Correlations in transverse momentum in $\pi^+ p$ and $K^+ p$ collisions at 250 GeV/c

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Abstract

We have measured the second-order normalized differential factorial moments as a function of the difference of transverse momentum ($\Delta p_T$) in $\pi^+ p$ and $K^+ p$ collisions at 250 GeV/c. The second-order differential factorial moments for like-charged pairs reveal a strong increase with decreasing $\Delta p_T$. In a small central rapidity window this increase is described by a simple power law. Such a behavior, if interpreted as originating from Bose-Einstein correlations, may indicate a structure of the transverse spatial distribution of the source similar to that recently predicted by Bialas and Peschanski for color-dipole emission in onium-onium scattering. The power of the rise obtained in the fit agrees with the predicted value.

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1 Introduction

It has recently been shown by Bialas and Peschanski\textsuperscript{1} that the cross-section for the emission of color dipoles in high-energy onium-onium scattering reveals a power law in transverse position of the emitted dipole. The authors of Ref. 1 use the formalism recently developed by Mueller\textsuperscript{2} in which an onium state resembles a collection of color dipoles of various sizes. The authors calculated the contribution to the cross-section from the emission of dipoles present in the initial state and released during the collision. This cross-section depends on the transverse position $r_T$ of the dipole as

$$\frac{d\sigma}{dx d^2r_T} \sim r_T^{-2+\gamma_M},$$

with $x$ being the transverse spatial size of the dipole and $\gamma_M \approx 0.37$. The quoted value of $\gamma_M$ does not depend on any physical parameters of the model, such as the strong coupling constant, the masses involved, etc. It is governed only by some very general properties of the underlying cascade.

The power law (1) follows from the self-similar character of gluon emission in the onium state and leads to a rise of the factorial moments\textsuperscript{3} with decreasing distance in transverse momentum between the emitted particles.

The exact shape of the transverse-position cross-section is also related to the Bose-Einstein correlation between identical particles\textsuperscript{4} as measured in the transverse momentum difference. Since the latter is the square of the Fourier transform of the source distribution, a transverse-position cross-section of the form (1) implies that the correlation depends on the absolute value of the transverse-momentum difference $\Delta p_T$ like $\Delta p_T^{-2+\gamma_M}$. Due to cut-offs in the cross-section (1) necessary for its normalization, this power-law behavior of the correlation is restricted to a certain region in $\Delta p_T$\textsuperscript{1,5}.

The result (1) of Ref. 1 was derived in perturbative QCD and one could argue that it holds only for virtually infinite energies. Nevertheless, in the derivation of Eq. (1) one operates only on color dipoles, which are colorless objects and interact only by colorless two-gluon exchange. One can expect thus that such an approach to a very-high-energy collision can describe to a good degree many phenomena occurring with hadrons (which are also colorless objects) at finite energies. This is not the case for the usual perturbative QCD calculations, which describe the dynamics of colored objects (quarks and gluons).

Thus, in spite of the fact that the transverse-position cross-section was derived for onium-onium scattering at an asymptotically high energy, it is tempting to verify whether there is any indication of such a behavior in normal hadron-hadron scattering.
This verification will be described in the present paper for $\pi^+p$ and $K^+p$ collisions at 250GeV/c.

2 Measured quantities

For measuring the two-particle correlations, we used the differential normalized factorial moments evaluated using the density integrals

$$DF_2(\Delta p_T) = \frac{1}{N_{cc}} \frac{Df_2(\Delta p_T)}{D\xi_2^{\text{norm}}(\Delta p_T)}$$

with

$$Df_2(\Delta p_T) = \int \rho_2(p_1, p_2) \delta_{12} d^3p_1 d^3p_2$$

and $\delta_{12}$ defined to be 1 when $|p_{T1} - p_{T2}|$ lies within a certain bin around $\Delta p_T$ and 0 otherwise. $D\xi_2^{\text{norm}}$ is defined by the integral

$$D\xi_2^{\text{norm}}(\Delta p_T) = \int \rho_1(p_1) \rho_1(p_2) \delta_{12} d^3p_1 d^3p_2$$

evaluated with particles 1 and 2 taken randomly from different events (“event mixing”). The property of unbiased estimators for the moments and their normalization is demonstrated in Ref. 7. The non-trivial modifications needed for events with non-uniform weights are derived in Ref. 8.

The normalization factor $N_{cc}$ depends on the charge combination of the measured pairs: $N_{cc} = \langle n(n - 1) \rangle / \langle n \rangle^2$, $N_{+-} = \langle n_+ n_- \rangle / \langle n_+ \rangle \langle n_- \rangle$, $N_{--} = \langle n_-(n_--1) \rangle / \langle n_- \rangle^2$, $N_{++} = \langle n_+(n_+-1) \rangle / \langle n_+ \rangle^2$ for all pairs, unlike-charge pairs, negative-negative, and positive-positive pairs, respectively. The symbols $n$, $n_-$, and $n_+$ stand for the numbers of total, negative, and positive particles, respectively, and $\langle \rangle$ stands for averaging over all events in the data sample used. Differential factorial moments normalized by the factor $N_{cc}$ are equal to 1 when there is no correlation between the particles.

On the other hand, the normalized differential factorial moments are equivalent to the disconnected correlation function measured at a given value of $\Delta p_T$, but integrated over the difference in the longitudinal momentum.

3 Results

For this CERN experiment, the European Hybrid Spectrometer (EHS) was equipped with the Rapid Cycling Bubble Chamber (RCBC) as an active vertex detector and
exposed to a 250 GeV/c tagged positive, meson-enriched beam. In data taking, a minimum-bias interaction trigger was used. The details of the spectrometer and the trigger can be found in previous publications\textsuperscript{9,10}.

For the reported analysis the inelastic non-single-diffractive sample consisting of 59 200 $\pi^+ p$ and $K^+ p$ events was used.

In Fig. 1 we show plots of the second-order differential factorial moments $D F_2$ obtained according to Eq. 2 for the negative-negative ($-$ $-$) pairs and for the positive-positive ($+$ $+$) ones. The plotted moments were obtained with the full data sample but the center-of-mass rapidity restricted to $|y| < 0.5, 1, 1.5$ and $2$ from top to bottom of Fig. 1, respectively.

The increase of $D F_2$ with decreasing $-\ln(\Delta p_T/(\text{GeV/c}))$ for all rapidity cuts and both charge combinations in the region of $\Delta p_T$ larger than $\sim 1 \text{GeV/c}$ (negative $-\ln \Delta p_T$) can be attributed to the conservation of transverse momentum: a particle of so large a $p_T$ is usually accompanied by a number of particles of the opposite transverse momentum, so that these particles differ from the former one by large $\Delta p_T$. Such pairs contribute to the large correlation observed.

The fast rise of $D F_2$ with decreasing $\Delta p_T$ (increasing $-\ln(\Delta p_T/(\text{GeV/c}))$) in the region of $\Delta p_T \leq 1 \text{GeV/c}$ ($-\ln(\Delta p_T) > 0$) corresponds to what is usually assumed to be due to Bose-Einstein correlations in pion interferometry (for a review see e.g. Ref. 11). If the observed correlation is indeed purely due to the Bose-Einstein effect and if the source of the particles is fully incoherent, then the disconnected correlation function can be expressed by the Fourier transform of the spatial density of the source:

$$C_2(\Delta p) = 1 + |\tilde{\rho}(\Delta p)|^2. \quad (5)$$

If the transverse part of the source distribution $\rho_T(r_T)$ follows a power law $r_T^{-2+\gamma_M}$ in some region of $r_T$, then the square of its Fourier transform is governed by the power law $\Delta p_T^{-2\gamma_M}$ in the corresponding region of the conjugate variable $\Delta p_T$. Hence\textsuperscript{5}, we can expect a similar power-law behavior of $D F_2$:

$$D F_2 = 1 + a(\Delta p_T)^{-\phi}. \quad (6)$$

In Fig. 1 we show the fits of the data with Eq. 6 as solid lines. The $\Delta p_T$ region in which momentum conservation has a substantial influence on the correlation is excluded from the fit. So, only data with $\Delta p < 1 \text{GeV/c}$ ($-\ln \Delta p_T > 0$) are used. The parameters obtained in the fits are given in Table 1. In all cases, the value of $\phi$ agrees (within 2 standard deviations) with the value $2\gamma_M \approx 0.74$ obtained by Bialas and
Figure 1: Logarithm of the second-order differential factorial moment $DF_2$ as a function of $-\ln(\Delta p_T/(\text{GeV/c}))$ for four different rapidity cuts. The bottom plots correspond to the full data sample. The solid lines represent the fit by Eq. [3].
Table 1: Comparison of parameters of the fit of the dependence of $D_{F2}$ on $\Delta p_T$ by Eq. 6 for various rapidity windows, in the range indicated by the full line in Fig. 1.

| charge combination: $-$ $-$ | rapidity cut | $\phi$ | $a \times 10^2$ | $\chi^2/NDF$ |
|--------------------------|-------------|--------|----------------|-------------|
| $|y| < 0.5$ | 0.83±0.12 | 4.6±1.2 | 11.6/13 |
| $< 1.0$ | 0.87±0.10 | 2.8±0.6 | 21.7/13 |
| $< 1.5$ | 0.92±0.10 | 1.9±0.4 | 27.7/13 |
| $< 2.0$ | 0.92±0.10 | 1.5±0.4 | 34.0/13 |

| charge combination: ++ |
|--------------------------|-------------|--------|----------------|-------------|
| $|y| < 0.5$ | 0.75±0.10 | 4.7±0.9 | 22.9/13 |
| $< 1.0$ | 0.84±0.09 | 2.4±0.5 | 15.7/13 |
| $< 1.5$ | 0.95±0.12 | 1.3±0.4 | 18.1/13 |
| $< 2.0$ | 0.93±0.16 | 1.0±0.4 | 23.6/13 |

Peschanski\textsuperscript{1}. The agreement (and the quality of the fit) is better for the smaller than for the bigger $y$-intervals. This can be understood from the fact that in the case of a broad rapidity range, the Bose-Einstein correlations are partly washed out due to the large difference possible in the longitudinal momentum.

The parameter $a$ governing the overall value of the correlation rises with decreasing size of the rapidity window. This observation is consistent with the Bose-Einstein interpretation of the correlation: for a finite longitudinal size of the source the Bose-Einstein correlation increases when the distance between the particles in longitudinal momentum decreases.

We conclude that a structure surprisingly similar to the one predicted in Ref. 1 for dipole emission can be seen in our hadron-hadron data.

4 Conclusions

We have measured the second-order differential factorial moments $D_{F2}$ in the difference of the transverse momentum $\Delta p_T$ in multiparticle production at 250GeV/$c$. $D_{F2}$ rises with decreasing $\Delta p_T$ for like-sign particle combinations. For narrow rapidity windows the $\Delta p_T$ dependence of $D_{F2}$ is fitted quite closely by a simple power law. If the rise
of $D_F^2$ is assumed to occur due to the Bose-Einstein correlation, this relationship indicates a power-law structure in the transverse-size distribution of the source. For all rapidity windows the slope of that power-law dependence is in agreement with the value predicted in Ref. 1 for the emission of color dipoles in onium-onium collisions.

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