Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Physics Letters B 637 (2006) 39–42

PHYSICS LETTERS B

www.elsevier.com/locate/physletb

Boost invariance and multiplicity dependence of the charge balance function in π^+p and K$^+$p collisions at $\sqrt{s} = 22$ GeV

EHS/NA22 Collaboration

M.R. Atayan [a], Yuting Bai [b], E.A. De Wolf [c], A.M.F. Endler [d], Jinghua Fu [b], H. Gulkanyan [a], R. Hakobyan [a], W. Kittel [e], Lianshou Liu [b], Zhiming Li [b], Na Li [b], Z.V. Metreveli [f,1], L.N. Smirnova [g], L.A. Tikhonova [g], A.G. Tomaradze [f,1], Yuanfang Wu [b,*], S.A. Zotkin [g,2]

[a] *Institute of Physics, AM-375036 Yerevan, Armenia*
[b] *Institute of Particle Physics, Hua-Zhong Normal University, Wuhan 430070, China*
[c] *Department of Physics, University of Antwerp, B-2610 Wilrijk, Belgium*
[d] *Centro Brasileiro de Pesquisas Fisicas, BR-22290 Rio de Janeiro, Brazil*
[e] *Radboud University Nijmegen/NIKHEF, NL-6525 ED Nijmegen, The Netherlands*
[f] *Institute for High Energy Physics of Tbilisi State University, GE-380086 Tbilisi, Georgia*
[g] *Scobeltsyn Institute of Nuclear Physics, Lomonosow Moscow State University, RU-119899 Moscow, Russia*

Received 8 February 2006; accepted 18 April 2006

Available online 27 April 2006

Editor: M. Doser

Abstract

Boost invariance and multiplicity dependence of the charge balance function are studied in π^+p and K$^+$p collisions at 250 GeV/c incident beam momentum with full acceptance coverage. Charge balance, as well as charge fluctuations, are found to be boost invariant over the whole rapidity region, but both depend on the size of the rapidity window. It is also found that the balance function becomes narrower with increasing multiplicity, which is consistent with the narrowing of the balance function with increasing centrality and/or system size, as observed in current relativistic heavy ion experiments.

PACS: 13.85.Hd; 25.75.Gz

Keywords: Balance function; Boost-invariance; Multiplicity

Charge balance and charge flow are measures of rapidity correlations between oppositely charged particles and have been used to study hadronization in hadron–hadron as well as in lepton–hadron and e$^+$e$^-$ collisions [1]. In the form of a charge balance function (BF) [2], they have recently gained new interest in relativistic heavy ion collisions. A narrowing of the BF is suggested as a signature for delayed hadronization, where charge–anticharge particle pairs are created later and correlate more tightly in momentum space due to the formation of a quark–gluon plasma (QGP) in the early stage of the collision. The integral of the BF is related to the event-by-event charge fluctuations [3], which are also expected to be suppressed in a QGP [4].

So far, two heavy ion experiments [5,6] have measured the BF at various centralities and for different colliding nuclei. A narrowing of the BF is indeed observed with increasing centrality of the collision and with increasing size of the colliding nuclei. Although this experimental result seems to be a support for the formation of QGP, the measured charge fluctuations, on the other hand, are consistent with those expected for a hadronic gas [7–9].

* Corresponding author.
E-mail address: wuyf@iopp.ccnu.edu.cn (Y. Wu).

[1] Now at Northwestern University, Evanston, USA.
[2] Now at DESY, Hamburg, Germany.

0370-2693
doi:10.1016/j.physletb.2006.04.027

Before drawing any conclusion from the observed narrowing of the BF, it is necessary to know how the BF behaves in hadron–hadron collisions [10], where no QGP is expected and hadronization is nearly instantaneous, and how the limited detector acceptance influences the width of the BF [2,3,11]. Since current heavy ion experiments [5,6,9] cover only a limited rapidity region, the measured BF's do not correspond to that for the full rapidity region. Whether the results from different heavy ion experiments are comparable or not depend on the influence of the acceptance.

A number of theoretical discussions [3,4,12] have been devoted to the influence of acceptance. In particular, in Ref. [3], based on the assumption of longitudinal boost invariance, Jeon and Pratt proposed a relation between the balance function in a rapidity window $B(\delta y|Y_{\mathrm{w}})$ and in the full rapidity range $B(\delta y|Y=\infty)$,

$$B(\delta y|Y_{\mathrm{w}}) = B(\delta y|\infty)\left(1-\frac{\delta y}{Y_{\mathrm{w}}}\right), \tag{1}$$

where Y_{w} is the size of the rapidity window and $B(\delta y|Y_{\mathrm{w}})$ can be measured by

$$B(\delta y|Y_{\mathrm{w}}) = \frac{1}{2}\left[\frac{\langle n_{+-}(\delta y)\rangle - \langle n_{++}(\delta y)\rangle}{\langle n_{+}\rangle} + \frac{\langle n_{-+}(\delta y)\rangle - \langle n_{--}(\delta y)\rangle}{\langle n_{-}\rangle}\right]. \tag{2}$$

Here, $n_{+-}(\delta y)$, $n_{++}(\delta y)$ and $n_{--}(\delta y)$ are the numbers of pairs of opposite- and like-charged particles satisfying the criteria that they fall into the rapidity window Y_{w} and that their relative rapidity equals δy; n_{+} and n_{-} are the numbers of positively and negatively charged particles, respectively, in the interval Y_{w}.

Conventionally, boost invariance refers to particle density being independent of rapidity, as originally assumed in [13] and applied in a simple solvable hydrodynamic model [14]. While this may be correct in a very restricted region at mid-rapidity for the *rapidity density* itself [15], boost invariance of the *balance function* only requires that the *charge correlation* between final state particles be the same in any longitudinally-Lorentz-transformed frame. Whether the BF is boost invariant over the *whole* rapidity region or only in the central region, cannot be simply deduced from the corresponding shape of the rapidity density distribution. This important issue has not yet been investigated in either its theoretical or its experimental aspects.

In this Letter, boost invariance and multiplicity dependence of the charge balance function is studied on π^{+}p and K^{+}p data at 250 GeV/c ($\sqrt{s}=22$ GeV) of the NA22 experiment. This experiment was equipped with a rapid cycling bubble chamber as an active vertex detector, had $\Delta p/p = 1.5\%$ momentum resolution and 4π acceptance. The latter feature allows, for the first time, to study the properties of the balance function in full phase space.

Since no statistically significant differences are seen between the results for π^{+} and K^{+} induced reactions, the two data samples are combined for the purpose of this analysis. A total of 44 524 non-single-diffractive events is obtained after all necessary selections (all tracks well reconstructed, exclusion of elastic and single-diffractive events), as described in detail in [16]. In particular, possible contamination from secondary interactions is suppressed by a double visual scan with 99.5% efficiency and the requirement that overall charge balance be satisfied within the whole event; γ conversions near the primary vertex are removed by electron identification.

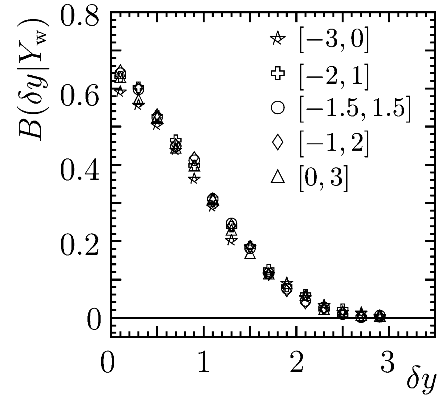

Fig. 1. The balance function for five different positions of a rapidity window of size $Y_{\mathrm{w}}=3$.

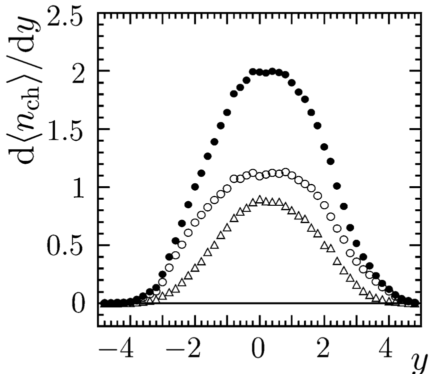

Fig. 2. The c.m. rapidity distributions of positively (open circles), negatively (open triangles), and all (solid circles) charged particles.

In Fig. 1, the balance function is shown for five rapidity windows of width $Y_{\mathrm{w}}=3$, located at different c.m. rapidity positions, $[-3,0]$, $[-2,1]$, $[-1.5,1.5]$, $[-1,2]$, and $[0,3]$. In this and the following figures, errors are smaller than the size of the symbols. The five functions coincide within the experimental errors, except that a few points in $[-3,0]$ are somewhat lower than the others. This is caused by very low multiplicities in the rapidity region $[-3,-2]$, where unidentified protons contribute and where the rapidity distribution is not completely symmetric to the rapidity region $[+2,+3]$. The figure demonstrates that, despite a strong rapidity dependence of the particle density given in Fig. 2, the balance function is largely independent of the position of the rapidity window, i.e., the charge correlation is essentially the same in any longitudinally-Lorentz-transformed frame.

Since boost invariance of the BF is found to be valid over the whole rapidity region, it is now interesting to verify if the BF in a limited rapidity window can be deduced from that in the full rapidity region by Eq. (1), and vice versa. In Fig. 3, the balance function, $B(\delta y|Y_{\mathrm{w}})$ (solid points), for four rapidity windows (central in Fig. 3(a), non-central in Fig. 3(b)), is

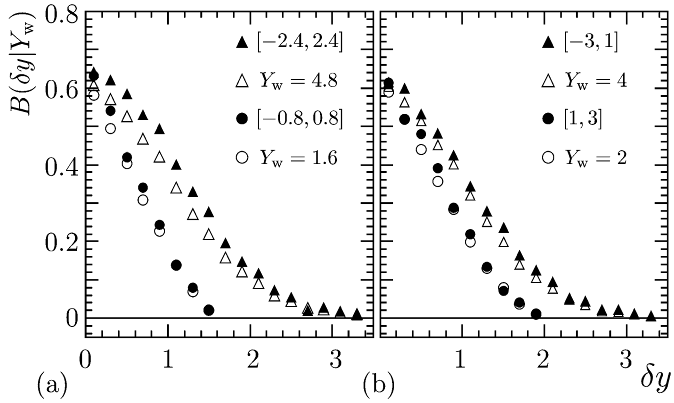

Fig. 3. The balance functions $B(\delta y|Y_w)$ (solid symbols) (a) for two central rapidity windows, $[-2.4, 2.4]$ and $[-0.8, 0.8]$ and (b) two asymmetric rapidity windows $[-3, 1]$, and $[1, 3]$, compared with the corresponding $B(\delta y|\infty) \cdot (1 - \frac{\delta y}{Y_w})$ (open symbols).

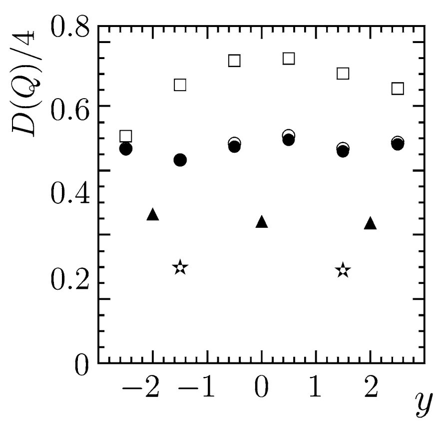

Fig. 4. $D(Q)/4$ versus the position of a rapidity window of size $Y_w = 1$ (circles), 2 (triangles), and 3 (stars). Open circles and open squares are, respectively, $D(Q)/4$ under the same transverse momentum and azimuthal angle cuts as used by STAR ($p_t > 0.1$ GeV/c) and PHENIX ($p_t > 0.2$ GeV/c and $\Delta\phi = \pi/2$) with a rapidity window of size $Y_w = 1.0$.

compared to $B(\delta y|\infty)(1 - \frac{\delta y}{Y_w})$ (open points) obtained for the corresponding window from the BF in the full region. The data confirm that the relation Eq. (1) is indeed approximately satisfied, independently of size or position of the window. This result is especially important for experiments with limited acceptance, in particular for the current heavy ion experiments.

Fig. 3 further illustrates that the BF becomes narrower with decreasing Y_w, in agreement with Eq. (1).

Since the charge fluctuation $D(Q)$ [3] is approximately related to the BF by

$$\frac{D(Q)}{4} = 1 - \int_0^{Y_w} B(\delta y|Y_w)\,\mathrm{d}\delta y + \mathcal{O}\left(\frac{\langle Q\rangle}{\langle n_{ch}\rangle}\right), \quad (3)$$

where $Q = n_+ - n_-$ and $n_{ch} = n_+ + n_-$, it is interesting to see how the charge fluctuation changes with position and size of a rapidity window. For this purpose, $D(Q)/4$ is presented in Fig. 4 for different positions and sizes of a rapidity window. The results confirm that for the given window size the measured charge fluctuation is independent of the position of that window [17], in agreement with boost invariance of the BF. The data also show that the smaller the rapidity window the larger the fluctuation. So it is necessary to give the exact size of the rapidity region when the fluctuation is treated quantitatively [4].

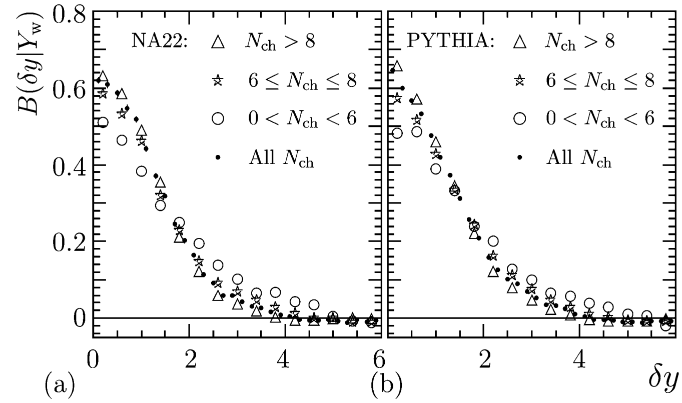

Fig. 5. The balance function for all charged particles and for three multiplicity intervals from NA22 and PYTHIA.

Table 1
The width of the BF in three multiplicity intervals and for all charged particles

Multiplicity	$\langle\delta y\rangle_{NA22}$	$\langle\delta y\rangle_{PYTHIA}$
$n_{ch} > 8$	0.957 ± 0.011	1.116 ± 0.011
$6 \leqslant n_{ch} \leqslant 8$	1.096 ± 0.014	1.307 ± 0.017
$0 < n_{ch} < 6$	1.359 ± 0.026	1.530 ± 0.012
All n_{ch}	0.991 ± 0.008	1.232 ± 0.007

As has been demonstrated in [17], $D(Q)$ also depends on the acceptance in transverse momentum and/or azimuthal angle. $D(Q)/4$ obtained under the same cuts as used by STAR ($p_t > 0.1$ GeV/c) and PHENIX ($p_t > 0.2$ GeV/c and $\Delta\phi = \pi/2$) with $Y_w = 1.0$ is presented in Fig. 4 as open points. The cut used by STAR has little influence on the result, while those used by PHENIX destroy the boost invariance of $D(Q)$. These results show that a limited acceptance can destroy the boost invariance of charge fluctuations and the effect is the larger the larger the percentage of particles lost.

In Fig. 5(a), the full-rapidity BF is presented for all charged particles as well as for three multiplicity intervals. The width of the BF, defined as

$$\langle\delta y\rangle = \frac{\sum_i B(\delta y_i|\infty)\delta y_i}{\sum_i B(\delta y_i|\infty)}, \quad (4)$$

for the corresponding multiplicity intervals and for all charged particles is listed in Table 1. The width decreases with increasing multiplicity, which is, at least qualitatively, consistent with the narrowing of the BF with increasing centrality observed in current heavy ion experiments [5,6]. The corresponding results from PYTHIA 5.720 with Bose–Einstein correlation (BEC) [18] are given in Fig. 5(b) and Table 1. The hadronization scheme with string fragmentation implemented in PYTHIA qualitatively reproduces the trend of the data. Therefore, before a narrowing of the BF with increasing centrality and increasing mass number of the colliding nuclei can be interpreted as due to delayed hadronization connected to the possible formation of a QGP, the multiplicity effect observed here, which has nothing to do with the formation of a new state of matter, should be properly taken into account. This will relax the apparent contradiction between the narrowing of BF and the charge-fluctuation measurement in current heavy ion experiments.

We have measured the boost invariance and multiplicity dependence of the charge balance function in π^+p and K^+p collisions at $\sqrt{s} = 22$ GeV. The results demonstrate the following issues: (1) In contrast to the strong dependence of the single-particle density on rapidity, the BF is found to be invariant under a longitudinal boost over the whole rapidity region. This property allows to determine the BF in full rapidity, $B(\delta y|\infty)$, from a measurement with limited rapidity acceptance. (2) The BF becomes narrower with decreasing size of the rapidity window. Therefore, only the full-rapidity BF can be used in comparing data from different experiments. (3) The BF becomes narrower with increasing multiplicity, an effect also observed in heavy ion interactions when the centrality of the collision increases. (4) Similar to the BF, the charge fluctuations are boost invariant but depend on the size of the rapidity window.

Acknowledgements

This work is part of the research program of the "Stichting voor Fundamenteel Onderzoek der Materie (FOM)", which is financially supported by the "Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO)". We further thank NWO for support of this project within the program for subsistence to the former Soviet Union (07-13-038). The Yerevan group activity is financially supported, in the framework of the theme No. 0248, by the Government of the Republic of Armenia. This work is supported in part by the NNSF of China with project Nos. 90503001, 10475030 and 90103019 and MOE of China with project No. CFKSTIP-704035 and by the Royal Dutch Academy of Sciences under the Project numbers 01CDP017, 02CDP011 and 02CDP032 and by the U.S. Department of Energy.

References

[1] D. Drijard, et al., Nucl. Phys. B 155 (1979) 269;
D. Drijard, et al., Nucl. Phys. B 166 (1980) 233;
I.V. Ajinenko, et al., Z. Phys. C 43 (1989) 37;
P. Allen, et al., Phys. Lett. B 112 (1982) 88;
M. Arneodo, et al., Z. Phys. C 36 (1987) 527;
H. Aihara, et al., Phys. Rev. Lett. 53 (1984) 2199;
H. Aihara, et al., Phys. Rev. Lett. 57 (1986) 3140;
P.D. Acton, et al., Phys. Lett. B 305 (1993) 415.
[2] S.A. Bass, P. Danielewicz, S. Pratt, Phys. Rev. Lett. 85 (2000) 2689.
[3] S. Jeon, S. Pratt, Phys. Rev. C 65 (2002) 044902.
[4] S. Jeon, V. Koch, Phys. Rev. Lett. 85 (2000) 2076;
M. Asakawa, V. Koch, M. Bleicher, S. Jeon, Nucl. Phys. A 698 (2002) 261.
[5] J. Adams, et al., STAR Collaboration, Phys. Rev. Lett. 90 (2003) 172301.
[6] C. Alt, et al., NA49 Collaboration, Phys. Rev. C 71 (2005) 034903.
[7] J.T. Mitchell, J. Phys. G 30 (2004) S819.
[8] J. Adams, et al., STAR Collaboration, Phys. Rev. C 68 (2003) 044905;
C.A. Pruneau, Heavy Ion Phys. 21 (2004) 261.
[9] K. Adcox, et al., PHENIX Collaboration, Phys. Rev. Lett. 89 (2002) 082301.
[10] T.A. Trainor, hep-ph/0301122.
[11] A. Białas, Phys. Lett. B 579 (2004) 31.
[12] C. Pruneau, S. Gavin, S. Voloshin, Phys. Rev. C 66 (2002) 044904;
S. Mrówczyński, Phys. Rev. C 66 (2002) 024902;
S. Mrówczyński, Phys. Lett. B 465 (1999) 8;
M. Bleicher, S. Jeon, V. Koch, Phys. Rev. C 62 (2000) 061902.
[13] R.P. Feynman, Phys. Rev. Lett. 23 (1969) 1415.
[14] F. Cooper, G. Frye, E. Schonberg, Phys. Rev. D 11 (1974) 192;
J.D. Bjorken, Phys. Rev. D 27 (1983) 140.
[15] G. Alner, et al., UA5 Collaboration, Z. Phys. C 33 (1986) 1;
F. Abe, et al., CDF Collaboration, Phys. Rev. D 41 (1990) 2330;
B.B. Back, et al., PHOBOS Collaboration, Phys. Rev. Lett. 91 (2003) 052303;
B.B. Back, et al., PHOBOS Collaboration, Phys. Rev. Lett. 93 (2004) 082301.
[16] M. Adamus, et al., NA22 Collaboration, Z. Phys. C 32 (1986) 475;
M.R. Atayan, et al., NA22 Collaboration, Eur. Phys. J. C 21 (2001) 271.
[17] M.R. Atayan, et al., NA22 Collaboration, Phys. Rev. D 71 (2005) 012002.
[18] T. Sjöstrand, Comput. Phys. Commun. 82 (1994) 74.