Like–particle ratios from $p+p$ collisions at $\sqrt{s}$=200 GeV over the rapidity interval $0 < y < 3.4$

I. G. Bearden [f], D. Beavis [a], C. Besliu [j], B. Budick [e], H. Bøggild [f], C. Chasman [a], C. H. Christensen [f], P. Christiansen [f], J. Cibor [c], R. Debbe [a], E. Enger [ℓ], J. J. Gaardhøje [f], M. Germinario [f], K. Hagel [h], A. Holm [f], A. K. Holme [ℓ], H. Ito [a], E. Jakobsen [f], A. Jipa [j], F. Jundt [b], J. I. Jørdre [i], C. E. Jørgensen [f], R. Karabowicz [g], T. Keutgen [h], E. J. Kim [a,k], T. Kozik [g], T. M. Larsen [ℓ], J. H. Lee [a], Y. K. Lee [d], G. Løvhøiden [ℓ], Z. Majka [g], A. Makeev [h], M. Mikelsen [ℓ], M. J. Murray [h,k], J. Natowitz [h], B. S. Nielsen [f], J. Norris [k], K. Olchanski [a], D. Ouerdane [f], R. Płaneta [g], F. Rami [b], C. Ristea [j], D. Röhrich [i], B. H. Samset [ℓ], D. Sandberg [f], S. J. Sanders [k], R. A. Scheetz [a], P. Staszel [f], T. S. Tveter [ℓ], F. Videbæk [a], R. Wada [h], A. Wieloch [g], Z. Yin [i] and I. S. Zgura [j]

(The BRAHMS Collaboration)

[a] *Brookhaven National Laboratory, Upton, New York 11973*

[b] *Institut de Recherches Subatomiques and Université Louis Pasteur, Strasbourg, France*

[c] *Institute of Nuclear Physics, Krakow, Poland*

[d] *Johns Hopkins University, Baltimore 21218*

[e] *New York University, New York 10003*

[f] *Niels Bohr Institute, Blegdamsvej 17, University of Copenhagen, Copenhagen 2100, Denmark*

[g] *Smoluchkowski Inst. of Physics, Jagiellonian University, Krakow, Poland*

[h] *Texas A&M University, College Station, Texas, 17843*

[i] *University of Bergen, Department of Physics, Bergen, Norway*

[j] *University of Bucharest, Romania*

[k] *University of Kansas, Lawerence, Kansas 66045*

[ℓ] *University of Oslo, Department of Physics, Oslo, Norway*

Preprint submitted to Phys. Lett. B *11 August 2004*

Abstract

We present a measurement of π^-/π^+, K^-/K^+ and $\bar{p}/p$ from $p+p$ collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ over the rapidity range $0 < y < 3.4$. For $p_T < 2.0\,\mathrm{GeV}/c$ we see no significant transverse momentum dependence of the ratios. All three ratios are also independent of rapidity for $y < 1.5$ and then steadily decline from $y = 1.5$ to $y \sim 3$. The π^-/π^+ ratio is below unity for $y > 2.0$. The $\bar{p}/p$ ratio is very similar for $p+p$ and 5% central $Au + Au$ collisions at all rapidities. In the fragmentation region the three ratios seem to be independent of beam energy when viewed from the rest frame of one of the protons. Theoretical models based on quark-diquark breaking mechanisms overestimate the $\bar{p}/p$ ratio up to $y \lesssim 3$. Including additional mechanisms for baryon number transport such as baryon junctions leads to a better description of the data presented here.

Key words:
PACS: 25.75.q, 25.40.-h, 13.75.-n

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1 Introduction

The ratios of particle production in hadronic interactions are important indicators of the collision dynamics [1,2]. By comparing large and small systems over a wide range of phase space, one can address both reaction mechanisms in simpler systems and the properties of hot and dense nuclear matter in large systems. A thorough understanding of $p+p$ collisions at ultrarelativistic energies is necessary both as input to detailed theoretical models of strong interactions, and as a baseline for understanding the more complex nucleus–nucleus collisions at RHIC energies. Soft particle production from ultrarelativistic $p+p$ collisions is also sensitive to the flavor distribution within the proton, quark hadronization and baryon number transport. Extensive data exist near midrapidity, but less is known about the forward rapidity region where fragmentation and isospin effects may be important.

In this Letter we present a measurement of charged hadron ratios from $p+p$ collisions at a center–of–mass energy of $\sqrt{s} = 200\,\mathrm{GeV}$ as a function of rapidity $y = 0.5 \cdot ln((E + p_z)/(E - p_z))$ and transverse momentum p_T, and make a comparison with similar BRAHMS results from 5% most central $Au + Au$ collisions at the same energy. We show that the $p+p$ and $Au + Au$ results on particle ratios are almost identical over three units of rapidity, in spite of the expected large differences in dynamics between these systems.

In $p+p$ collisions at RHIC energies two main mechanisms for particle production are expected. At midrapidity the Bjorken picture [3] predicts that particles will be formed mainly from string fragmentation, yielding values of antiparticle–to–particle ratios close to unity. At forward rapidities, close to the beam rapidity ($y_b = 5.3$ at $\sqrt{s} = 200\,\mathrm{GeV}$), cross–sections are instead known to be dominated by leading particles and projectile fragments (the fragmentation region). This means that the conservation of original charge and isospin will become increasingly important for particle production as we approach y_b. Our data show that in $p + p$ collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ there is a midrapidity region extending out to $y \approx 1.5$ where the particle ratios follow the Bjorken picture. Beyond this all three ratios start to drop, indicating the onset of fragmentation region physics. Shifting the ratios by the beam rapidity and comparing to lower energy data, we find a range of at least two units of rapidity where ratios of particle production is independent of the incident beam energy when viewed from the rest frame of one of the protons (limiting fragmentation [4]).

The traditional quark–diquark breaking picture of a $p + p$ collision fails to reproduce baryon transport in available midrapidity data [5–7]. In this Letter we also provide a comparison of experimental results with different model predictions, which, especially away from midrapidity, provides new and important constraints for calculations. We show that the commonly used event generator PYTHIA [8] does not reproduce the ratio of antiproton to proton production seen in the data at any rapidity, while the additional hypothesis of a baryon junction within the HIJING/B [9] model yields a good agreement with both the magnitude and rapidity dependence of the $\bar{p}/p$ ratio.

2 The analysis

The data presented in this Letter were collected with the BRAHMS detector system during 2001. BRAHMS consists of two movable magnetic spectrometers and a suite of detectors designed to measure global multiplicity and forward neutrons [10]. In addition, a minimum bias collision trigger was provided by eight rings of plastic scintillator [11], four on each side of the interaction point. To reduce the contribution of background events a software trigger was also employed, selecting only events from the three outer rings on each side. Using a GEANT simulation with the HIJING event generator [12] as input, we estimate that this trigger setup saw $71\pm5\%$ of the $41\,\mathrm{mb}$ $p + p$ total inelastic cross–section. Two spectrometer triggers were also in use to select events that had at least one track in the spectrometers. For this analysis we used data taken at 90^o, 60^o, 45^o, 40^o, 35^o, 20^o, 12^o, 4^o and 3^o with respect to the beam, yielding a rapidity coverage of $0 < y < 3.4$ for pions. The analysis methods employed here are similar to those described in [13,14].

Charged particle ratios have been obtained by constructing and dividing normalized transverse momentum spectra for negative and positive particles, so that most corrections for geometrical acceptance and detector efficiencies cancel out. Figure 1 shows selected particle ratios as a function of p_T. Within our statistical errors we do not see any significant dependence on p_T. The resulting distributions were then fitted to a constant over the range $0.5 < p_T < 1.5\,\mathrm{GeV}/c$, the limits varying by $\pm 0.5\,\mathrm{GeV}/c$ to match the limits of our acceptance for the different angle settings of the spectrometer (see Fig. 1).

The ratios have been corrected for particle absorption and in–flight decay as discussed in Ref. [13]. In addition we have corrected for antiproton absorption in the spectrometer trigger slats, which removed $\approx 10\%$ of the $\bar{p}$ yield at $p < 1\,\mathrm{GeV}/c$, dropping to $\approx 5\%$ at $p = 2\,\mathrm{GeV}/c$. Since the spectrometers have a small solid angle the effects of feed–down from weak decays are not large and tend to cancel in the ratios [14], with the exception of the $\bar{p}/p$ ratio which is sensitive to the evolution with rapidity of the Λ/p ratio. Using published STAR data at $y = 0$ from $p+p$ [15,16] collisions as well as our own data away from midrapidity as input, we have employed a GEANT simulation to estimate the size of this correction. Estimating $\Lambda/\mathrm{p} \sim 0.5$ from data at $y = 0$, assuming a constant behavior with rapidity and estimating $\bar{\Lambda}/\Lambda \sim \bar{p}/p \cdot K^+/K^-$ [17] we find that the feed-down from Λ and $\bar{\Lambda}$ causes a net increase of $\bar{p}/p$ at all rapidities. At midrapidity this contribution is <5% and at forward rapidity <10% within our acceptance. Since there is no available data to calculate the exact magnitude of this effect, we have however not explicitly corrected our data for feed–down from weak decays.

3 Particle ratios vs. rapidity

Figure 2 shows the resulting ratios of antiparticle to particle yields as a function of rapidity (left panel). Two independent analyses were performed. By comparing these and varying their kinematic cuts we estimate our point-to-point systematic errors to be <2% for pions and protons, and <3% for kaons. These uncertainties are reflected in the error bars in Fig. 2. In addition we estimate an overall systematic uncertainty of <5% from corrections for absorption and in–flight weak decays, and from the normalization to the inelastic cross–section.

For all three ratios in Fig. 2 there is a clear midrapidity plateau and subsequent decrease with rapidity. The midrapidity values of the ratios are $\pi^-/\pi^+ = 1.02 \pm 0.01 \pm 0.05$, $K^-/K^+ = 0.96 \pm 0.05 \pm 0.06$ and $\bar{p}/p = 0.74 \pm 0.04 \pm 0.04$, consistent within statistical errors with values reported by STAR [18]. Numbers at other rapidities are given in Table 1. Assuming that the (anti-)quarks from pair creation are equally likely to form particles and anti-particles, one expects the same number of protons and anti-protons from such processes.

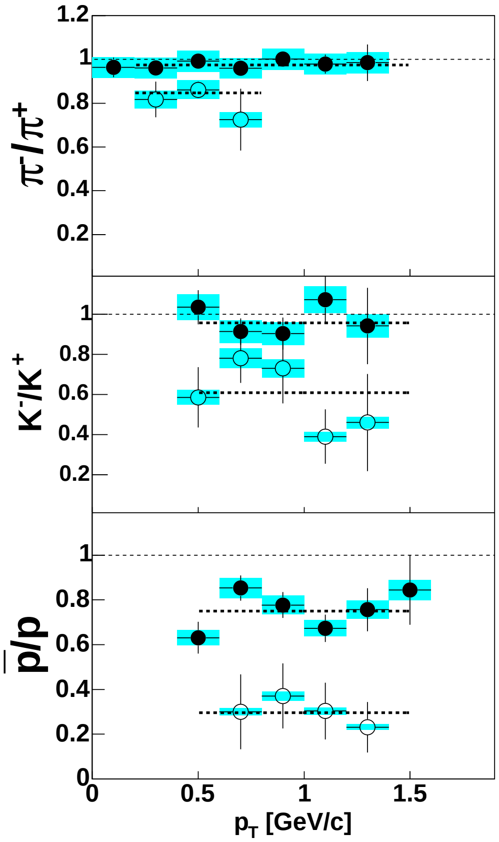

Fig. 1. Particle ratios vs. p_T at $y = 0$ (solid circles) and $y \sim 3$ (open circles). The lines show a constant fit to the data. The shaded area indicates our estimate of the systematic error.

Proton excess, therefore, is due to the transport of baryon number from the initial beam. Our $\bar{p}/p$ ratio would imply that at midrapidity 15% of the protons carry baryon number that has been transported from the beam region at y=5.3 [5]. We note that it has been shown (see [19]) that one may need to correct for isospin effects before generalizing these results from p+p to hadron–hadron collisions. This could in principle be done by deducing (anti)neutron production from (anti)deuteron production. We unfortunately do not have the necessary data at $\sqrt{s} = 200\,\mathrm{GeV}$ to make such a correction at this time.

At $y \lesssim 1.5$ the $Au + Au$ ratios for the 5% most central collisions reported in [13] are strikingly similar to the present results, with values at midrapidity deviating by less than 2%. Above $y = 1.5$ the pion ratios in $p + p$ start to drop below those for $Au + Au$ and consequently below unity, while the kaon and proton ratios remain consistent with $Au + Au$ over our entire acceptance range. This is surprising in view of the different dynamics one might expect of the two systems. A heavy–ion system has multiple initial collisions as well as significant rescattering and may reach thermal equilibrium before freezeout occurs, while the significantly smaller $p + p$ system should not interact much

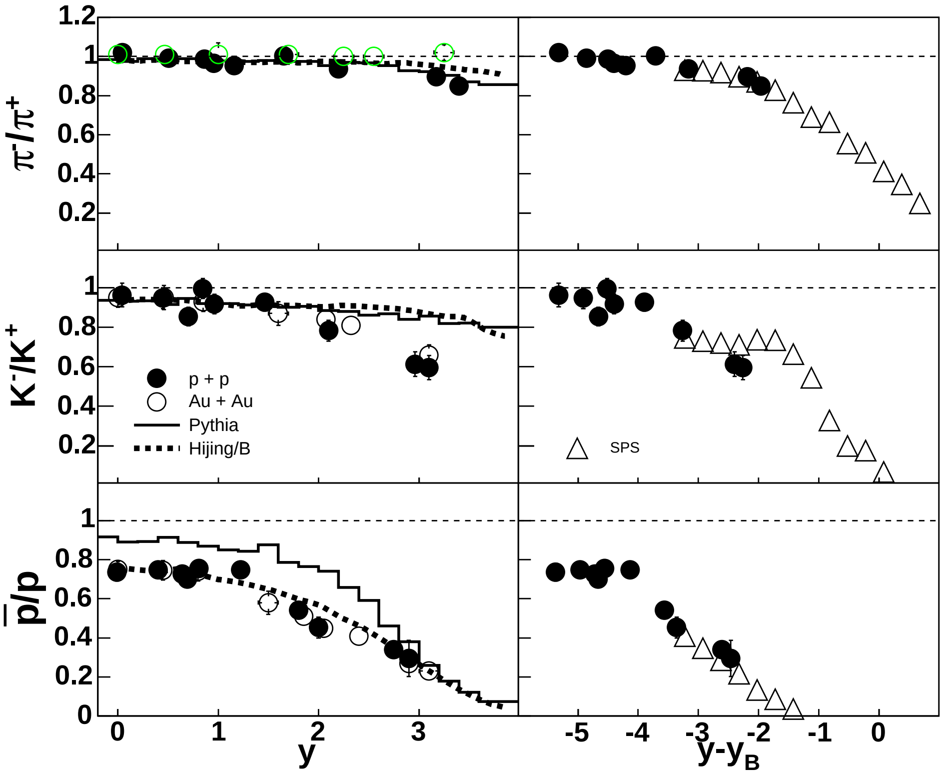

Fig. 2. **Left:** Charged particle ratios from $p+p$ at $\sqrt{s} = 200\,\mathrm{GeV}$ (solid points), compared with $Au+Au$ [13] (open points) and predictions from PYTHIA [8] (solid histogram) and HIJING/B [9] (thick dashed line). **Right:** Ratios shifted by y_b, compared with data from NA27 (triangles) at $\sqrt{s} = 27.5\,\mathrm{GeV}$ [20].

beyond the initial reactions. For all three species the ratios start to drop near $y = 1.5$, indicating a transition from a string breaking dominated regime at midrapidity and into the fragmentation region. The drop in the pion ratio at high rapidity can be attributed to isospin and charge conservation in the fragmentation region. This effect is not seen for $Au+Au$, where the production of charged particles per unit rapidity is much larger.

The right panel of Fig. 2 shows the present data and data from NA27 at $\sqrt{s} = 27.5\,\mathrm{GeV}$ [20] (open triangles) shifted by the respective beam rapidities. Overlaying the two datasets, we observe a region of at least two units of rapidity where the particle ratios are independent of the incident beam energy when viewed from the rest frame of one of the protons. This is consistent with the idea of limiting fragmentation that has also been observed for charged hadrons in nucleus–nucleus collisions [21,22]. This hypothesis states that the excitation of the leading protons saturates at a moderate energy, leaving more available kinetic energy for particle production below the beam rapidity. We also note a transition in behavior at $y - y_b = -4$, indicative of a divide between the midrapidity and fragmentation regions. At RHIC energies we observe a

Rapidity	π^-/π^+	Rapidity	K^-/K^+	Rapidity	$\bar{p}/p$
0.0	1.02±0.02	0.0	0.96±0.06	0.0	0.74±0.04
0.5	0.99±0.02	0.4	0.95±0.05	0.4	0.75±0.03
0.9	0.99±0.02	0.7	0.85±0.05	0.6	0.73±0.03
1.0	0.97±0.02	0.8	1.00±0.05	0.7	0.70±0.03
1.2	0.95±0.02	1.0	0.92±0.05	0.8	0.76±0.03
1.7	1.00±0.02	1.5	0.93±0.04	1.2	0.75±0.03
2.2	0.94±0.02	2.1	0.78±0.05	1.8	0.54±0.03
3.2	0.90±0.02	3.0	0.61±0.06	2.0	0.45±0.05
3.4	0.85±0.04	3.1	0.60±0.06	2.7	0.34±0.04
				2.9	0.29±0.09

Table 1

Numerical values for charged particle ratios as a function of rapidity. Errors reflect statistical and point–to–point systematic uncertainties. In addition there is an overall systematic uncertainty of $< 5\%$ from normalization and corrections.

region of constant relative particle production that was not present at SPS, extending out almost two units of rapidity from $y = 0$.

4 Predictions from models

To interpret these results further, we confront predictions from theoretical models of hadron-hadron collisions with the data. The curves in the left panel of Figure 2 compares our results to the predictions of two such calculations, PYTHIA Ver. 6.303 [8] [1] and HIJING/B [9], using the same p_T range as the present analysis. Both models give a good description of the pion data and for kaons at midrapidity, but do not reproduce the magnitude of the decrease with rapidity seen for K^-/K^+ as the rapidity approaches that of the fragmentation region. Also, PYTHIA clearly overestimates the $\bar{p}/p$ ratios. This is a well–known problem since PYTHIA employs only quark–diquark breaking, while several authors have pointed out [5,6] that to describe stopping at midrapidity in high–energy hadronic collisions one needs an additional mechanism to transport baryon number away from the beam rapidities.

A possible basis for such a mechanism are gluonic structures known as baryon

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[1] PYTHIA version 6.3 is at the time of writing still labeled as ‘experimental’, but we find no difference in the results between this version and the latest in the 6.2 series.

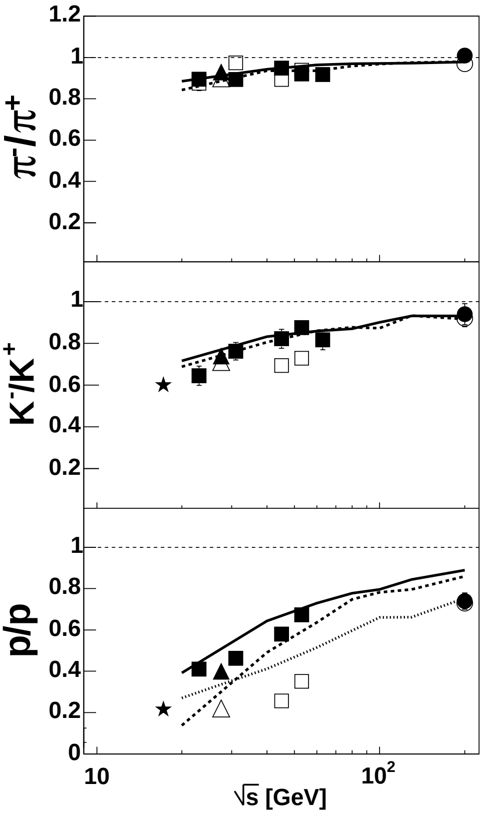

Fig. 3. $\sqrt{s}$ dependence of particle ratios at $y = 0$ (closed symbols) and $y = 1$ (open symbols). Circles are the present data, errors represent statistical and point–to–point systematic uncertainties. Also shown are $p + p$ data from ISR (squares), NA27 (triangles) and NA49 (stars) [20,26]. NEED PROPER NA49 REF!. Solid lines: PYTHIA prediction for $p+p$ at y=0, dashed lines: same for y=1. Dotted line: HIJING/B prediction at y=0.

junctions[5,23], that allow for easy transport of baryon number toward midrapidity while energy balance is maintained through an increased production of forward mesons. The baryon junction scenario, incorporated as a model prediction in the HIJING/B event generator [9], has successfully predicted the slow $\sqrt{s}$ dependence of the $p + p$ and $\bar{p} + p$ cross–sections [5,24]. The dashed lines in Fig. 2, showing the HIJING/B prediction for $\bar{p}/p$ at $\sqrt{s} = 200\,\mathrm{GeV}$, exhibit a much better agreement with the data both in terms of overall magnitude and the width of the distribution. In Ref. [25] the authors show that baryon stopping in $p + p$ and $Au + Au$ collisions at SPS and RHIC energies can be described using the same parameters for the baryon junction couplings, and predict that at RHIC the shapes of the rapidity distributions for $p + p$ and $Au + Au$ will be similar for $|y| \lesssim 2$. The similarity of $\bar{p}/p$ in $p + p$ and $A + A$ up to $|y| < 3$ indicate that over this range no additional coupling is needed.

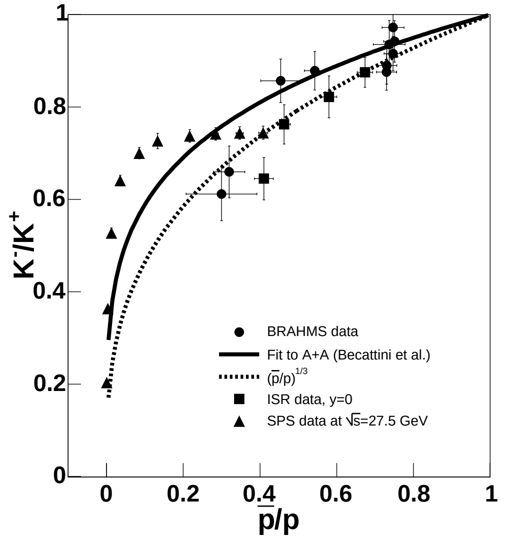

Fig. 4. Correlation between K^-/K^+ and $\bar{p}/p$ at different rapidities from the present data and data at lower energies. The lines show a fit to $A+A$ data [27] (solid) and the prediction from a thermal model in the limit of vanishing strangeness (dashed).

5 Particle ratio excitation functions

The present data allow for an extended study of the excitation function of the particle ratios around midrapidity. In Figure 3 we have plotted our data at $y = 0$ and $y \sim 1$ together with fits to ISR data [26] from $p + p$ collisions in the range $23 < \sqrt{s} < 63\,\mathrm{GeV}$. Where possible the fits have been made over the same p_T range as our data, the notable exception being the $\bar{p}/p$ ratios at $y = 1$ where the available data cover $2.0 < p_T < 4.0\,\mathrm{GeV}/c$. Points from NA27 at $\sqrt{s} = 27.5\,\mathrm{GeV}$ are also shown. Both at midrapidity and at $y = 1$ the ratios depend logarithmically on $\sqrt{s}$, but the slope of this dependence is steeper at $y = 1$. At lower energies there is a significantly larger fraction of K^- and antiprotons at $y = 0$ than at $y = 1$, an effect that is much smaller at RHIC energies. This again indicates that at RHIC we have a midrapidity source extending out least 1.5 units of rapidity that is almost free of net strangeness and baryon number. The transition to this regime from SPS and ISR energies appears smooth, rather than developing through some definite transition point.

The lines in Fig. 3 show the prediction for the particle ratio excitation function from PYTHIA. At midrapidity all three ratios are well reproduced except for the $\bar{p}/p$ ratio at RHIC energies, but the drop in the K^-/K^+ and $\bar{p}/p$ ratios observed at $y = 1$ is poorly described. The dotted lines show the prediction for $\bar{p}/p$ from HIJING/B at $y = 0$. Like PYTHIA it shows a smooth rise with energy, failing to reproduce the apparent kink at around $\sqrt{s} = 50\,\mathrm{GeV}$. For pions and kaons HIJING/B reproduces the PYTHIA curves shown.

6 Ratio correlations over three units of rapidity

For nucleus–nucleus collisions at ultrarelativistic energies it has been observed that all particle production ratios can be described by a grand canonical model of the emitting source, i.e. with only temperature and baryochemichal potential as parameters [27]. Our analysis in Ref. [13] on data from $Au{+}Au$ collisions at $\sqrt{s} = 200\,\text{GeV}$ shows that one can parametrize the kaon and proton ratios at different rapidities as a power law: $K^-/K^+ = (\bar{p}/p)^\alpha$, and found that $\alpha^{Au+Au} = 0.24 \pm 0.02$. Figure 4 shows a similar analysis based on the present data, where the K^-/K^+ ratios have been interpolated to the same rapidities as the $\bar{p}/p$ data. It is clear that the $p{+}p$ results at $\sqrt{s} = 200\,\text{GeV}$ follow roughly the same trend. A fit to the points gives an exponent of $\alpha^{p+p} = 0.29 \pm 0.03$, consistent within errors with the Au+Au result but dominated by measurements at mid-rapidiy. At $y > 2.5$ we find the correlation to be significantly below the Au+Au result.

For comparison Fig. 4 shows the corresponding results for $p + p$ collisions at $\sqrt{s} = 27.5\,\text{GeV}$ [20] and midrapidity data at ISR energies, as well as a fit to $A + A$ data by Becattini et al. [27]. We note that this curve describes the data from the midrapidity region well but misses the points from the fragmentation region. This indicates that at RHIC energies the midrapidity zone may be described in a grand canonical framework, while at forward rapidities one may need to use a microcanonical description to take e.g. the event–by–event conservation of strangeness into account. Such a description is being developed e.g. by the authors of Ref. [28]. The dashed line in Fig. 4 shows the relationship $K^-/K^+ = (\bar{p}/p)^{\frac{1}{3}}$ which is derived by simple quark counting in the limit of vanishing strangeness, μ_s. This relationship reproduces well the ISR $y = 0$ data at $\sqrt{s}$ =23.0–53.0 GeV. This curve also describes the fragmentation region measurements at $\sqrt{s} = 200\,\text{GeV}$. We observe therefore, in contrast to the Au+Au results, an evolution from a grand canonical type thermal description at midrapidity to a description with vanishing strangeness at higher rapidity.

7 Conclusions

In conclusion, the BRAHMS experiment has measured the ratios of charged antihadron to hadron production from $p + p$ collisions at $\sqrt{s} = 200\,\text{GeV}$. All the ratios are roughly independent of transverse momentum for $p_T < 2.0\,\text{GeV}/c$. For kaons and protons we find an overall consistency with results from $Au + Au$ collisions at the same energy over three units of rapidity. The π^-/π^+ ratio falls steadily below the $Au + Au$ results for $y = 2.0 - 3.4$, as expected from conservation of initial charge and isospin. When viewed from the rest frame of one of the protons all ratios seem to be independent of the projectile beam energy over several units of rapidity. Models based on quark–diquark breaking of the initial protons give a reasonable description of π^-/π^+ but cannot describe our $\bar{p}/p$ ratio unless additional mechanisms of baryon transport are invoked. Introducing a baryon junction scheme to add additional baryon transport to midrapidities yields a good description of our $\bar{p}/p$ data over our full coverage of $0 < y < 2.9$.

This work was supported by the Division of Nuclear Physics of the Office of Science of the U.S. Department of Energy under contracts DE-AC02-98-CH10886, DE-FG03-93-ER40773, DE-FG03-96-ER40981, and DE-FG02-99-ER41121, the Danish Natural Science Research Council, the Research Council of Norway, the Jagiellonian University Grants, the Korea Research Foundation Grant, and the Romanian Ministry of Education and Research (5003/1999,6077/2000).

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