Correlations in proton-proton collisions with ALICE

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Abstract

Particle correlations and particle multiplicity distributions cannot be approached independently: a unified description of correlations and multiplicity distributions is always needed in order to understand the underlying dynamics in high energy collisions. In this light, we review the most recent and interesting results on rapidity and momentum correlations, emphasising the possibilities of measurements with the ALICE detector.

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1 Particle correlations in pseudo-rapidity

Particle correlations and particle multiplicity distributions (MD’s) cannot be approached independently: a unified description of correlations and multiplicity distributions is always needed in order to understand the underlying dynamics in high energy collisions. The warning comes from charged particle $H_q$ moments oscillations and shoulder structure in charged particle multiplicity distributions both in $p\bar{p}$ collisions and $e^+e^-$ annihilation, which have been shown to have a common origin in the weighted superposition of different classes of events or topologies, each one described by the same multiplicity distribution, i.e., a negative binomial (NB) (Pascal) MD with characteristic parameters for each substructure [2, 3]. Accordingly, this Section should be considered the natural continuation of Ref. [1] on global event properties.

Attention here will be on differential variables whose integrated versions have been already discussed in the just mentioned Reference. Indeed, $n$-particle exclusive cross-section density

$$\frac{1}{\sigma_{\text{inel}}} \frac{d^n \sigma_n}{d\eta_1 \ldots d\eta_n}$$

(1)

integrated over $\eta_1, \ldots, \eta_n$, corresponds to $n$-particle multiplicity distribution $P_n = \frac{\sigma_n}{\sigma_{\text{inel}}}$, with $\sigma_n$ the $n$-particle topological cross-section and $\sum_{n} \sigma_n = \sigma_{\text{inel}}$, and $n$-particle inclusive cross-section density

$$\frac{1}{\sigma_{\text{inel}}} \frac{d^n \sigma}{d\eta_1 \ldots d\eta_n} = \rho_n(\eta_1 \ldots \eta_n)$$

(2)

integrated over $\eta_1, \ldots, \eta_n$, corresponds to $n$-th order factorial moments, $F_n$, of the multiplicity distribution $P_n$. In order to avoid inessential contributions due to inclusive lower order combinatorics, the $n$-particle correlation functions $C_n(\eta_1, \ldots, \eta_n)$ are introduced. They are linked, via standard cluster expansion of statistical mechanics, to $\rho_n(\eta_1 \ldots \eta_n)$. Integrals of $C_n(\eta_1, \ldots, \eta_n)$ over $\eta_1 \ldots \eta_n$ define factorial cumulant moments, $K_n$, of the multiplicity distribution $P_n$. All the above mentioned variables are not normalised, their corresponding normalised version can be obtained by dividing by the product of the single inclusive cross-sections.

It should be pointed out that $C_n(\eta_1 \ldots \eta_n) = 0$ indicates lack of $n$-particle correlations, a positive $C_n(\eta_1 \ldots \eta_n)$ the tendency of the $n$ particles to be correlated and to group together and a negative $C_n(\eta_1 \ldots \eta_n)$ anti-correlations among particles. They prefer to stay far apart one from the other.

Moreover the description of different classes of events in hadron-hadron collisions by NB (Pascal) MD’s would suggest two-particle correlation dominance in rapidity intervals as required by the hierarchical nature of $n$-particle correlations in each class of events [4].

2 Two-particle pseudo-rapidity correlations

Two-particle pseudo-rapidity correlations

$$C_2(\eta_1, \eta_2) = \rho_2(\eta_1, \eta_2) - \rho_1(\eta_1)\rho_1(\eta_2)$$

(3)

have been shown to be strong at small rapidity distances and to depend on the particles’ charge combination. It should be reminded that by integrating $C_2(\eta_1, \eta_2)$ over $\eta_1$ and $\eta_2$ one gets
Figure 1: $C_2, C_L$ and $C_S$ at various c.m. energies [7]

Figure 2: Same as previous figure but only 546 GeV is shown. [8]
$D^2 - \bar{n}$, where $D$ is the dispersion. In hadron-hadron collisions, the energy dependence of $C_2(\eta_1 = 0, \eta)$ from ISR \[5\] to UA5 \[6\] energies is described in Fig. 1a.

Inclusive two-particle correlation functions $C_2(\eta_1, \eta_2)$ can be written in terms of semi-inclusive single- and two-particle densities for particles $a$ and $b$:

$$\rho_1^{(n)}(\eta) = \frac{1}{\sigma_n} \frac{d^n \sigma_n^a}{d\eta}$$  \hspace{1cm} (4)

and

$$\rho_2^{(n)}(\eta_1, \eta_2) = \frac{1}{\sigma_n} \frac{d^n \sigma_n^{ab}}{d\eta_1 d\eta_2}$$  \hspace{1cm} (5)

by mixing events of different multiplicities $n$: two new functions can be defined:

$$C_2(\eta_1, \eta_2) = C_S(\eta_1, \eta_2) + C_L(\eta_1, \eta_2)$$  \hspace{1cm} (6)

where

$$C_S(\eta_1, \eta_2) = \sum_n P_n C_2^{(n)}(\eta_1, \eta_2)$$  \hspace{1cm} (7)

and

$$C_L(\eta_1, \eta_2) = \sum_n P_n [\rho_1^{(n)}(\eta_1) - \rho_1(\eta_1)] - \sum_n P_n [\rho_2^{(n)}(\eta_2) - \rho_1(\eta_2)]$$  \hspace{1cm} (8)

with

$$C_2^{(n)}(\eta_1, \eta_2) = \rho_2^{(n)}(\eta_1, \eta_2) - \rho_1^{(n)}(\eta_1) \rho_1^{(n)}(\eta_2)$$  \hspace{1cm} (9)

i.e., the two-particle correlation function at fixed multiplicity $n$.

$C_S$ is the average of the semi-inclusive correlation functions and is more sensitive to dynamical correlations, and $C_L$ describes the mixing of different topological single particle densities. As shown in Fig. 1, $C_S$ does not depend significantly on energy. This fact should be contrasted with $C_L$ behaviour which is strongly energy dependent and is the result of mixing different topological single particle densities. In Fig. 1b and 1c are shown the energy dependence of $C_S$ and $C_L$: the contribution of $C_L$ to $C_2(\eta_1, \eta_2)$ is dominant with respect to $C_S$, in addition it increases significantly with energy whereas $C_S$ does not grow as much with energy around $\eta = 0$: in addition $C_S$ is positive in the just mentioned region and becomes negative for $|\eta| > 1$.

The overall behaviour of $C_2$, $C_L$ and $C_S$ at fixed c.m. energy is summarised in Fig. 2.

It should be pointed out that

$$\int C_S(\eta_1, \eta_2) d\eta_1 d\eta_2 = -\bar{n}$$  \hspace{1cm} (10)

and

$$\int C_L(\eta_1, \eta_2) d\eta_1 d\eta_2 = D^2.$$  \hspace{1cm} (11)

These equations clarify the meaning of the two contributions to total two particle correlations $C_2(\eta_1, \eta_2)$ and point out what quantity should be measured with ALICE in the allowed pseudo-rapidity range.
3 Bose-Einstein correlations

Among two-particle correlations, Bose-Einstein (BE) correlations are of particular interest in high energy collisions. The production of two identical bosons $a, b$ from two particle sources is controlled by an amplitude which is symmetrised with respect to the interchange of bosons $a, b$ and leads to an enhanced emission probability if bosons have similar momenta.

BE correlations are measured in terms of the second order normalised factorial cumulant $R_2$, i.e.,

$$R_2(q_a, q_b) = \frac{\rho_2(q_a, q_b)}{\rho_1(q_a)\rho_1(q_b)} - 1,$$

(12)

the ratio of two-particle inclusive cross-section $\sigma^{-1}d^2\sigma/dq_adq_b$ over the product of single- $a$ and $b$ particle inclusive cross-sections $\sigma^{-1}d\sigma/dq_a, \sigma^{-1}d\sigma/dq_b$.

$R_2$ function is directly related to the Fourier transform of the space-time distribution of particle production points. Accordingly, space distribution and lifetime of boson sources can be measured. In the standard Goldhaber parametrisation

$$R_2(Q) = \lambda \exp \left(-G^2 Q^2\right),$$

(13)

with $Q^2 = -(q_a - q_b)^2$, the square of the four momentum difference of particles $a$ and $b$, $\{q_{a,b} \equiv (\vec{p}_{a,b}, E_{a,b})\}$; $\lambda$ is the strength of the effect and $G$ is a measure of the source size.

The effect depends strongly on the masses of particles used in the analysis. It is well known that the range of the radius of the source from which pions are produced in $e^+e^-$ annihilation at LEP lies between $\approx 0.7-1.0$ fm, the range of the radius of the source from which K particles are emitted between $\approx 0.5-0.7$ fm and that for $\Lambda$ particles between $\approx 0.1-0.2$ fm. In conclusion the most external shell produces particle pairs of lower mass (pions) and higher mass particles pairs (lambdas) are coming from most internal shells.

Are different particle production shells visible also in pp collisions in the TeV region? does a connection exist between low pair mass scale and short distance scale of QCD mini-jets? Extremely high ALICE statistics should allow to clarify all these points. Bose-Einstein effect depends also on $p_t$ intervals considered and on related multiplicity densities [10, 9]. A sample of 2,400,000 non-single-diffractive $p\bar{p}$ events at c.m. energy 630 GeV measured by the UA1 central detector have been used. Only vertex associated charged tracks with $p_t > 0.15$ GeV/c, and $|\eta| < 3$ have been considered. The azimuth angle has been restricted to $45^\circ < |\phi| < 135^\circ$.

Three subsamples for like-sign (ls) and opposite-sign (os) pion pairs have been selected with respect to pion transverse momentum $p_t$:

i. the all-$p_t$ sample;

ii. a low-$p_t$ subsample of charged particles with $p_t < 0.7$ GeV/c (attention is paid in order to reduce the number of particles originated from jets or mini-jets);

iii. a high-$p_t$ subsample with $p_T > 0.7$ GeV/c (particles come here predominantly from jets or mini-jets).

Then the behaviour of second order normalised cumulant correlation functions has been studied in the three subsamples for particle multiplicity densities $dN/d\eta = 1.22, 2.72$ and 6.85. BE correlations show in hadron-hadron collisions a pronounced dependence on multiplicity in
the BE strength parameter lambda or equivalently the cumulant of second order $K_2$ at $Q = 0$. In particular the high-$p_t$ sample cumulants exceeds one (which would indicate full coherence in pure BE correlations) and is hence concluded that this data sample is dominated by processes other than BE correlations (Fig. 3).

As far as the low-$p_t$ sample is concerned it is shown that the dependence of the correlation strength and of higher order cumulants on multiplicity is important in order to test different theoretical models (Monte Carlos are totally inadequate here): for this task the low $p_t$ cut-off of ALICE at LHC is required.

4 Higher moment correlations in small pseudo-rapidity intervals

The presence of very short range correlations and its connection with BE interference is indeed an important topic to be investigated, as in more general terms it is the search of local fluctuations of multiplicity distributions in momentum space and related scaling properties. Large concentrations of particle number in small pseudo-rapidity intervals for single events have been seen in the JACEE event for a pseudo-rapidity binning $\delta \eta = 0.1$ (local fluctuations up to $dn/d\eta \approx 300$ with a signal-to-background ratio about 1:1) \[11\] and in the NA22 event (local fluctuation in rapidity of 60 times the average density) \[12\].

A possible explanation of these spikes was related to an intermittent behaviour, i.e., to the guess that there exist a correlations at all scales which implies a power low dependence of
normalised factorial moments $F_q(\delta)$ on the size $\delta$ of the phase space bins:

$$F_q(\delta) \langle n(\delta) \rangle^q = \delta^{-\alpha_q};$$  \hspace{1cm} (14)

the slope $\alpha_q$ was shown to increase as $q$ increases, see Fig. 4.

Since ALICE allows to study with its high statistics moments properties up to order $q = 14$, it will be particularly interesting to analyse both intermittent behaviour as bin size decreases and the influence on this phenomenon on BE correlations together with resonance production.

If the above mentioned scaling law will be confirmed in the LHC energy domain a new horizon will be open on self-similar cascading structure and fractal properties of hadron hadron collisions, a fascinating perspective also for more complex collisions, like heavy ions.

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