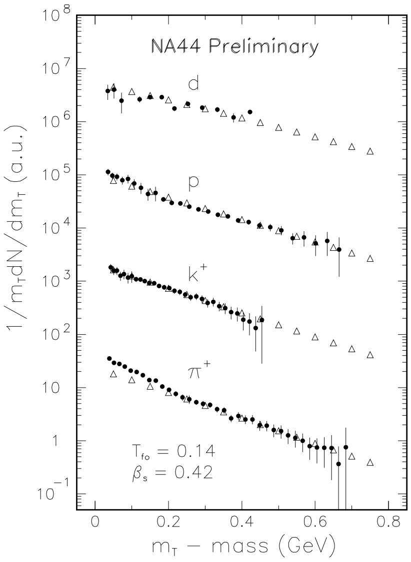

Figure 3: Invariant cross-section (arbitrary units) for π^+, K^+, p and d in central SPb collisions (shaded circles). Also shown (open triangles) are the results of fitting to (1).

used to measure the distribution of hadrons at the point of last interaction, or "freeze-out". The parameters extracted from the correlation functions can, in addition to characterising the collision, signal a transition to a deconfined state, since they measure the duration of particle emission, which is expected to be long in both a first- and second-order phase transition[6].

NA44 has measured correlations of charged pions and kaons produced close to midrapidity in both pA and AA collisions. The analysis follows the method employed by Hanbury-Brown and Twiss[7] to measure the size of stellar objects via two-photon interferometry. Correlation functions in relative momentum space are constructed from the ratio of the two-particle cross-section to the product of the individual single particle cross-sections, evaluted using particles taken from different events. Under the assumptions of a chaotic source of non-interacting bosons, and with no kinematic correlations, the measured correlation function then represents the Fourier transform of the particle distribution inside the emitting source.

Experimentally, the data are corrected for the momentum resolution of the spectrometer and the two-particle acceptance[1]. Distortions of the single particle spectra (which form the denominator of the correlation function in the event-mixing technique) induced by two-particle correlations are corrected using an iterative procedure[8]. Finally, the effect of Coulomb interactions between the two particles is taken into account using the standard Gamow correction.

High-statistics data make it possible to perform multi-dimensional fits of the cor-

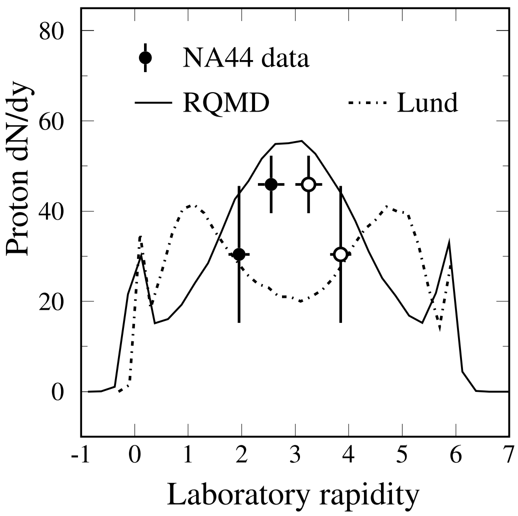

Figure 4: PRELIMINARY proton rapidity distribution from semi-central PbPb collisions (open circles indicate points reflected about $y_{mid} = 2.9$). Error bars are statistical; estimated systematic errors are 20%. Also shown are predictions from the RQMD and Lund models for the same centrality selection.

relation functions. For the data shown here, a three-dimensional analysis has been performed[9], in which the relative momentum vector q is decomposed into a longitudinal component, q_L, parallel to the beam axis, and two transverse components, q_{TO} and q_{TS}: q_{TO} is parallel to the transverse momentum sum of the two particles, and q_{TS} perpendicular to it. Assuming a Gaussian source distribution in each component, the data are fitted to the function:

$$C_2 = C(q_{TO}, q_{TS}, q_L) = A(1 + \lambda \exp^{(-q_{TO}^2 R_{TO}^2 - q_{TS}^2 R_{TS}^2 - q_L^2 R_L^2)}) \qquad (2)$$

where λ is the chaoticity parameter, and R is the correlation length for each component. The data are analysed in the longitudinal centre-of-mass reference frame, where the momentum sum of the particle pair along the beam direction is zero.

Figure 5 shows the two-pion (π^+) correlation function from semi-central PbPb collisions (approximately the 15% most central interactions). The results of both a one-dimensional fit (in q_{inv}), and the three-dimensional fit described above, are shown. The assumption of a Gaussian-distributed source gives a reasonable fit to the data, however event generator studies indicate that the shape of the correlation function is modified by contributions from resonance decays. In the case of π^+correlations, the η and ω mesons in particular contribute in the region of the Bose-Einstein signal, and modify the extracted R and λ parameters. Since the relative contribution of resonance decay products is p_T dependent, measuring the p_T dependence of the correlation

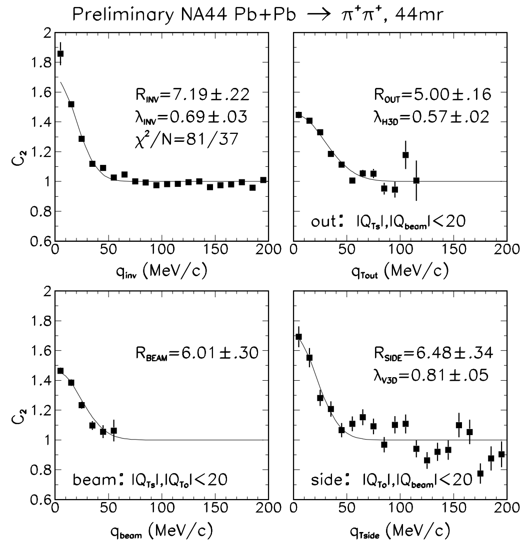

Figure 5: The two-pion (π^+) correlation function measured in semi-central PbPb collisions. The upper left panel shows a one-dimensional fit in q_{inv}, while the remaining three panels show results of the three-dimensional fit (in q_{TO}, q_L, q_{TS}). Also shown are the extracted R (fm) and λ parameters.

function can help disentangle the effects of resonances and (possible) transverse flow. This is discussed further below.

The results of the three-dimensional fit show similar values for all 3 radius parameters (i.e. $R_{TO} \approx R_{TS} \approx R_L$). R_{TO} is sensitive to the duration of freezeout ($\Delta\tau$) of the source[6], which can be extracted from the fit parameters by:

$$R_{TO}^2 - R_{TS}^2 = \beta^2 \Delta\tau^2 \tag{3}$$

The similarity of R_{TO} and R_{TS} indicates therefore that the duration of freezeout is short (less than a few fm/c), although it should be cautioned that collective expansion, if present, may complicate this interpretation.

Figure 6 shows a summary of two-pion and two-kaon correlation results from pPb, SPb and PbPb collisions. The three-dimensional fit function described above (2) has been used in all cases. Focussing first on the pion results, there is a clear increase in the R parameters as the size of the collision system increases. The similarity of the three R parameters noted above for PbPb collisions is also seen in the lighter systems. The values themselves are comparable to, or larger than, the corresponding projectile radii, indicating that there is significant expansion before freezeout occurs. The pPb data have been divided into two p_T bins; a "low-p_T" sample for which $<p_T> \approx 150$ MeV/c, and a "high-p_T" sample with $<p_T> \approx 450$ MeV/c. High-p_T pions have smaller R parameters than low-p_T pions. This behaviour is also seen in the SPb data (see

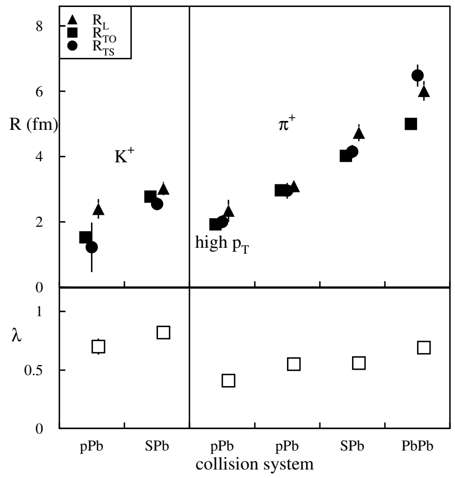

Figure 6: Pion and kaon correlation results from pPb, SPb and PbPb collisions. The figure shows the three R parameters and λ obtained from fits to (2). For the pion data, $<p_T>\approx$ 150 MeV/c; for the kaons, $<p_T>\approx$ 240 MeV/c; and for the "high-p_T" pions, $<p_T>\approx$ 450 MeV/c.

Figure 7), and might be explained by a decreasing resonance decay contribution to the correlation function as p_T increases. The associated increase of the λ parameter with p_T which would be expected in this scenario is not however observed. Turning to the kaon results, the increase in correlation lengths with system size is also seen for kaons, however the R parameters are smaller, and the λ values larger, than those for pions from the same collision system. One possible explanation for this result is that the resonance decay contribution to the correlation function is much smaller for K^+ than for π^+. This is in approximate agreement with results from RQMD simulations[10]. A second possible explanation is in terms of collective expansion of the source. This is examined below.

Figure 7 shows pion and kaon R parameters from SPb collisions as a function of m_T: the correlation lengths decrease with increasing m_T, and in fact scale $\propto 1/\sqrt{m_T}$. This trend is reproduced qualitatively by RQMD, which shows strong correlations between the position and momentum of emitted particles[11]. Because of these correlations, which indicate a collective expansion, the R parameters from the correlation function are consistently smaller than the source position distribution, and are momentum dependent. The results have also been compared to a simple hydrodynamical model[12], in which collective expansion leads to position-momentum correlations in both longitudinal and transverse directions[13]. This three-dimensional expansion leads to the prediction that the R parameters should scale as $1/\sqrt{m_T}$ for all mesons,

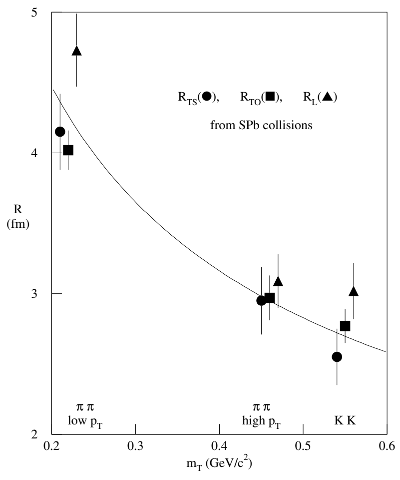

Figure 7: Results of three-dimensional fits to the pion and kaon correlation functions from central SPb collisions. The pion data are divided into two p_T samples, and the three data sets plotted versus m_T. The solid line indicates $2/\sqrt{m_T}$.

as observed in the data. Both models include collective expansion, explicitly in the hydrodynamical case, and as a consequence of rescattering in RQMD. The data indicate the presence of expansion, but cannot address the relative validity of the two models.

4. Conclusions

NA44 has measured single- and two-particle distributions of identified hadrons produced near midrapidity in pA and AA collisions.

Single particle transverse mass distributions can be described by exponentials in m_T whose inverse slopes increase with system size and particle mass in AA collisions, but are roughly constant in pA interactions. This illustrates the importance of rescattering in the nucleus-nucleus collisions. The m_T distributions are consistent with a thermal model including significant transverse flow.

Two-particle correlation measurements show that the radius parameters increase with the size of the collision system, and that the kaon source is significantly smaller than the pion source. Comparisons with microscopic models such as RQMD indicate that the radius parameters extracted from the correlation functions are smaller than the true 'geometric' source sizes, due to strong dynamical correlations. Multi-dimensional analysis of the correlation functions shows that the three radius parameters R_L, R_{TO} and R_{TS} decrease with m_T and exhibit a common $1/\sqrt{m_T}$ dependence.

This is consistent with a cylindrically-symmetric source expanding in three dimensions, and with significant transverse flow velocities.

5. References

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