Mid-Rapidity Protons in 158A·GeV Pb + Pb Collisions

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Abstract

Proton distributions at mid-rapidity ($2 \leq y \leq 3$) have been measured for 158A·GeV Pb + Pb collisions in the focusing spectrometer experiment NA44 at CERN. From baryon number conservation and by comparing the experimentally measured dN/dy distribution with the transport model RQMD, we conclude that a rather high degree of nuclear stopping has been reached for the truly heavy-ion collisions at these energies. Transverse mass distributions exhibit characteristically thermal shapes and the slope parameters increase with the mass of the colliding system.

The production of hot and dense hadronic matter in the laboratory, along with the possible transition to a de-confined quark-gluon-plasma phase motivate the study of ultra-relativistic heavy-ion collisions. In November 1994, 158A·GeV ($\sqrt{s} \approx 17.5$A·GeV) lead beams were delivered from the CERN Super Proton Synchrotron (SPS). This is the heaviest heavy-ion beam with the highest energy produced to date.

The goal of heavy-ion physics is to create high particle and energy densities. Nucleon distributions yield information on nuclear stopping in nucleus-nucleus collisions, providing a measure of how much initial kinetic energy is deposited into the system during the collisions [1]. The higher the nuclear stopping, the more initial energy is converted into excitation of the system. For p+p collisions at beam energy $E_{beam} \approx 200$ GeV, the proton rapidity distribution shows two distinct peaks near beam and target rapidity i.e. baryon stopping and production at midrapidity is small. Experimentally it has been found [2] that nuclear stopping in symmetric S+S collisions is higher than in p+p collisions. For p-nucleus collisions [3] significant nuclear stopping was already concluded from the analysis of the final proton rapidity distributions of 100 GeV p+Pb collisions [4, 5, 6].

In this letter, we report the first measurement of identified proton transverse momentum and rapidity density distributions from 158A·GeV Pb+Pb central collisions around mid-rapidity ($2 \leq y \leq 3$). The slope parameter, extracted from the transverse mass distribution, is found to be higher in the Pb system than that from the lighter symmetric systems p+p and S+S. An interpretation is that a larger transverse flow is reached in the heavy system with a fixed freeze-out temperature. We also compare the experimentally measured distribution with results from transport model RQMD (v1.08) [7] and FRITIOF model [8] calculations.

The NA44 spectrometer is a magnetic focusing spectrometer with two angular settings (44 and 129 mrad). The magnetic system includes two room temperature dipoles and three superconducting quadrupoles; the momentum ranges in this analysis cover $\pm$ 20% around the nominal 4 and 8 GeV/c momentum settings. Particles originating from the target are focused at a plane about 10 meters downstream and detected by a tracking system consisting of a pad chamber - time-of-flight (TOF) complex. Particle identification is done with two threshold Cherenkov counters (C1 and C2) and two highly segmented TOF hodoscopes. The time-of-flight start signal is derived from a Cherenkov beam counter with a time resolution of ≈ 35 ps.

For the proton distributions, all events with one or more pions in the spectrometer were rejected online via a combination of two Cherenkov counters in the spectrometer, leaving kaons, protons, and deuterons in the data sample. While for the 4 GeV/c setting time-of-flight alone is sufficient to separate kaons from protons, at the 8 GeV/c setting, the first Cherenkov counter C1 was used in separating particles. Tracks are reconstructed from the hits on the two scintillator hodoscopes, the pad chamber, and two strip chambers. Fig. 1 displays particle identification in time-of-flight vs momentum. On the top plot, Fig.1(a), all particles are included. When a cut is placed on C1, only kaons and protons are left, see Fig.1(b).

The phase-space coverage (transverse momentum p_T vs. rapidity y) of the NA44 setup can be optimized by the combination of the spectrometer angle and magnetic settings. For the 4 and 8 GeV/c settings, the proton coverages in [p_T(GeV/c): y] are: [(0.0-0.8):(1.9-2.4)] and [(0.0-1.6):(2.4-2.9)], respectively. The mean rapidities are 2.1 and 2.7 for 4 and 8 GeV/c settings. The transverse momentum resolution is typically 6 MeV/c and the TOF counters have an average time resolution of 100 ps. More details of the spectrometer can be found elsewhere [9].

The lead target has a thickness of 1.14g/cm^2, approximately 2.1% of an interaction length for a lead projectile. The beam intensity is approximately 3 million lead ions per 4 second burst. The online centrality trigger is provided by 2 rectangular scintillator paddles (T_0) downstream of the target, covering the pseudo-rapidity range approximately $1.3 \leq \eta \leq 3.5$. The large number of delta electrons from the lead beam traversing the target limit our ability to use a minimum bias trigger. The trigger requires valid beam (determined by a Cherenkov beam counter 0.6 m upstream of target), a large signal on the T_0 counter (corresponding to high multiplicity), and at least one hit on each of the TOF hodoscopes. As all events containing pions are rejected at the trigger level, a correction is made for the loss due to the online pion rejection when estimating the proton cross section (see discussion below). In the offline analysis, a silicon-pad multiplicity detector with 2π azimuthal coverage over the pseudo-rapidity range $1.5 \leq \eta \leq 3.3$ is used for further event selection. The trigger selects the most central collisions, 6.4$\pm$1.5% and 5.1$\pm$1.3% of the total geometrical cross section ($\sim 6.4b$) for 4 and 8GeV/c setting, respectively.

A Monte Carlo procedure is used to correct the results for the geometrical acceptance and tracking efficiency. Contamination of the protons by kaons and pions is estimated to be less than 5%. A correction is made for the number of protons that are rejected by an accompanying pion due to the on-line cut on the Cherenkov counters: Let N_p^{tot} be the total number of protons, $N_{p\pi}$ be the number of protons with at least one accompanying pion[1], and N_p is the number of protons alone in the spectrometer. Then $N_p^{tot} = N_p + N_{p\pi} = N_p(1+\alpha)$, with $\alpha = N_{p\pi}/N_p$. This factor is determined from the pion runs where we did not apply any cut on the Cherenkov counters.

The systematic errors on proton transverse mass distributions arise primarily from uncertainties in the acceptance corrections. They are estimated via the match between the two spectrometer angle settings to be less than 10%. The systematic errors on the proton rapidity density are dominated by errors in centrality selection, the pion veto correction, and total number of beam particles. These contribute about 25%, 15%, and 10% systematic uncertainties to dN/dy, respectively. Assuming there are no correlations among the errors and adding them in quadrature, the overall systematic uncertainties in the final rapidity distribution dN/dy are 26.8% and 32.7% for 4 and 8GeV/c setting, respectively.

The proton transverse momentum distributions, normalized per event and per unit rapidity, are shown in Fig. 2. They are plotted as a function of transverse kinetic energy $m_T - m_p$ (where $m_T = \sqrt{p_T^2 + m_p^2}$ and m_p is the mass of proton) from the 4 and 8 GeV/c momentum settings. The dashed lines represent the best fit with a single exponential function in m_T:

$$f(m_T, T) = A \cdot exp(-m_T/T) \tag{1}$$

The mid-rapidity slope parameters T for p+Be,[2] S+S, and from Pb+Pb (present study) collisions are listed in Table I. These data were measured with the same spectrometer and analyzed using similar methods. For heavier collision systems, the slope parameter is larger, implying that a stronger transverse flow is reached in the heavier systems [11]. The rapidity dependence of the proton slope parameters is shown in the inset of Fig. 2. Experimental data are shown as filled circles and the open symbols are the mirror reflection points around mid-rapidity $y_{mid} = 2.9$. In a static locally thermalized system, the rapidity dependence of the slope parameter can be expressed as $T_{mid}/cosh(y - y_{mid})$. This is shown as the dashed line in the inset with $T_{mid} = 300$ MeV. It should be noted that the rapidity dependence of the slope parameters is different for an isotropic fireball and for boost-invariant longitudinal flow [12]. However, a rather broad rapidity dependence of the slopes was found at lower energies [13]. A measurement with wider rapidity coverage is needed to test the validity of the simple thermal model.

[1] Electrons are also included.

[2] The proton beam energy was 450GeV. For details of the analysis see ref. [10].

Table I. Mid-rapidity ($y \approx 2.8$) proton m_T inverse slope parameters (in MeV unit) for 3 colliding systems measured in the NA44 spectrometer at CERN SPS energies. Error bars are statistical only.

	p + Be	S + S	Pb + Pb
proton	158±5	206±4	289±7
$\sigma_{trig}/\sigma_{geom}$	84±3.5%	8.7±%	6.4±1.5%

In fact, the extracted T depends on the mass of the particle under study [11, 14, 15], *i.e.* higher mass particles exhibit higher values of T. As predicted by Landau [16], this mass dependence should reflect transverse flow (see also ref. [17]). In Table I, where the proton inverse slope parameters are listed from p+Be, S+S, and Pb+Pb collisions, the slope parameter increases as the size of the collision system becomes larger. The highest proton inverse slope T in Table I is for Pb+Pb collisions, implying that the largest transverse flow has indeed been developed in the heaviest ion collisions.

The number of protons per unit rapidity can be calculated by the sum of the protons within the spectrometer p_T coverage and protons from extrapolated region. The exponential function Equ. (1) is used for the extrapolation. These protons are about 5% and 15% of total number of protons for 8 and 4 GeV/c settings, respectively. Fig. 3 shows number of protons per unit rapidity, where filled circles are measured data and open circles are the same data points mirrored around $y_{mid} = 2.9$. The vertical error bars are statistical only. Unlike in proton-proton and light ion collisions, we observe a large proton rapidity density around midrapidity indicating the incoming projectile and target protons undergo a large rapidity shift. The observed $\bar{\mathrm{p}}$/p ratio for the Pb+Pb collisions is about 7.1±2.2% and it is flat around the mid-rapidity region [15]. The smaller value of the $\bar{\mathrm{p}}$/p ratio, compared to lighter colliding systems, is because a large number of protons piled up around the mid-rapidity region.

The RQMD(v1.08) model [7] proton rapidity distributions are shown in the figure as a solid line. Protons from decays, primarily from Λ's, have been included in the calculation within the experimental acceptance (87±13% from Λ decays are accepted. This value should be regarded as a upper limit for the 8 GeV/c momentum setting.). Without the decay protons the maximum proton number would be 38 per unit rapidity in the RQMD model. A realistic centrality cut, measured by the T_0 counter, was used in the model calculation. Spectator protons appear at target and projectile rapidity, and constitute about 16% of the total protons. This is consistent with the impact parameter cut used in the calculation.

The inverse slope parameter from RQMD, extracted in the similar way as for the experimental data is 263±4 MeV, close to the experimental value of 289±7 MeV, showing that the strong transverse flow largely originates from multiple collisions without any specific collective interaction. The measured values for proton dN/dy around mid-rapidity are lower than the RQMD values by $\approx$ 30% indicating that the observed stopping is smaller than the RQMD mean rapidity shift $\langle \Delta y \rangle$ of 1.8. The $\langle \Delta y \rangle$ value predicted from systematics (y-scaling) in ref. [18] is close to the RQMD value.

In contrast to the RQMD results, the FRITIOF model [8] predicts a dip at mid-rapidity in net proton production from central Pb+Pb collisions. The dot-dashed line in Fig. 3 shows four distinct peaks in the distribution. In addition to the spectator peaks, the struck protons are visible as peaks about one unit away from the spectators. This is a low-stopping or transparency result for heavy-ion collisions. The model predicts such a small rapidity shift in heavy-ion collisions because it assumes that the scattered(or undressed[19]) nucleons suffer no additional collisions and eventually materialize outside the collision zone.

The present data shows a large amount of stopping, at least comparable to that observed for 200A·GeV S+S central collisions ($\langle \Delta y \rangle \approx 1.6$ [2]). Given the systematic uncertainties in the dN/dy measurements, a definitive conclusion on the amount of stopping cannot be reached. However the observed proton slope parameter and Coulomb effect [20, 21, 22], free of such systematic errors, favor the RQMD multi-collision model.

In summary, we have reported mid-rapidity proton transverse momentum distributions and rapidity densities from central Pb+Pb collisions at $\sqrt{s} = 17.5$A·GeV. A large number of protons are observed at midrapidity, indicating a high degree of stopping in the collision. This is consistent with the strong Coulomb effect and systematic trend in slope parameters [15] observed recently by the NA44 collaboration [20] and the high energy density result from NA49 transverse energy E_T measurement [23] in the Pb+Pb collisions. The proton inverse slopes increase with the size of the colliding system and indicate a large amount of transverse expansion. This is a direct consequence of high stopping and copious secondary particle production.

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References

[1] M. Gyulassy, Nucl. Phys. **A590**, 431c(1995).

[2] J. Bachler *et al.*, (NA35 Collaboration), Phys. Rev. Lett. **72**, 1419(1994).

[3] D.S. Barton, *et al.*, Phys. Rev. **D27**, 2580(1983).

[4] W. Busza and A.S. Goldhaber, Phys. Lett. **B139**, 235(1984).

[5] W. Busza and R. Ledoux, Ann. Rev. Nucl. Part. Sci., **V38**, 119(1988).

[6] S. Datè, M. Gyulassy, and H. Sumiyoshi, Phys. Rev. **D32**, 619(1985).

[7] H. Sorge *et al.*, Phys. Lett. **B289**, 6(1992).

[8] B. Andersson *et al.*, Nucl. Phys. **B281**, 289(1987).

[9] H. Beker *et al.*, (NA44 Collaboration), Phys. Lett. **B302**, 510(1993).

[10] H. Beker *et al.*, (NA44 Collaboration), in preparation.

[11] J. Dodd *et al.*, (NA44 Collaboration), Nucl. Phys. **A590**, 523c(1995) and B.V. Jacak *et al.*, (NA44 Collaboration), Nucl. Phys. **A590**, 215c(1995).

[12] J.D. Bjorken, Phys. Rev. **D27**, 140(1983).

[13] T. Abbott *et al.*, (E802 Collaboration), Phys. Rev. **C50**, 1024(1994), and M. Gonin, (E802/E866 Collaboration), Nucl. Phys. **A566**, 601c(1994).

[14] P. Braun-Munzinger, J. Stachel, H. Wessels, and N. Xu, Phys. Lett. **B344**, 43(1995), *ibid* **B356**, 1(1996).

[15] N. Xu, (NA44 Collaboration), Quark Matter '96, May 20-24 1996, Heidelberg, Germany.

[16] L.D. Landau, '*Collected papers of Landau*', Gordon and Breach, New York, 1965.

[17] E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. **C48**, 2462(1993), and E. Schnedermann, J. Sollfrank, and U. Heinz, *'Particle Production in Highly Excited Matter '*, p175, Ed. H. Gutbrod and J. Rafelski, Plenum Press, New York, 1992.

[18] F. Videbæk and Ole Hansen, Phys. Rev. **C52**, 2684(1995).

[19] E.L. Feinberg, Soviet Phys., JETP, **23**,132(1966).

[20] H. Bøggild *et al.*, (NA44 Collaboration), Phys. Lett. **B372**, 339(1996).

[21] J. Pluta *et al.*, private communications. Using RQMD plus longitudinal co-moving charge of Z_{eff}=40 per unit rapidity, the observed $N(\pi^-)/N(\pi^+)$ ratio [20] can be well reproduced.

[22] H.W. Barz, J. P. Bondorf, and J.J. Gaardhøje, to be published. They also calculate the pion ratio successfully within the framework of a thermal model. There the collective flow and longitudinal expansion are specifically included.

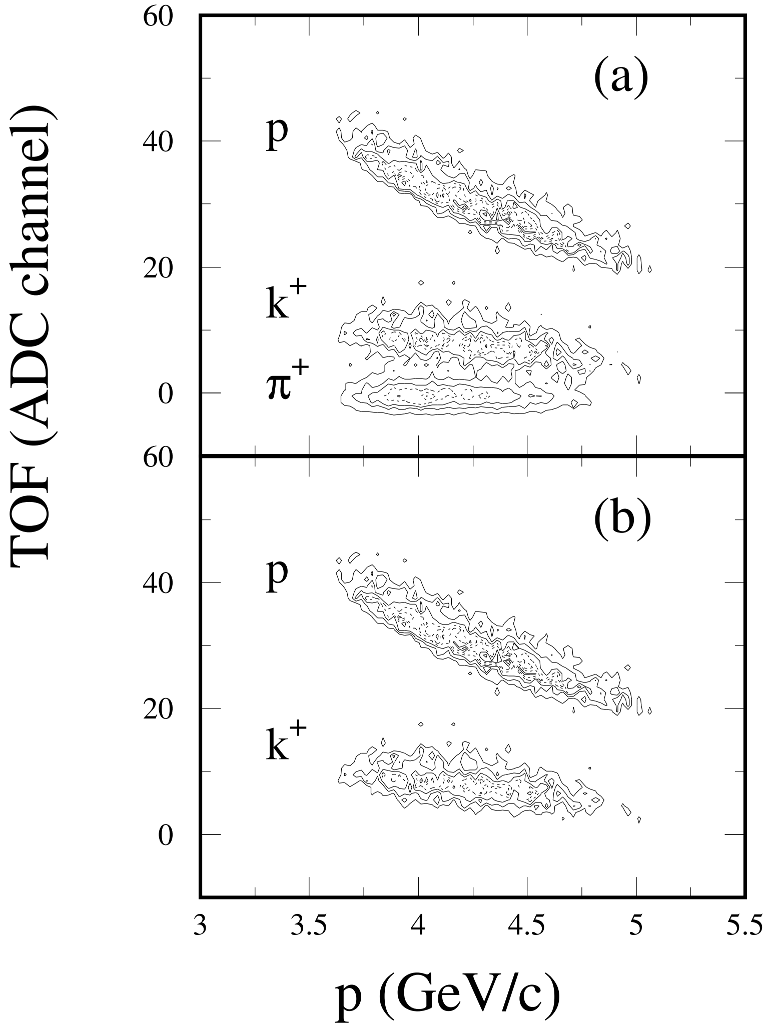
[23] T. Alber *et al.*, (NA49 Collaboration), Phys. Rev. Lett., **75**, 3814(1995).

Figure Captions

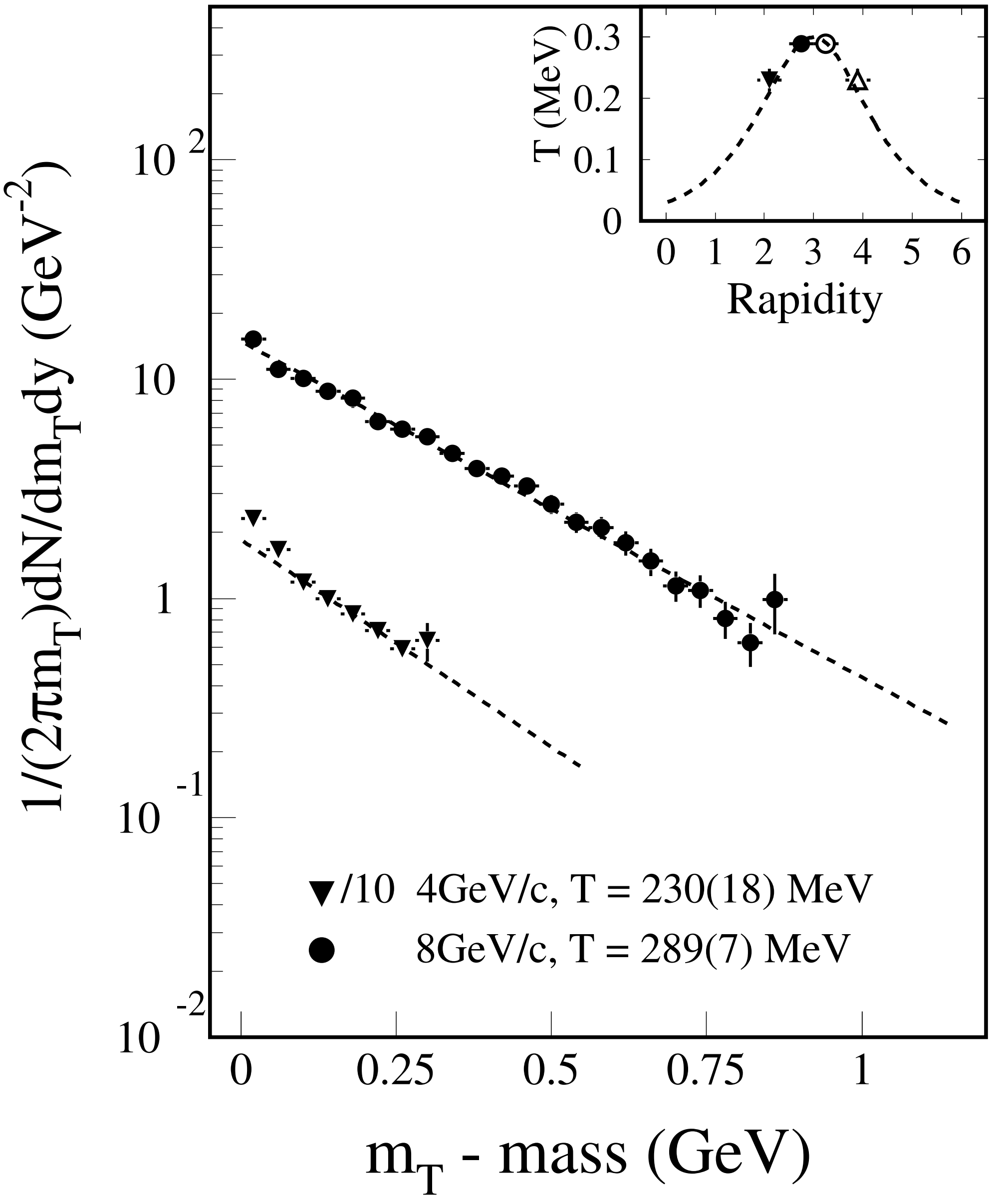
Fig. 1 Particle identification in time-of-flight vs momentum plot. (a) All particles; (b) With Cherenkov counter C1 cut.

Fig. 2 Proton transverse momentum distributions for 4 (triangles) and 8 (dots) GeV/c settings. The 4GeV/c data points are reduced by a factor of 10 in the figure. The exponential fits are shown as dashed lines. The error bars shown in the figure are statistical only. Systematic errors were estimated to be less than 5%. Fitted slope parameters are also listed and shown in the inset where the dashed line is the function $T_{mid}/cosh(y)$ with $T_{mid} = 0.3$ GeV. (Open symbols are mirrored at $y_{mid} = 2.9$.)

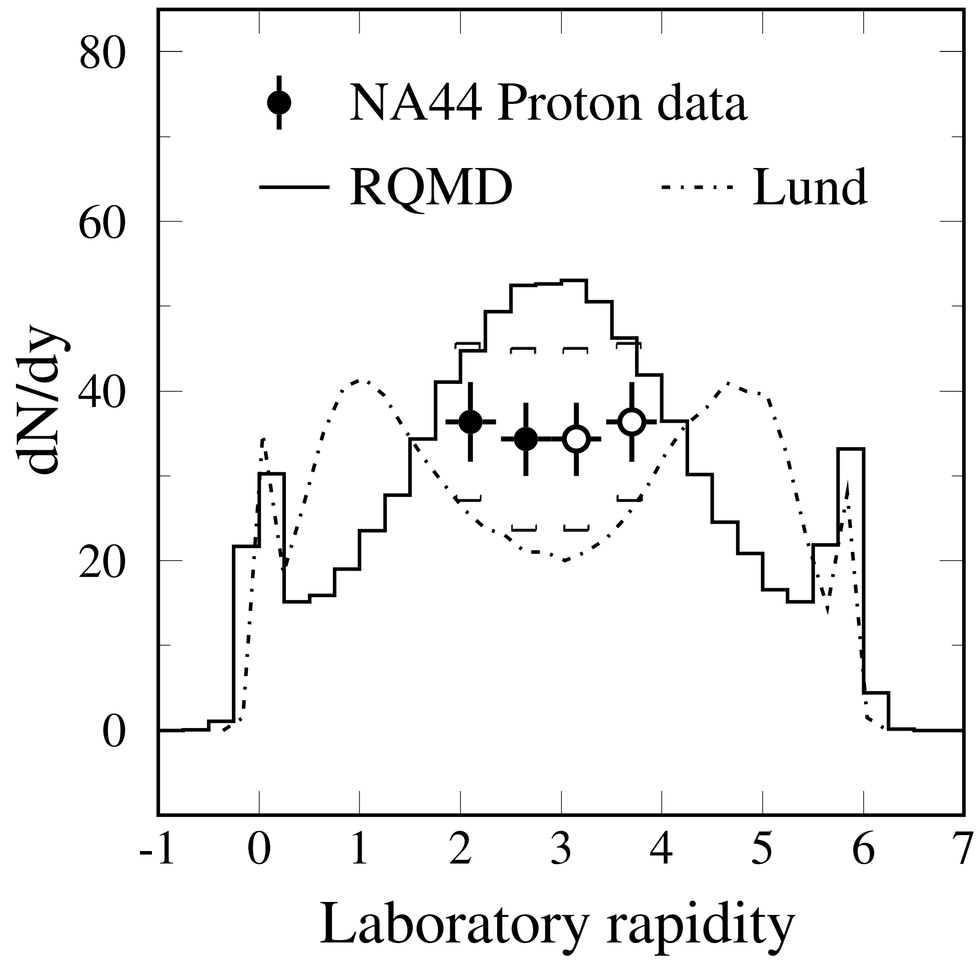
Fig. 3 Proton rapidity distributions from central ($\sigma_{trig}/\sigma \approx 6\%$)Pb + Pb collisions. The open circles are the mirrored points about $y_{mid} = 2.9$. Statistical errors are shown as vertical bars and the systematic errors are shown by the vertical brackets. The horizontal error bars represent the rapidity coverage for each momentum setting. The RQMD calculation, including all resonance decays, is shown as a solid line. The FRITIOF model prediction is shown as a dot-dashed line.



TOF (ADC channel)
(a)
p
k$^+$
π^+
(b)
p
k$^+$
60
40
20
0
3
3.5
4
4.5
5
5.5
p (GeV/c)



T (MeV)
0.3
0.2
0.1
0
0 1 2 3 4 5 6
Rapidity
10^2
10
1
10^{-1}
10^{-2}
$1/(2\pi m_T)dN/dm_Tdy$ (GeV^{-2})
▼/10 4GeV/c, T = 230(18) MeV
● 8GeV/c, T = 289(7) MeV
0 0.25 0.5 0.75 1
m_T - mass (GeV)


80
NA44 Proton data
RQMD
Lund
60
dN/dy
40
20
0
-1
0
1
2
3
4
5
6
7
Laboratory rapidity