Scale-dependence of transverse momentum correlations in Pb-Au collisions at 158A GeV/c

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Abstract

We present results on transverse momentum correlations of charged particle pairs produced in Pb-Au collisions at 158A GeV/c at the Super Proton Synchrotron. The transverse momentum correlations have been studied as a function of collision centrality, angular separation of the particle pairs, transverse momentum and charge sign. We demonstrate that the results are in agreement with previous findings in scale-independent analyses at the same beam energy. Employing the two-particle momentum correlator \( \langle \Delta p_{t,i}, \Delta p_{t,j} \rangle \) and the cumulative \( p_t \) variable \( x(p_t) \), we identify, using the scale-dependent approach presented in this paper, different sources contributing to the measured correlations, such as quantum and Coulomb correlations, elliptic flow and mini-jet fragmentation.

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I. INTRODUCTION

Strongly interacting matter is expected to exist in different phases. At high temperature and vanishing density, QCD calculations on the lattice indicate the formation of a deconfined system with partonic degrees of freedom, the Quark-Gluon Plasma (QGP) (see [1] for a recent review). The QGP is separated from the hadronic phase by a transition line of yet unknown order. Lattice QCD calculations at finite baryon chemical potential $\mu_B$ are more difficult, but substantial progress has been achieved recently [1]. While the transition is most likely a rapid cross-over at vanishing density, it is expected to be first order at large $\mu_B$. The conjecture of the existence a critical point arises naturally in this configuration, however, non-standard scenarios without critical endpoint have also been discussed [2].

Collisions of heavy nuclei at high energies provide experimental access to the phase structure of hot and dense nuclear matter. If thermalization is achieved in the early stage of the collision, a phase transition to a Quark-Gluon-Plasma may occur. Experimental signatures of the phase transition and QGP formation are often based on event-averaged distributions of final state particles. Additional information may be derived from the study of fluctuations, which are related to the thermodynamic properties of the system (for a review see [3]). Event-by-event fluctuations of intensive quantities like temperature, reflected in the mean transverse momentum $M_{pt}$ of hadrons, have been proposed as a possible signature for critical phenomena connected with the passage of the system through the phase boundary, and may therefore constitute an independent probe to pin down the properties of the QCD phase diagram [4, 5, 6, 7, 8, 9, 10].

Fluctuations of the mean transverse momentum are associated to the heat capacity of the system, which has a maximum at the QCD phase boundary. As a consequence, transverse momentum fluctuations in the final state could be suppressed if the system retains its memory from the phase transition. On the other hand, long-range correlations associated with the vicinity of the system to the QCD critical point may lead to an enhancement of transverse momentum fluctuations.

Recent measurements of event-by-event fluctuations of the mean transverse momentum at SPS and RHIC demonstrated a clear excess beyond the statistical expectation [11, 12, 13, 14, 15, 16]. Different regions of the QCD phase diagram have been probed by variation of experimental control parameters, such as beam energy and system size. It was argued that
passage of the system through the critical point or the phase boundary would be signaled by a sudden change of the fluctuation pattern. While the energy dependence turned out to be structureless within the SPS and RHIC energy regime, a characteristic centrality and system size dependence has been observed, exhibiting a non-monotonic behaviour with a maximum at system sizes corresponding to about 100-150 participating nucleons. However, a strong connection of these findings to critical behaviour in the vicinity of the phase transition has not yet been made.

This inconclusive result is partially caused by the difficulty to identify and disentangle various contributions to the different fluctuation measures. While the implications of finite number statistics are well under control, there are a number of sources of correlations on different transverse momentum scales, which are expected to contribute to the fluctuation measures, such as quantum statistics, final state interactions, collective flow, resonance decays or jet fragmentation. Typically, the sensitivity to these contributions is tested with the help of Monte-Carlo studies.

In this paper, we follow a novel approach by studying the scale-dependence of transverse momentum correlations. The aim is to identify and separate different sources of correlations by a differential, scale-dependent analysis of the two-particle correlation pattern. A similar approach to a scale-dependent correlation analysis has been followed at RHIC, using different variables and an elaborated inversion technique [17, 18]. The formalism used in this paper allows to relate the measured differential correlation strength to the global fluctuation measures used in previous analysis, such as $\Phi_{pt}^{19}$, $\sigma_{dyn}^{20}$, or $\Sigma_{pt}^{11}$. The present results are based on an analysis of a high statistics data set of Pb-Au collisions at 158A GeV/c recorded with the Time Projection Chamber of the CERES experiment at CERN-SPS.

II. MEASURES OF CORRELATIONS AND FLUCTUATIONS

Fluctuations of the event-by-event mean transverse momentum $M_{pt}$ are composed of statistical fluctuations arising from the finite number of tracks per event, and a possible non-statistical (dynamical) contribution. The mean transverse momentum $M_{pt,k}$ of event $k$ with $N_k$ charged particles is defined as

$$M_{pt,k} = \frac{\sum_{i=1}^{N_k} p_{t,i}}{N_k}. \quad (1)$$
As a measure for event-by-event fluctuations, we employ the dynamical fluctuation $\sigma_{pt,\text{dyn}}^2$ that is derived from the variance of the inclusive single track $p_t$ distribution $\Delta p_t^2$, the variance of the event-by-event mean transverse momentum distribution $\langle \Delta M_{pt}^2 \rangle$ and the average number $\langle N \rangle$ of charged particles per event:

$$\sigma_{pt,\text{dyn}}^2 = \langle \Delta M_{pt}^2 \rangle - \frac{\Delta p_t^2}{\langle N \rangle}.$$  \hspace{1cm} (2)

For the calculation of the variance $\langle \Delta M_{pt}^2 \rangle$, the mean transverse momentum $M_{pt,k}$ of each event $k$ has been weighted by the number of tracks $N_k$ in this event. The dynamical fluctuation $\sigma_{pt,\text{dyn}}^2$ is zero by definition if all fluctuations are purely statistical. For convenience, the normalized dynamical fluctuation $\Sigma_{pt}$ is introduced \[11\] :

$$\Sigma_{pt} = \text{sgn}(\sigma_{pt,\text{dyn}}^2) \sqrt{\frac{\sigma_{pt,\text{dyn}}^2}{p_t}},$$  \hspace{1cm} (3)

where $\overline{p_t}$ is the inclusive mean transverse momentum of all tracks from all events. The measure $\Sigma_{pt}$ is dimensionless and specifies the dynamical contribution to event-by-event $M_{pt}$ fluctuations in units of $\overline{p_t}$. For the case of independent particle emission from a single parent distribution, $\Sigma_{pt}$ vanishes.

Most of the previous studies of $M_{pt}$ fluctuations have been performed in a scale-independent way, integrating over all short- and long-range contributions present in the detector acceptance. For such a scale-independent approach, the measures presented above are well suited. However, more details about the origin of non-statistical fluctuations can be obtained by the study of their scale dependence. For this purpose, an additional measure will be introduced.

The occurrence of non-statistical fluctuations of $M_{pt}$ goes along with correlations among the transverse momenta of particles. Such correlations can be calculated employing the two-particle transverse momentum correlator \[15\] :

$$\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle = \frac{1}{\sum_{k=1}^{n_{ev}} N_k^{\text{pairs}}} \sum_{k=1}^{n_{ev}} \sum_{i=1}^{N_k} \sum_{j=i+1}^{N_k} (p_{ti} - \overline{p_t})(p_{tj} - \overline{p_t}).$$  \hspace{1cm} (4)

As for the measures defined earlier, $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ can be calculated for distinct classes of tracks after application of single track cuts, like cuts on $p_t$, pseudorapidity or charge sign. In this case, the number of pairs in event $k$ is given by $N_k^{\text{pairs}} = 0.5 \cdot N_k (N_k - 1)$, where $N_k$ is the number of particles of a given class in event $k$, and $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ is approximately equal to $\sigma_{pt,\text{dyn}}^2$.
Since $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ is a particle pair observable, it is possible to apply cuts on the pair level, contrary to the situation for the measures introduced above. An example is the study of $p_t$ correlations between particles of different charge sign. In this case, the correlator is calculated in the following way:

$$
\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle^{(+)} = \frac{1}{\sum_{k=1}^{n_{\text{ev}}} N_k^+ N_k^-} \sum_{k=1}^{n_{\text{ev}}} \sum_{i=1}^{N_k^+} \sum_{j=1}^{N_k^-} (p_{ti} - \overline{p}_t)(p_{tj} - \overline{p}_t).
$$

(5)

Moreover, it is also possible to study the scale dependence of $p_t$ correlations in angular space by calculating the correlator in bins of the angular separation $\Delta \eta, \Delta \phi$ of particle pairs:

$$
\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle(\Delta \eta, \Delta \phi) = \frac{1}{\sum_{k=1}^{n_{\text{ev}}} N_{\text{pairs}}(\Delta \eta, \Delta \phi)} \sum_{k=1}^{n_{\text{ev}}} \sum_{i=1}^{N_k^+} \sum_{j=i+1}^{N_k^-} (p_{ti} - \overline{p}_t)(p_{tj} - \overline{p}_t).
$$

(6)

In this case, only particle pairs with a given $\Delta \eta, \Delta \phi$ contribute to the correlator sum.

III. EXPERIMENT AND DATA ANALYSIS

The CERES experiment at the CERN Super Proton Synchrotron (SPS) has been designed for the study of electron-pair production at mid-rapidity in hadronic and nuclear collisions. By the addition of a cylindrical Time Projection Chamber (TPC) and a new magnet system in 1998, the momentum resolution of the spectrometer was significantly improved [21]. Moreover, the excellent tracking capability of the TPC for charged particles provides the opportunity to study also hadronic observables. The TPC is located about 4 m downstream of a segmented gold target and covers a polar angle range from 7° to 15° at full azimuth. Charged particles create a trace of ionization in the Ne-CO$_2$ (80:20) gas mixture. Ionization electrons drift radially outwards to the read-out plane where up to 20 subsequent hits are detected along the particle track. Taking the drift time into account, the TPC allows a three-dimensional reconstruction of the charged particle trajectory. The tracking efficiency in the TPC is about 85% for transverse momenta greater than 0.1 GeV/$c$. In azimuth, the read-out plane is subdivided into 16 read-out chambers, arranged along the polygon-like outer perimeter of the TPC. Efficiency losses occur predominantly for tracks which cross between two adjacent read-out chambers.

The TPC is operated inside an inhomogenous magnetic field with a radial component of up to 0.75 T. By the measurement of its deflection, the momentum of a charged particle can be reconstructed with a resolution of $\Delta p/p = 2\% \oplus 1\% \cdot p$ (GeV/$c$) [21].
In the year 2000, a sample of $3.2 \cdot 10^7$ central ($\sigma/\sigma_{geo} \approx 8\%$) and about $10^6$ minimum bias Pb-Au events have been recorded. The centrality selection is based on the pulse height in a scintillator Multiplicity Counter (MC) \[22\]. By the use of a geometric nuclear overlap model \[23\], the centrality can be expressed in terms of the number $\langle N_{part} \rangle$ of nucleons participating in the collision.

The analysis presented here is based on $10^7$ central and $2 \cdot 10^6$ min bias Pb-Au events at $158A \text{ GeV}/c$ from the year 2000 \[24\]. We use charged particles reconstructed in the TPC in the kinematic range $2.2 < \eta < 2.7$ and $0.1 < p_t < 1.5 \text{ GeV}/c$. A minimum of 12 detected hits per track is required to provide sufficient momentum resolution. Background from decays and conversions is suppressed by the requirement that the back-extrapolation of the TPC tracks into the target plane should not miss the interaction point by more than 10 cm in transverse direction.

In the scale-independent analysis, the measures $\sigma^2_{p_t,dyn}$, $\Sigma_{p_t}$, and $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ have been calculated for positive and negative particles separately, as well as without charge selection. In addition, transverse momentum correlations between particles with opposite charge sign are analyzed employing the measure $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle^{(+,-)}$.

For the study of the scale dependence, the momentum correlator $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle(\Delta \eta, \Delta \phi)$ has been evaluated in bins of the relative angular separation $\Delta \phi = |\phi_i - \phi_j|$ and $\Delta \eta = |\eta_i - \eta_j|$ of the particle pair. We have chosen bins of 7.5 degrees in azimuth and 0.1 in pseudorapidity which corresponds to approximately equal granularity in polar and azimuthal angle.

Fig.\[1\] shows the inclusive mean transverse momentum $p_t$ measured in the TPC as function of $\eta$ and $\phi$. A decrease of $p_t$ by a few percent as function of pseudorapidity is observed. The decrease can be explained by the kinematical acceptance of the TPC, combined with a pseudorapidity-dependent proton-to-pion ratio. This has been verified by a Monte-Carlo simulation. In azimuth, the 16-fold structure of the TPC read-out plane is visible. This effect arises as a consequence of efficiency losses in the vicinity of the gaps between adjacent read-out chambers. In detail, efficiency losses depend on the curvature of the track, hence giving rise to local variations of $p_t$.

If a correlation analysis is performed in bins of relative angular space, such variations lead to trivial (anti-) correlations of transverse momenta as function of $\Delta \phi$ and $\Delta \eta$. A correction of the final results for these correlations can be obtained by a mixed-event procedure. Pairs of particles from different events are free of correlations except those arising from the single
FIG. 1: Mean transverse momentum as function of $\eta$ and $\phi$. Negative particles (left) and positive particles (right) are shown separately.

particle acceptance of the detector. Mixed-event correlations can therefore be used as a reference to correct the same-event results for such effects.

The result for the momentum correlator in the $\Delta\phi - \Delta\eta$ plane for mixed-event pairs is shown in Fig.2. Statistical errors range from about 2 MeV/c$^2$ in the first $\Delta\eta$ bin to about 7 MeV/c$^2$ in the last $\Delta\eta$ bin. In $\Delta\phi$ direction, the observed variations are small. This is expected from the high frequency pattern in Fig.1 (right panel): By averaging over all combinations, correlations and anti-correlations cancel to a large extent. In Fig.2, only a residual structure of the read-out plane segmentation is visible, showing up as a weak repetitive pattern in azimuthal direction. The wave length of the structure is 3 bins or $22.5^\circ$ in Fig.2, corresponding to $360^\circ/16$, the azimuthal size of one TPC read-out chamber.

The situation is different in $\Delta\eta$. Due to the monotonic decrease of $\bar{p}_T$ as function of pseudorapidity, pairs are preferentially correlated at small $\Delta\eta$ and anti-correlated at large
\( \Delta \eta \). This is demonstrated in Fig. 2 where a significant monotonic decrease of the correlator as function of \( \Delta \eta \) can be observed.

The momentum correlator has been calculated for mixed-event pairs as function of \( \Delta \eta \) and \( \Delta \phi \) and for all possible charge combinations. These results have been subtracted bin-wise from the corresponding results of the same-event analyses presented below.

It should be noted that, in scale-independent analyses of the momentum correlator, correlations due to the single track \( p_t \) acceptance cancel. The result of a scale-independent mixed-event analysis averaging over all relative angles yields \( \langle \Delta p_t,i, \Delta p_t,j \rangle_{\text{mixed}} = -0.049 \pm 0.314 \text{ MeV}^2/c^2 \), although the differential analysis (Fig. 2) shows significantly non-zero results.

Statistical errors are calculated by division of the total event sample into \( N_{\text{sub}} \) subsamples of equal size. The variance \( V \) of the results from the subsample analysis was used to determine the final statistical errors for the full sample given by \( \sqrt{V/N_{\text{sub}}} \). The systematic uncertainties have been estimated by variations of the cut values and yield about 5 MeV\(^2/c^2\).
FIG. 3: Normalized dynamical fluctuation $\Sigma_{p_t}$ in central Pb-Au and Au-Au collisions as function of $\sqrt{s}$.

in $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$.

IV. RESULTS

A. Scale-independent analysis

In Table I results are shown of a scale-independent analysis of about $10^7$ central Pb-Au events at 158$A$ GeV/c with $\sigma/\sigma_{\text{geo}} = 0 - 8\%$. The measures $\sigma^2_{p_t,\text{dyn}}$, $\Sigma_{p_t}$ and $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ have been calculated with and without charge selection. Results for $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle^{(+)}$ using pairs of different charge sign are also shown.

For a given charge combination, the results obtained for $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ and $\sigma^2_{p_t,\text{dyn}}$ are consistent within statistical errors. For negative particles, the results are slightly higher than
FIG. 4: The momentum correlator $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ (left) and $\langle dN_{ch}/d\eta \rangle \cdot \langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ (right) from all particle combinations as function of $\langle N_{part} \rangle$.

for positive particles. Momentum correlations between unlike-sign particles are comparable to those between particles of the same charge. The normalized dynamical fluctuation $\Sigma_{p_t}$ is of order 1% of mean $p_t$ in all cases, in good agreement with previously reported measurements in central events at SPS and RHIC (see Fig.3 [11, 12, 15]).

The centrality dependence of $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ for all charged particles is shown in Fig.4 and summarized in Table II. The correlator $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ exhibits a monotonic decrease, consistent with recent results at SPS and RHIC [12, 15]. This is partially explained by a dilution effect which occurs in case of an independent superposition of colliding nucleons. To explore this behaviour in more detail we multiply the correlator by the charged particle multiplicity $\langle dN_{ch}/d\eta \rangle$ in each bin, as shown in Fig.4. Similar to previous observations of related quantities at SPS and RHIC, $\langle dN_{ch}/d\eta \rangle \cdot \langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ is not independent of centrality but rather indicates a non-monotonic shape with a maximum at $\langle N_{part} \rangle \approx 150$. Different mechanisms have been proposed as possible explanations for this phenomenon, such as correlations due to jets and jet quenching [16], onset of thermalization [25], elliptic flow [13, 16], or enhanced fluctuations signalling a geometric phase transition in the vicinity of the percolation point [26]. Also, a possible connection to enhanced multiplicity fluctuations observed in the same centrality region [27] has been demonstrated [28]. A comprehensive and convincing explanation, however, is not yet at hand.
B. Correlation analysis in $\Delta \eta - \Delta \phi$

To address this question in more detail, the scale dependence of the momentum correlations in relative angular space was investigated. This study will help to identify and disentangle different contributions to the observed fluctuation pattern. Fig.5 shows the momentum correlator $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ as function of $\Delta \eta$ and $\Delta \phi$. The left panel is before, the right panel after subtraction of the mixed-event correlations. The most pronounced feature is a strong positive correlation at small opening angle. The width of this peak is similar in $\Delta \eta$ and $\Delta \phi$. At $\Delta \phi \approx \pi/2$, a small but significant negative correlation is observed, turning into a positive plateau as $\Delta \phi$ approaches 180 degrees. The smooth decrease with $\Delta \eta$ observed in the uncorrected data is caused by acceptance effects and disappears after subtraction of the mixed-event data.

The strong peak at small angles is most likely due to short range correlations caused by quantum statistics and Coulomb final state interactions. This hypothesis is substantiated when the momentum correlations are calculated for different charge combinations. In Fig.6, the correlator $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle (\Delta \eta, \Delta \phi)$ is shown for positive, negative and unlike-sign pairs. The peak structure for positive and negative pairs is very similar, pointing to HBT correlations as a likely origin.

In contrast, the peak is restricted to very small opening angles for unlike-sign pairs, where no HBT correlations are present. Here, the correlation is likely to be caused by attractive Coulomb final state interactions. Also $e^+e^-$ pairs from conversions may contribute at very
small opening angles. It is interesting to note that the narrow spike is observed on top of a broad bump with much smaller amplitude, which has similar width in $\Delta \eta$ and $\Delta \phi$. This may be caused by resonance decays, but also by correlations from mini-jet fragmentation, where a stronger contribution to the unlike-sign correlations as compared to the like-sign case is expected as a consequence of charge ordering.

In the next step, we present the scale-dependence as function of the centrality of the collision. For reasons of limited statistics in the minimum bias data set, we do not perform a charge-dependent analysis of the centrality dependence. Furthermore, we neglect the $\Delta \eta$ dependence and focus on $\Delta \phi$, integrating the data over the $\Delta \eta$ acceptance.

The momentum correlator $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ as function of $\Delta \phi$ for different centralities is shown in Fig. 7. The data show a pronounced $\Delta \phi$ dependence, exhibiting a strong peak in the first bin on top of a harmonic pattern with a second peak for back-to-back pairs. Significant anti-correlations are observed in the angular region around $\Delta \phi \approx 1$. The strength of the correlation decreases towards more central events.

**FIG. 6:** The momentum correlator $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ as function of $\Delta \eta$ and $\Delta \phi$. Upper left: positive pairs, upper right: negative pairs, lower panel: unlike-sign pairs.
FIG. 7: The momentum correlator $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ as function of $\Delta \phi$ for different centrality classes.

Fig. 8 shows $\langle dN_{ch}/d\eta \rangle \cdot \langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ as function of $\langle N_{\text{part}} \rangle$ in different regions of $\Delta \phi$. The non-monotonic behaviour observed in the scale-independent analysis turns out to exhibit a significant dependence on $\Delta \phi$. As expected, the correlation is largest at the smallest $\Delta \phi$. In this angular range, the data show a maximum around $\langle N_{\text{part}} \rangle \approx 150$, however, the data seem to be biased by a large offset possibly arising from a centrality-independent contribution from HBT and Coulomb effects. With increasing $\Delta \phi$, the correlation strength decreases and turns negative around $\Delta \phi = \pi/2$. In this angular range, the data indicate a minimum in semi-central events. As $\Delta \phi$ increases further, the correlations become again positive with a maximum around $\langle N_{\text{part}} \rangle \approx 150$. Note that in the angular range $30^\circ < \Delta \phi < 60^\circ$ the result for the correlator is consistent with zero at all centralities.

The angular pattern of the momentum correlations as well as the extrema observed in semi-central events suggest a connection to elliptic flow as a possible origin. In the following, an estimate of the expected flow contribution to the momentum correlations, based on
measurements of the elliptic flow strength $v_2$ is presented. The Fourier coefficient $v_2$ of the second order harmonic of the azimuthal anisotropy of particle emission has been measured in Pb-Au events at 158A GeV/c as function of $p_t$ \[29\]. We employ a parametrization of the $p_t$ dependence of $v_2$ in the most central event class (0-8%). Two alternative approaches have been tested to estimate its contribution to $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$. In the first method, a weight $f_{ij}$ is introduced for each particle pair $i, j$ which depends on the parametrized $v_2$ value at the particle’s $p_t$:

$$f_{ij} = 1 + 2v_2(p_{t,i})v_2(p_{t,j}) \cos(2|\phi_i - \phi_j|).$$

Employing the mixed-event technique, the correlator $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle_{\text{mixed,flow}}$ has been evaluated by weighting each pair of particles from different events with $f_{ij}$ and normalization by
FIG. 9: Estimated contribution of elliptic flow to the momentum correlator \( \langle \Delta p_{t,i}, \Delta p_{t,j} \rangle \) as function of \( \Delta \phi \), obtained from a Monte Carlo simulation. The results are parametrized by a harmonic function.

The sum over all weights \( F_{ij} = \sum f_{ij} \):

\[
\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle_{\text{mixed,flow}} = \frac{1}{F_{ij}} \sum_{i,j} f_{ij} (p_{ti} - \overline{p}_t) (p_{tj} - \overline{p}_t),
\]

(8)

with particles \( i \) and \( j \) from different events. To account for the single particle acceptance, the unweighted mixed-event correlator has been subtracted

\[
\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle_{\text{flow}} = \langle \Delta p_{t,i}, \Delta p_{t,j} \rangle_{\text{mixed,flow}} - \langle \Delta p_{t,i}, \Delta p_{t,j} \rangle_{\text{mixed}}.
\]

(9)

The resulting correlation as function of \( \Delta \phi \) in the range \( 0 < \Delta \eta < 0.1 \) is shown in Fig.9. As expected, the flow contribution has a characteristic \( \cos(2\Delta \phi) \)-shape. However, the estimated flow contribution fails to describe the measured correlation in shape and in magnitude, as demonstrated in Fig.10. The same quantitative result has been obtained by a Monte-Carlo method, where parametrizations of the measured \( p_t \) distributions and \( v_2 \) values have been used to calculate the correlator \( \langle \Delta p_{t,i}, \Delta p_{t,j} \rangle_{\text{flow}} \).
FIG. 10: The momentum correlator $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ as function of $\langle N_{\text{part}} \rangle$ in $0 < \Delta \eta < 0.1$ compared to the expectation from elliptic flow (curve).

C. Two-particle $p_t$ correlations

In this section, we try to obtain further insight into the origin of the observed $p_t$ correlations by the investigation of their $p_t$ dependence. Non-zero $p_t$ correlations as observed in the measure $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ must be related to (anti-)correlated particle production at the corresponding angular scale. A localization of correlations in transverse momentum space may help to distinguish between different mechanisms which could possibly lead to such correlations. To this end, we study two-particle correlations in the $(x(p_t)_1, x(p_t)_2)$-plane, where the cumulative $p_t$ variable $x(p_t)$ is defined as [13, 30]:

$$ x(p_t) = \frac{\int_{0.1 \text{ GeV}/c}^{p_t} \rho(p'_t) dp'_t}{\int_{0.1 \text{ GeV}/c}^{1.5 \text{ GeV}/c} \rho(p'_t) dp'_t}, \quad (10) $$

In Fig.11, $x(p_t)$ is shown as function of $p_t$ next to the inclusive $p_t$ distribution $\rho(p_t)$. Due to the limited statistics of our peripheral data set we focus on central collisions (0-5%) in the following discussion.

For the study of two-particle $p_t$ correlations, the $x(p_t)$-values of particle pairs
(x(p_t)_{1}, x(p_t)_{2}) are filled into two-dimensional arrays. The same procedure has been applied to mixed-event pairs to study residual p_t correlations caused by detector acceptance effects. Such correlations may occur in differential analyses, if local deviations from the inclusive p_t distributions are present. For the final results presented below, the real-event distributions have been corrected for detector effects through division by the corresponding mixed-event distributions.

In Fig.12 the two-particle correlation function from central Pb-Au events (0-5%) is shown in the (x(p_t)_1, x(p_t)_2)-plane for different values of the relative azimuthal separation Δφ of the pair. For small Δφ (0 < Δφ < 30°) we observe a strong positive correlation along the x_1 \approx x_2 - diagonal, most pronounced in the low p_t-region. This is consistent with short-range correlations of particles with small momentum differences as induced by quantum statistics and Coulomb final state interactions. The short-range contribution vanishes for large angular separations. At Δφ \approx 90° an anti-correlation at large transverse momenta appears, which turns to a substantial positive correlation as the angular separation approaches Δφ = 180°.

The charge-dependent correlation functions in the (x(p_t)_1, x(p_t)_2)-plane for small (0 < Δφ < 30°) and large (150 < Δφ < 180°) azimuthal separations of the particle pair are shown in Fig.13. The correlations of positive and negative particle pairs look similar at small Δφ, pointing to a common mechanism such as HBT. On the other hand, the correlation of unlike-sign particles is restricted to significantly lower p_t, as expected from Coulomb interaction and contaminations from e^+e^- - pairs. The positive high-p_t correlation at large Δφ appears
FIG. 12: Two-particle correlations as function of \((x(p_t)_1, x(p_t)_2)\) in different regions of \(\Delta \phi\). No charge selection has been applied.

very similar for all charge combinations.

From this pattern, the following picture arises: the strong positive values of \(\langle \Delta p_t,i, \Delta p_t,j \rangle\) at small \(\Delta \phi\) are dominated by HBT and Coulomb correlations. In contrast, the characteristic structure in Fig[7] at \(\Delta \phi > 30^\circ\) is caused by (anti-) correlations at high \(p_t\) which can not be attributed to elliptic flow. Using the flow model described before, we found that the value of \(v_2\) needed to be three times larger than the experimental \(v_2\) value in order to account for the observed correlations. Similar conclusions have been drawn from an analysis of azimuthal correlations with respect to a high-momentum trigger particle at the same beam energy, where the observed correlation pattern is significantly larger than the contribution expected from elliptic flow [31]. Such triggered correlation functions are usually attributed to jet correlations arising from the fragmentation of hard-scattered partons with large transverse momentum. Related studies of two-particle \(p_t\)-correlations have been performed by STAR.
at RHIC [32], where similar observations have been discussed in the context of initial state semi-hard parton scattering and minijet dissipation in the medium.

D. Summary

Based on the large statistics data set of Pb-Au collisions at 158 A GeV/c, recorded with the CERES Time Projection Chamber at the CERN-SPS, a novel analysis of transverse momentum correlations has been performed. In a differential analysis of two-particle correlations as function of the charge sign and the relative angular separation of the particle pairs, the scale dependence of $p_t$ correlations was determined. We found that the previously observed non-statistical transverse momentum fluctuations can be decomposed into different contributions. First, a short range component at small angles and low transverse momentum has been identified, which is most likely due to HBT (in the case of like-sign particle pairs) and Coulomb interactions and conversions (in the case of unlike-sign particle pairs).
TABLE I: Results of a scale-independent analysis of central Pb-Au events at 158\,A GeV/c ($\sigma/\sigma_{\text{geo}} = 0 - 8\%$).

|                      | Positive pairs | Negative pairs | All pairs    | Unlike-sign pairs |
|----------------------|----------------|----------------|--------------|-------------------|
| $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ (MeV$^2$/c$^2$) | 21.59 ± 0.63   | 26.63 ± 0.61   | 22.71 ± 0.32  | 24.71 ± 0.43      |
| $\sigma_{p_{t,\text{dyn}}^2}$ (MeV$^2$/c$^2$)       | 20.65 ± 0.61   | 26.16 ± 0.54   | 21.98 ± 0.44  |                   |
| $\Sigma_{p_{t}}$ (%)                                    | 0.95 ± 0.01    | 1.24 ± 0.01    | 1.04 ± 0.01   |                   |
| $n$                                                  | 9009425        | 9009425        | 10003672     | 9009425           |
| $\langle N \rangle$                                   | 84.21 ± 0.01   | 70.63 ± 0.01   | 154.83 ± 0.01|                   |
| $\overline{p_t}$ (MeV/c)                              | 479.78 ± 0.01  | 414.10 ± 0.01  | 449.82 ± 0.01|                   |

Second, a pronounced long-range component in $\Delta \phi$ is observed, located at large transverse momentum and exhibiting minima and maxima, which are distinctly different from those expected for elliptic flow. A possible interpretation is that this component originates in kinematic correlations arising from jet fragmentation of energetic partons.

Beyond these contributions, we could not identify additional sources of particle correlations. In particular, no trace of non-trivial event-by-event fluctuations has been found but it may well be overwhelmed by the dominant contributions discussed in this paper. We note, however, that the angular range $30^\circ < \Delta \phi < 60^\circ$ is essentially free of such contributions. In this region, the observed correlations are consistent with zero. Based on the studies presented here, we suggest to optimize the sensitivity of future investigations to this angular range as it appears to offer the cleanest window for the observation of non-trivial fluctuations connected to the critical point.

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TABLE II: Centrality dependence of mean $p_t$ correlation results in Pb-Au at 158$A$ GeV/$c$. No charge selection was applied.

| Centrality | $n$  | $\langle N\rangle$ | $\vec{p}_t$ | $\langle \Delta p_{t,i}, \Delta p_{t,j} \rangle$ | $\sigma_{pt,dyn}^2$ |
|------------|-----|------------------|------------|----------------------------------|-----------------|
|            |     |                  |            | (MeV/$c$)                         | (MeV$^2/c^2$)   |
| 40-50%     | 64  | 38197            | 32.72 ± 0.06 | 436.17 ± 0.25                     | 145.79 ± 29.73  |
| 30-40%     | 102 | 39763            | 50.07 ± 0.07 | 441.57 ± 0.2                      | 114.81 ± 14.41  |
| 20-30%     | 153 | 39496            | 73.37 ± 0.08 | 445.31 ± 0.17                     | 81.61 ± 9.99    |
| 10-20%     | 221 | 40146            | 104.81 ± 0.1 | 448.52 ± 0.14                     | 36.74 ± 6.39    |
| 0-8%       | 328 | 10003672         | 154.83 ± 0.01| 449.82 ± 0.01                     | 22.71 ± 0.32    |

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