Transverse-Momentum Fluctuations in $\pi^+ p$ and $K^+ p$ Collisions at 250 GeV/c

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We report results on event-by-event fluctuations of transverse momentum, Φ_{p_t}, in $\pi^+ p$ and $K^+ p$ collisions at 250 GeV/c. For the first time, their dependence on rapidity region, transverse momentum acceptance, multiplicity, mean transverse momentum per event, and on the correlation between transverse momentum and multiplicity are systematically presented. The results are compared with those from the PYTHIA Monte Carlo generator. The fluctuations under the same acceptance cuts as used in current heavy-ion experiments are also presented.

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Since the introduction of the measure Φ_{p_t} for event-by-event fluctuations of transverse momentum [1], this variable has drawn a lot of attention in relativistic heavy-ion collisions (see [2] for a review). It is considered to be one of the important tools in the attempt to identify a quark-gluon plasma phase transition [3], where large fluctuations in energy density are expected. Φ_{p_t} is defined by the second-moment difference,

$$\Phi_{p_t} = \sqrt{\langle Z^2 \rangle / \langle n \rangle} - \sqrt{\langle z^2 \rangle}, \tag{1}$$

where $z = p_t - \langle p_t \rangle$ is the deviation of the single-particle transverse momentum from its sample average, $Z = \sum_{i=1}^{n} z_i$, with summation over all n (charged) particles in an event. If the particles are emitted independently, $\langle Z^2 \rangle / \langle n \rangle = \langle z^2 \rangle$, and Φ_{p_t} vanishes.

However, results reported in heavy-ion collisions differ from each other [4,5]. To help understand these differences, it is necessary to find out how phase space cuts influence the measurement of Φ_{p_t}. This is possible in the hadron-hadron experiment NA22, which is equipped with a rapid cycling bubble chamber as an active vertex detector and has excellent momentum resolution over its full 4π acceptance.

Another question of common interest is the origin of the fluctuations. Originally, it was assumed that they are mainly due to the correlations between transverse momentum and multiplicity [1]. This was confirmed by Monte Carlo simulations [6]. Later, the influences of other correlations such as two-particle, in particular, Bose-Einstein, correlations (BEC) to the fluctuations were considered [7,8].

In this Letter, a study is presented of Φ_{p_t} in $\pi^+ p$ and $K^+ p$ collisions at 250 GeV/c from NA22. A total of 44 524 non-single-diffractive events is obtained after all necessary rejections. The selection of the data is described in detail in [9]. Secondary interactions are suppressed by a visual scan and the requirement of charge balance, γ conversion near the vertex by electron identification.

In Fig. 1(a), Φ_{p_t} is presented for six central rapidity regions $|y| < Y_c$, where the solid triangles are the data. The value of Φ_{p_t} increases as the rapidity region widens from the center, but reaches its saturation value at $Y_c \approx 2$. Thus, when only part of the central rapidity region is covered in the measurement, the value of Φ_{p_t} will be lower than the one for the full region. However, once the central plateau

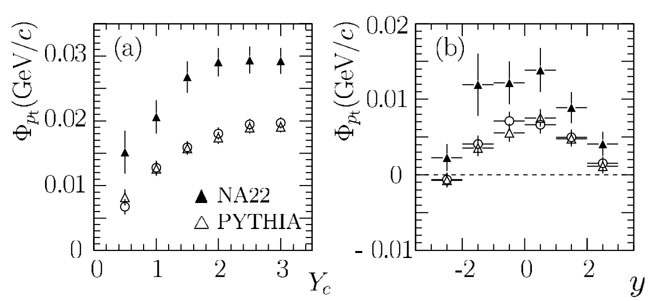

FIG. 1. The dependence of Φ_{p_t} on (a) the size of a central rapidity region $|y| < Y_c$ and (b) the position of a noncentral rapidity bin indicated by the horizontal bar.

region is totally covered, Φ_{p_t} is representative for the full rapidity region. Figure 1(b) shows Φ_{p_t} for six noncentral rapidity intervals of unit width, confirming that the contribution of particles to the fluctuations in the fragmentation regions is negligible.

Figure 1 gives also the results from PYTHIA 5.720 with (circles) and without BEC (triangles), with Parj(21) = 0.484 tuned to the p_t distributions [10]. They show a similar tendency but underestimate the fluctuations. In the central rapidity region $|y| < 2$, the value of Φ_{p_t} for the NA22 data is $\Phi_{p_t} = 29.06 \pm 2.22$ MeV/c, significantly larger than observed in heavy-ion experiments [4,5]. The corresponding PYTHIA result without BEC is $\Phi_{p_t} = 17.38 \pm 0.94$ MeV/c.

In Fig. 2, the correlation between average transverse momentum $\langle p_t \rangle_n$ and multiplicity n is examined in different central rapidity regions. Contrary to Fig. 1, here PYTHIA gives a very good description of the data in all six regions. From the $\langle p_t \rangle_n$ values and the slopes of the decrease with increasing multiplicity n, it is observed that the correlation only changes very slowly with the size of the region. This implies that the correlation is not as closely related to the fluctuations as was expected in [1]. In the following, the analysis uses the interval $|y| < Y_c = 2$.

Besides different acceptance in y, different experiments have different acceptance for particles with very low transverse momentum. Therefore, four subsamples are studied, defined by $p_t > p_t^{cut}$, with $p_t^{cut} = 0.1$, 0.2, 0.3, and 0.4 GeV/c, respectively. The corresponding results for the data and for PYTHIA are listed in Table I. The higher the p_t^{cut}, the smaller are the fluctuations. Therefore, an experiment with bad low-p_t acceptance will measure smaller fluctuations than one with good low-p_t acceptance.

The $\langle p_t \rangle_n$ vs n correlations in the four subsamples are given in Fig. 3. The lowest-p_t^{cut} subsample has the strongest negative correlation and the highest-p_t^{cut} sample has the strongest positive one (see also [11]). This trend changes smoothly with increasing p_t^{cut} and the strongest-correlation subsample ($p_t^{cut} = 0.4$ GeV/c) has the smallest fluctuations. Again, this is in contradiction with the argument that the p_t fluctuations are mainly due to the correlations between $\langle p_t \rangle_n$ and n [1].

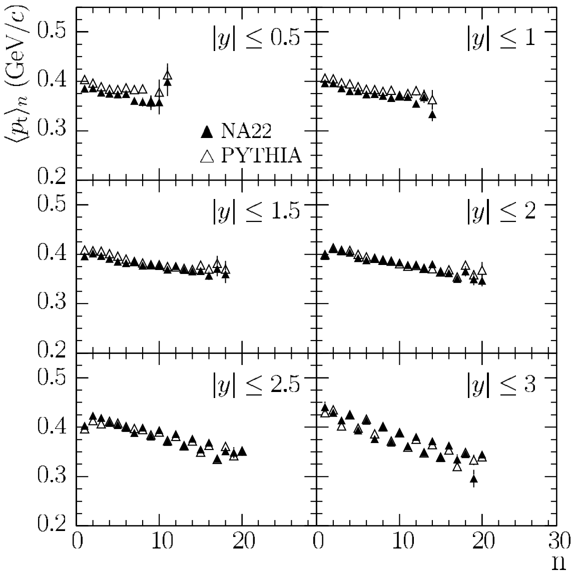

FIG. 2. $\langle p_t \rangle_n$ vs n in different rapidity regions.

Having established how the fluctuations depend on rapidity region and low-p_t acceptance in the NA22 data, one can investigate the influence of the acceptance cuts as used in current heavy-ion experiments. The results are listed in Table II. The value of 0.6 ± 1.0 MeV/c measured for central PbPb collisions at 158A GeV/c by the experiment NA49 [4] is considerably less than the value 7.8 ± 0.9 measured for central PbAu collisions at the same beam energy by CERES [5], while an extrapolation from NA22 would predict the opposite. Therefore, it will be interesting to see what the measured Φ_{p_t} will be in STAR, as compared to the values listed in the last three rows of Table II.

Since Φ_{p_t} measures event-by-event fluctuations, it is interesting to study its behavior in event subsamples distinguished by different values of typical global event variables. One such variable is the charged-particle multiplicity n. Another one, which roughly describes the hardness or softness degree of an event, is the mean

TABLE I. Φ_{p_t} for four different p_t^{cut} subsamples.

p_t^{cut} GeV/c	Sample	Number events	$\langle p_t \rangle$ GeV/c	$\langle n \rangle$	Φ_{p_t} MeV/c
0.1	NA22	43489	0.412 ± 0.0006	6.45 ± 0.02	25.79 ± 2.18
	PYTHIA	97723	0.419 ± 0.0004	5.94 ± 0.01	16.12 ± 0.94
0.2	NA22	42912	0.474 ± 0.0007	5.25 ± 0.02	20.73 ± 2.14
	PYTHIA	96730	0.483 ± 0.0004	4.85 ± 0.01	15.78 ± 0.96
0.3	NA22	41505	0.557 ± 0.0008	3.95 ± 0.02	16.79 ± 2.40
	PYTHIA	94308	0.561 ± 0.0004	3.72 ± 0.01	14.61 ± 1.00
0.4	NA22	38583	0.649 ± 0.0009	2.92 ± 0.01	14.09 ± 2.85
	PYTHIA	89111	0.646 ± 0.0005	2.82 ± 0.01	12.74 ± 1.08

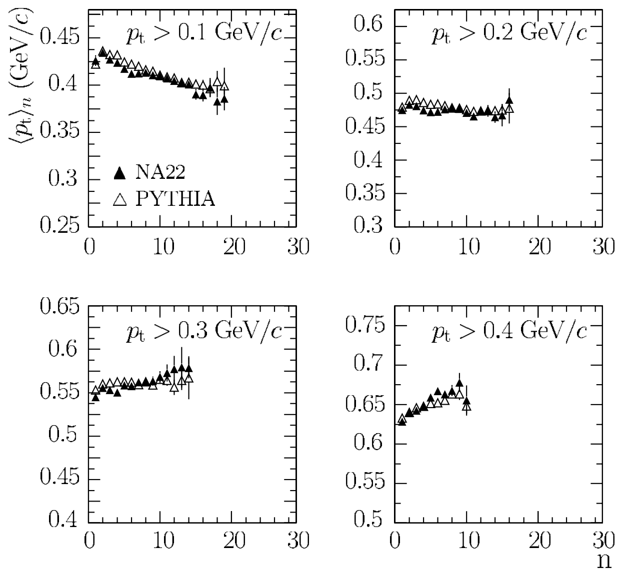

FIG. 3. $\langle p_t \rangle_n$ vs n for $p_t > 0.1$, 0.2, 0.3, and 0.4 GeV/c.

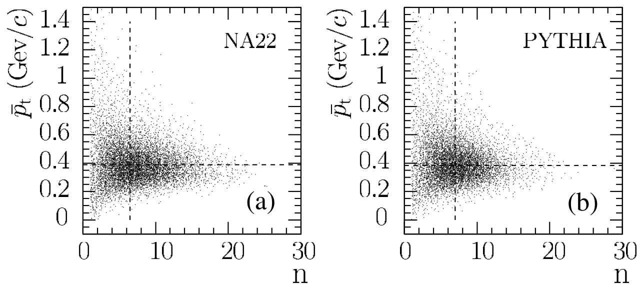

FIG. 4. Scatter plot of $\bar{p}_t$ vs n for NA22 data and PYTHIA Monte Carlo.

transverse momentum per event [12] defined as $\bar{p}_t = \sum_{i=1}^{n} p_{t_i}/n$. The scatter plots of $\bar{p}_t$ vs n are provided in Figs. 4(a) and 4(b) for the data and PYTHIA, respectively. At low multiplicity n, small-, intermediate-, and high-$\bar{p}_t$ events contribute. When the multiplicity increases, $\bar{p}_t$ is focused on intermediate values only.

First, the dependence of Φ_{p_t} on multiplicity n is studied. From Fig. 5, it is observed that Φ_{p_t} is always positive and increases with increasing multiplicity n. The results from PYTHIA show the same trend, but at lower Φ_{p_t} values. Since a linear n dependence of Φ_{p_t} is an interesting theoretical problem [2], which relates to the role of two-particle momentum correlations in the fluctuations, also Φ_{p_t}/n is provided in the figure (full squares). Except for the lowest n values, Φ_{p_t}/n is approximately constant, i.e., Φ_{p_t} indeed shows a linear dependence on n. This observation is supported by PYTHIA.

Next, the dependence of Φ_{p_t} on $\bar{p}_t$ is studied. The full sample is split into two by the cut (a) $\bar{p}_t < \langle p_t \rangle$ and (b) $\bar{p}_t \geq \langle p_t \rangle$, where $\langle p_t \rangle$ is the average over all events. The values of Φ_{p_t} and related quantities for these two subsamples are given in Table III.

TABLE II. Φ_{p_t} (in MeV/c) under the same acceptance cuts as used in current heavy-ion experiments.

	Acceptance cuts in cms	Heavy ion	NA22
NA49	$1.1 < y < 2.6$	0.6 ± 1.0	10.91
	$0.005 < p_t < 1.5$ GeV/c		± 1.54
CERES	$-0.8 < y < -0.25$	7.8 ± 0.9	2.16
	$0.05 < p_t < 1.5$ GeV/c		± 1.81
STAR	$-1 < y < 1$		14.57
	$0.15 < p_t < 2.0$ GeV/c		± 1.93
STAR	$-0.75 < y < 0.75$		12.52
	$0.15 < p_t < 2.0$ GeV/c		± 2.09
STAR	$-0.5 < y < 0.5$		9.77
	$0.15 < p_t < 2.0$ GeV/c		± 2.25

The negative Φ_{p_t} values can be understood from the definition of Z and $\bar{p}_t$. Whenever the region of $\bar{p}_t$ is restricted, the width of the Z distribution will be reduced. On the other hand, the distribution of z will not be modified significantly by the constraint. The width of the $Z/\langle n \rangle^{1/2}$ distribution, $\sigma(Z/\langle n \rangle^{1/2}) = 0.1470 \pm 0.0015$ GeV/c, is smaller than that of the z distribution, $\sigma(z) = 0.1960 \pm 0.0012$ GeV/c, so that Φ_{p_t} is negative.

Furthermore, Φ_{p_t} as a function of $\bar{p}_t$ is presented in Fig. 6. The Φ_{p_t} are negative at all $\bar{p}_t$ values and decrease monotonously with increasing $\bar{p}_t$. PYTHIA shows the same trend.

The $\langle p_t \rangle$ vs n correlations in subsamples (a) and (b) are given in Fig. 7. A positive correlation is observed at low n in subsample (a), followed by a saturation at higher n values. In subsample (b), on the contrary, the correlation is always negative. The corresponding results from PYTHIA show the same behavior. It is interesting to note that the opposite behavior of the $\langle p_t \rangle$ vs n correlations in the two subsamples does not result in qualitatively different fluctuations Φ_{p_t}.

The results can be summarized as follows: (i) Φ_{p_t} strongly depends on the rapidity region under consideration. The contributions from the fragmentation regions are negligible. Only the measurements in the total central plateau region are representative for the behavior in the

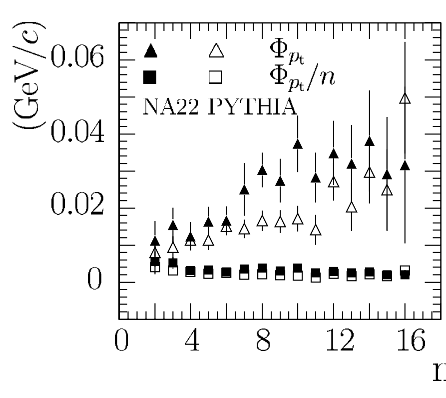

FIG. 5. The dependences of Φ_{p_t} and Φ_{p_t}/n on n.

TABLE III. Φ_{p_t} for two different $\bar{p}_t$ subsamples.

	Sample	Number events	$\langle p_t \rangle$ GeV/c	$\langle n \rangle$	Φ_{p_t} MeV/c
(a)	NA22	22 844	0.309 ± 0.0005	7.18 ± 0.04	-49.58 ± 1.67
	PYTHIA	52 363	0.313 ± 0.0002	6.63 ± 0.02	-57.65 ± 0.70
(b)	NA22	20 836	0.478 ± 0.0007	6.72 ± 0.03	-80.91 ± 3.08
	PYTHIA	45 628	0.481 ± 0.0004	6.29 ± 0.02	-84.94 ± 1.34

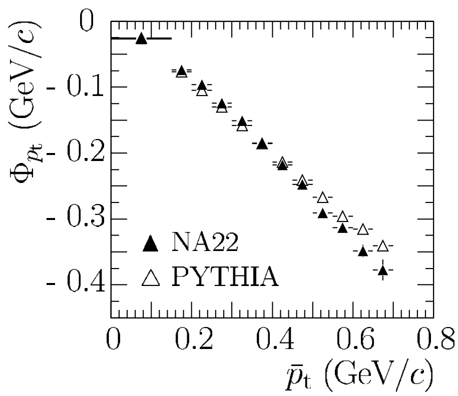

FIG. 6. The dependence of Φ_{p_t} on $\bar{p}_t$.

full rapidity region. Measurements in only part of the central plateau region will underestimate the fluctuations. (ii) The loss of low-p_t particles due to detector acceptance will significantly reduce the Φ_{p_t} measurement. (iii) Φ_{p_t} increases approximately linearly with increasing multiplicity. (iv) Φ_{p_t} is negative for any subsample with restricted mean transverse momentum per event. (v) The correlation between average transverse momentum and multiplicity is not the main origin of the fluctuations. (vi) PYTHIA underestimates the fluctuations in all rapidity regions and also in the relation with multiplicity. However, the relation between the fluctuations and mean transverse momentum per event are reproduced by PYTHIA.

In summary, we have presented new measurements on transverse momentum fluctuations in $\pi^+ p$ and $K^+ p$ collisions. The dependences of the fluctuations on the rapidity region and low-p_t demonstrate that the measurements for the fluctuations are better presented in the full central rapidity region and high low-p_t acceptance. The results obtained are helpful in clarifying the current debate on the origin of the fluctuations.

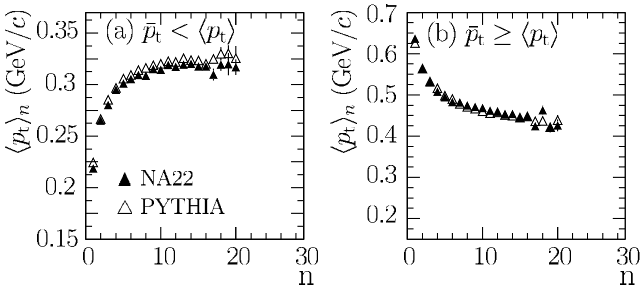

FIG. 7. $\langle p_t \rangle_n$ vs n correlations in two different $\bar{p}_t$ subsamples.

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