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Rapidity, azimuthal, and multiplicity dependence of mean transverse momentum and transverse momentum correlations in π^+p and K$^+$p collisions in $\sqrt{s} = 22$ GeV

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Rapidity, azimuthal and multiplicity dependence of mean transverse momentum and transverse momentum correlations of charged particles is studied in π^+p and K$^+$p collisions at 250 GeV/c incident beam momentum. For the first time, it is found that the rapidity dependence of the two-particle transverse momentum correlation is different from that of the mean transverse momentum, but both have similar multiplicity dependence. In particular, the transverse momentum correlations are boost invariant. This is similar to the recently found boost invariance of the charge balance function. A strong azimuthal dependence of the transverse momentum correlations originates from the constraint of energy-momentum conservation. The results are compared with those from the PYTHIA Monte Carlo generator. The similarities to and differences with the results from current heavy ion experiments are discussed.

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The transverse momenta of final state particles are produced after the collision and carry information on system expansion. Their fluctuations are considered to be a good probe for the formation of a quark-gluon plasma (QGP) [1,2] and a trace of local thermal equilibrium [3]. Therefore, these fluctuations have attracted a lot of attention from both theoretical and experimental investigations on relativistic heavy ion collisions [4].

All current heavy ion experiments report substantial dynamical fluctuations of transverse momentum $p_{\rm t}$. Preliminary PHENIX and STAR data on Au + Au collisions show that $p_{\rm t}$ fluctuations increase as centrality increases and a similar increase is observed in the mean transverse momentum [5,6]. However, it is not clear how these fluctuations differ from those observed in elementary collisions, where no QGP is expected.

In general, it is believed that transverse expansion extends over a wide rapidity range and correlates with longitudinal expansion [7]. However, exactly how the transverse expansion relates to the longitudinal one is unexplored even for the elementary collisions. Detailed investigation on these phenomena in elementary collisions is important for a correct evolution picture of high energy collisions and for the understanding of the related phenomena in current heavy ion experiments. This kind of investigation is possible only in an experiment with full acceptance, such as the hadron-hadron experiment NA22, which makes use of a rapid cycling bubble chamber as an active vertex detector and has excellent momentum resolution in full 4π acceptance.

Since the measure of transverse momentum fluctuation in terms of a variable $\Phi_{p_{\rm t}}$ was suggested [8], a number of other variables have been recommended [3,6,7,9–12] to extract the genuine dynamical fluctuations. The common and essential part of these variables is the event two-particle transverse momentum correlation $\sum_{i=1}^{n_{\rm ch}} \sum_{j=1,i\neq j}^{n_{\rm ch}} p_{{\rm t}i} p_{{\rm t}j}$. Hence, in the following, we shall focus on this most simple correlation.

There are two schemes of normalization for this correlation. One is to normalize by the number of charged-particle pairs $n_{\rm ch}(n_{\rm ch}-1)$ of an event in the considered window and the corresponding average of the event mean transverse momentum of charged particles, $\langle \bar{p}_{\rm t} \rangle$, i.e.,

$$R(p_{{\rm t}i}, p_{{\rm t}j}) = \left\langle \frac{\sum_{i=1}^{n_{\rm ch}} \sum_{j=1,i\neq j}^{n_{\rm ch}} p_{{\rm t}i} p_{{\rm t}j}}{n_{\rm ch}(n_{\rm ch}-1)} \right\rangle \frac{1}{\langle \bar{p}_{\rm t} \rangle^2}, \qquad (1)$$

where $n_{\rm ch}$ is the number of charged particles and $p_{{\rm t}i}$ is the absolute value of transverse momentum of the ith particle. The bar corresponds to the average over all charged particles in an event and $\langle \ldots \rangle$ is the average over all events. The variable R defined in this way is referred to as the *event mean two-particle transverse momentum correlation*. It is one unit larger than the measure

$$\langle \Delta p_{\rm ti} \Delta p_{\rm tj} \rangle = \left\langle \frac{\sum_{i=1}^{n_{\rm ch}} \sum_{j=1, i\neq j}^{n_{\rm ch}} (p_{\rm ti} - \langle \bar{p}_{\rm t} \rangle)(p_{\rm tj} - \langle \bar{p}_{\rm t} \rangle)}{n_{\rm ch}(n_{\rm ch} - 1)} \right\rangle \times \frac{1}{\langle \bar{p}_{\rm t} \rangle^2} \qquad (2)$$

as used by the STAR Collaboration [11].

Another scheme is to normalize by the average number of charged-particle pairs $\langle n_{\rm ch}(n_{\rm ch} - 1)\rangle$ and by the inclusive mean transverse momentum of charged particles $\langle p_{\rm t} \rangle$, i.e.,

$$R'(p_{{\rm t}i}, p_{{\rm t}j}) = \frac{\langle \sum_{i=1}^{n_{\rm ch}} \sum_{j=1, i\neq j}^{n_{\rm ch}} p_{{\rm t}i} p_{{\rm t}j} \rangle}{\langle n_{\rm ch}(n_{\rm ch} - 1)\rangle \langle p_{\rm t} \rangle^2}. \qquad (3)$$

This normalization is strongly recommended by S. Voloshin *et al.* [7,10], who argue that it is directly related to the well defined two-particle transverse momentum correlation. This is different from the supposedly "bad" ratiolike observables, such as R defined in Eq. (1) or the charge ratio [13]. Under this normalization, the measure of Eq. (2) becomes:

$$\langle \Delta p_{{\rm t}i} \Delta p_{{\rm t}j} \rangle = \frac{\langle \sum_{i=1}^{n_{\rm ch}} \sum_{j=1, i\neq j}^{n_{\rm ch}} (p_{{\rm t}i} - \langle p_{\rm t} \rangle)(p_{{\rm t}j} - \langle p_{\rm t} \rangle) \rangle}{\langle n_{\rm ch}(n_{\rm ch} - 1)\rangle \langle p_{\rm t} \rangle^2}. \qquad (4)$$

However, this measure is not directly related to the two-particle correlation R' since it contains an extra $p_{\rm t}$-$n_{\rm ch}$ correlation.

It is clear that a good measure should be sensitive to the underlying dynamics and less dependent on the effects from detector acceptance (e.g., rapidity, azimuthal and $p_{\rm t}$ regions used to calculate the observables), the colliding system size, and the collision centrality [14]. The NA22 data allow to test the robustness of these two measures—R and R'.

In the present paper, we study the rapidity, azimuthal and multiplicity dependence of the mean transverse momentum and the two-particle transverse momentum correlations of charged particles defined by Eqs. (1) and (3) in π^+p and K$^+$p collisions at 250 GeV/c ($\sqrt{s} = 22$ GeV) of the NA22 experiment. Since no statistically significant differences are seen between the results from 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, as described in detail in [15]. In particular, possible contamination from secondary interactions is suppressed by a visual scan and the requirement that overall charge balance be satisfied within the whole event; γ conversions near the primary vertex are removed by electron identification. The systematic uncertainties of the analysis are smaller than the statistical errors and no correction for resonance decays is applied in the analysis.

In Fig. 1, $\langle p_{\rm t} \rangle$, R and R' are presented for different central rapidity windows with $|y| < Y_{\rm c}$ (upper row), as well as for a rapidity window of unit width centered at different positions (lower row). In these and the following figures, the full circles and triangles correspond to the data and the corresponding open ones are the results of PYTHIA 5.720 [16] Monte Carlo simulation.

From Figs. 1(a) and 1(c), we can see that the inclusive mean transverse momentum is small in the central, target and projectile regions but relatively large in the two mid-rapidity regions $[+1, +2]$ and $[-1, -2]$. This result is consistent with the well-known sea-gull effect [17]. On the other hand, for Au-Au collisions at 200 GeV [5] it keeps decreasing with increasing size of the central rapidity window. This shows that the sea-gull effect is smeared in nuclear collisions.

The results from PYTHIA are flat in a rather wide central rapidity region ranging from -2 to 2, but decrease in the target and projectile regions. Though the difference between data and PYTHIA is large in the central region, the results tend to be close in the full rapidity region since PYTHIA gives lower estimates in both target and projectile regions, cf. Fig. 1(c).

The event two-particle transverse momentum correlations measured by R, as shown in Figs. 1(b) and 1(d), are nearly independent of size and position of the rapidity window. An exception are the left-most and right-most windows $[-3, -2]$ and $[+2, +3]$, where R is lower than in the other ones. The former is caused by the contribution from unidentified protons in the region $[-3, -2]$, where the rapidity distribution is not completely symmetric to the rapidity region $[+2, +3]$. These results agree with those from the most central Au-Au collisions at 200 GeV, but are different from those from the peripheral collisions where a dependence on the size of the rapidity window is observed [11].

It can be seen from the same figures that R' decreases with increasing rapidity window and also depends on the position of that window, in a way similar to the behavior of the rapidity density distribution itself [18]. This shows that R' still contains the multiplicity effect, which is proportional to the rapidity density. So R is less dependent on the rapidity region used in an experiment than R'.

The approximate rapidity independence of R demonstrates that the transverse momentum correlation is longitudinal momentum independent or boost invariant. This is similar to the boost invariance of the charge balance function found recently [18]. PYTHIA qualitatively reproduces the trend of the data.

The azimuthal window-size dependence of the inclusive mean transverse momentum $\langle p_{\rm t} \rangle$ and the two-particle transverse momentum correlation R is shown in

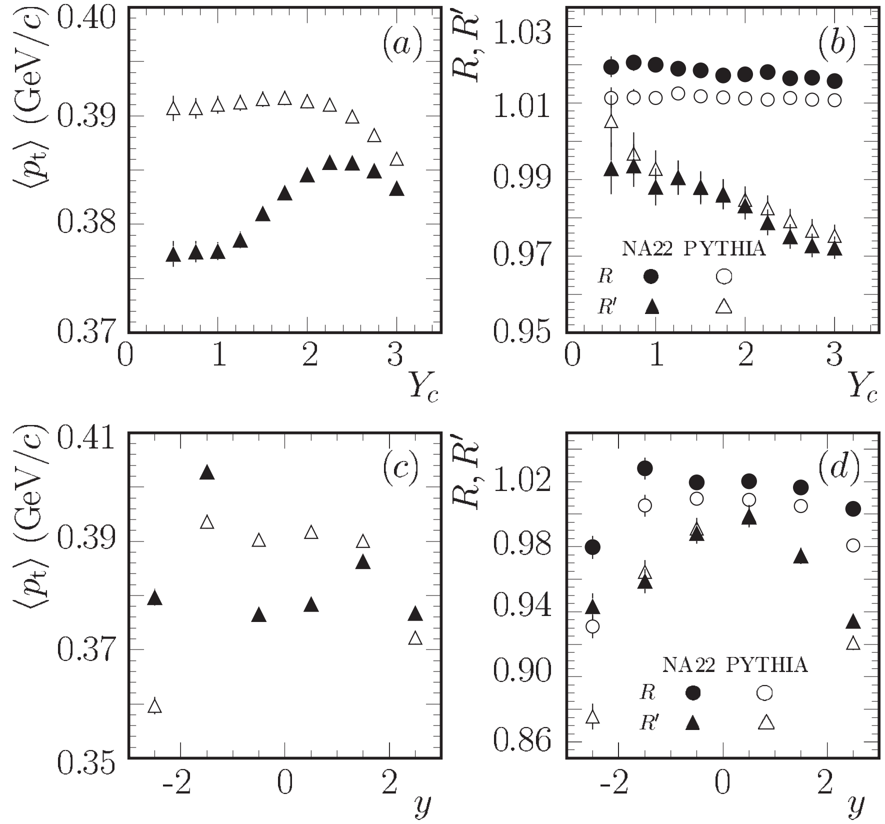

FIG. 1. The inclusive mean transverse momentum $\langle p_t \rangle$ of charged particles, (a) and (c), and two-particle transverse momentum correlation measures R and R' of charged particles, (b) and (d), in different central rapidity windows with $|y| < Y_c$ (upper row), as well as in a unit rapidity window at different positions (lower row).

Figs. 2(a) and 2(b), respectively. Here, the azimuthal angle ϕ_i of every charged particle is referenced to a fixed direction in the laboratory frame and each point in the figures represents the measures for a subsample of tracks with an azimuthal angle less than $\phi_{\rm cut}$, i.e., $\phi_i < \phi_{\rm cut}$. It can be seen from Fig. 2(a) that $\langle p_t \rangle$ is independent of the azimuthal window size within experimental errors. On the other hand, R increases with increasing $\phi_{\rm cut}$.

This dependence can be understood from the constraints of energy-momentum conservation. The constraint of energy conservation suppresses large transverse momentum particles on the same side of the ϕ plane, so that the correlation decreases when $\phi_{\rm cut} < \pi$. The increase of the correlation at $\pi < \phi_{\rm cut} < 2\pi$ originates from the back-to-back correlation due to transverse momentum conservation in the full ϕ plane.

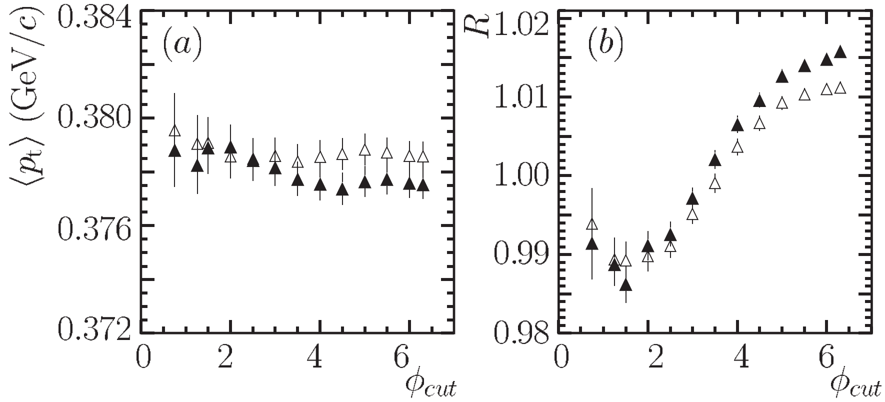

FIG. 2. The inclusive mean transverse momentum $\langle p_t \rangle$ of charged particles (a) and two-charged-particle transverse momentum correlation R (b) for different azimuthal angular cuts.

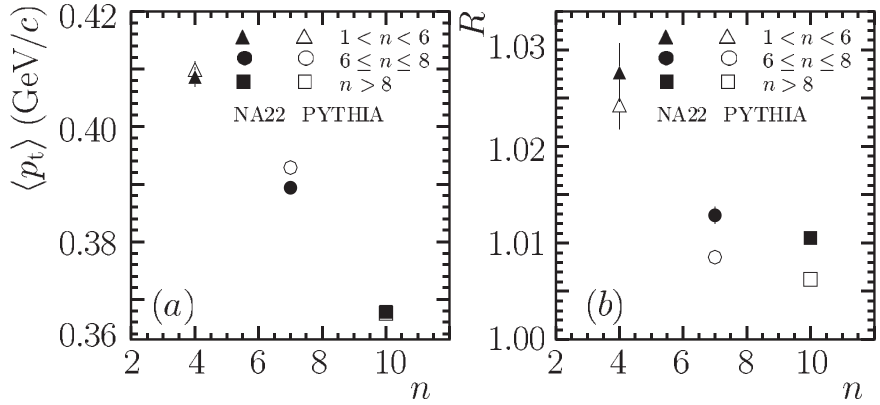

FIG. 3. The multiplicity dependence of inclusive mean transverse momentum $\langle p_t \rangle$ of charged particles (a) and two-charged-particle transverse momentum correlation R (b).

The above result shows that the transverse momentum correlation is indeed influenced by the size of the azimuthal window. This explains why the transverse momentum fluctuation is larger in NA22 [19] than in NA49 [20]. So, although the mean transverse momentum is uniformly distributed in the ϕ plane, the two-particle transverse momentum correlations vary with the size of the azimuthal window, due to the constraint of energy-momentum conservation in the full ϕ plane. PYTHIA reproduces this dependence.

The multiplicity dependence of the mean transverse momentum $\langle p_t \rangle$ and the two-particle transverse momentum correlation R is presented in Figs. 3(a) and 3(b), respectively. Both $\langle p_t \rangle$ and R decrease with increasing multiplicity. The latter effect is consistent with the centrality dependence of $\langle \Delta p_{ti} \Delta p_{tj} \rangle$ observed by STAR and HIJING for nuclear collisions at different colliding energies, though the results from HIJING are much lower than those of STAR [21]. So, the smaller the event multiplicity, the stronger are the event mean two-particle transverse momentum correlations.

We have measured the rapidity, azimuthal and multiplicity dependence of mean transverse momentum and transverse momentum correlations of charged particles in π^+p and K$^+$p collisions at $\sqrt{s} = 22$ GeV$/c$. The results show the following:

(1) $\langle p_t \rangle$ depends both on the size and on the position of the rapidity window, in agreement with the well-known sea-gull effect.

Contrary to the measure of R', the event mean two-particle transverse momentum correlation measured by R is nearly independent of the size and the position of the rapidity window. This reveals for the first time that the transverse momentum correlations are nearly longitudinal momentum independent, or boost invariant. This is similar to the boost invariance of the charge balance function. Our result is consistent with the results for the most central Au-Au collisions at 200 GeV, rather than those for the peripheral ones where the correlation depends on the size of the rapidity region.

The PYTHIA Monte Carlo can roughly describe the rapidity dependence of R but not that of $\langle p_t \rangle$.

(2) The inclusive mean transverse momentum $\langle p_t \rangle$ is uniformly distributed in the ϕ plane, but due to energy-momentum conservation, R strongly depends on the size of the azimuthal window.

(3) $\langle p_t \rangle$ and R decrease with increasing multiplicity. This is consistent with the centrality dependence of $\langle \Delta p_{ti} \Delta p_{tj} \rangle$ as reported by STAR for colliding energies from 20 to 200 GeV [21], while $\langle p_t \rangle$ increases with increasing multiplicity when the collision energy is above ISR energy [22].

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