Hadron production and QCD coherence at LEP

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Abstract. Two analyses are presented based on the high statistics sample of hadronic $Z^0$ decays recorded at LEP with the OPAL detector. First, Bose-Einstein correlation functions are studied in intervals of the average pair transverse momentum and of the pair rapidity, in order to study possible correlations between the pion production points and their momenta. The Yano-Koonin and the Bertsch-Pratt parameterizations are fitted to the measured correlation functions to estimate the space-time parameters of the source. The source rapidity is found to scale approximately with the pair rapidity, and both the longitudinal and transverse source dimensions decrease for increasing average pair transverse momenta, indicating that the source of pions expands during particle emission. In the second analysis, QCD coherence effects are studied measuring the correlations of particles with restricted transverse momenta. Due to colour coherence, the multiplicity distribution of particles with restricted transverse momenta is predicted to become Poissonian as the cut in transverse momentum decreases. The expected correlation pattern is observed for cuts down to $\approx 1$ GeV but not at lower transverse momenta. This study indicates difficulties with the Local Parton-Hadron Duality (LPHD) hypothesis when applied to many-particle inclusive observables of soft hadrons.

1. Bose-Einstein study of position-momentum correlations
Bose-Einstein correlations (BECs) in pairs of identical bosons can be analysed in terms of the correlation function

$$C(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho_0(p_1, p_2)}$$

(1)

where $p_1$ and $p_2$ are the 4-momenta of the two bosons, $\rho(p_1, p_2)$ is the pair density and $\rho_0(p_1, p_2)$ is the two-particle density in the absence of BECs. From the experimental correlation function the space-time extension of the source of particles can be extracted. Most of the results on BECs published by the LEP collaborations have been obtained under the hypothesis that the momentum distribution of the emitted particles is homogeneous throughout the source elements, as would happen if the source is static. In the case of a dynamic source, the dimension of the regions of homogeneity (i.e. the “radius” of the source element) varies with the momentum of the emitted particles, because the expansion induces correlations between the space-time emission points and the particle 4-momenta (position-momentum correlations). The correlation function is therefore expected to depend on the average 4-momentum of the pair $K = (p_1 + p_2)/2$, in addition to the relative 4-momentum $q$: $C(p_1, p_2) = C(q, K)$ [1], so that the measured radii correspond to regions of homogeneity in $K$, i.e. source elements of pairs with momentum $K$. Models based on different assumptions [2, 3] predict that BECs radii decrease with the transverse mass of the pair for sources created in $e^+e^-$ collisions.

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1.1. Analysis and Results
The correlations were measured as functions of two different sets of variables, \((q_t, q, q_0)\) and \((Q_t, Q_{\text{side}}, Q_{\text{out}})\), components of the pair 4-momentum difference \(q\) \([4]\). The dependence of the correlation functions \(C(q_t, q, q_0)\) and \(C(Q_t, Q_{\text{side}}, Q_{\text{out}})\) on the pair average 4-momentum \(K\) has been analyzed by selecting pions in different intervals of two components of \(K\): the pair rapidity \(|Y|\) and the pair average transverse momentum \(k_t\) with respect to the event thrust direction \([4]\).

To extract the spatial and temporal extensions of the pion source, the Bertsch-Pratt (BP) \([5]\)
\[
C(Q_t, Q_{\text{side}}, Q_{\text{out}}) = 1 + \lambda e^{-\left(Q_t^2 R_{\text{long}}^2 + Q_{\text{side}}^2 R_{\text{side}}^2 + Q_{\text{out}}^2 R_{\text{out}}^2 + 2Q_t Q_{\text{out}} R_{\text{long},\text{out}}^2\right)}
\]
and the Yano-Koonin (YK) \([6]\)
\[
C(q_t, q, q_0) = 1 + \lambda e^{-\left(q_t^2 R_{\text{long}}^2 + q^2 R_{\text{side}}^2 + q_0^2 R_{\text{out}}^2 + \gamma (q_t - v q_0)^2 R_{\text{long}}^2 + \gamma^2 (q_0 - v q_0)^2 R_{\text{out}}^2\right)}
\]
parameterizations were fitted to the measured correlation functions in all intervals of \(k_t\) and \(|Y|\).

From Figure 1 it may be seen that, in both parameterizations, the longitudinal and transverse source dimensions decrease with increasing \(k_t\), the longitudinal radii \(R_{\text{long}}\) and \(R_t\) being larger than the corresponding transverse radii \(R_{\text{side}}\) and \(R_0\). This is in agreement with a source which is elongated in the thrust direction and that expands during the particle emission process.

The difference between the BP “out” and “side” transverse parameters, \((R_{\text{out}}^2 - R_{\text{side}}^2)\), and the YK radius \(R_0^2\) are expected to measure the time duration of the particle emission process.

**Figure 1.** (a) (d) (g) The best-fit longitudinal radius \(R_{\text{long}}^2\) of the Bertsch-Pratt parameterization (open dots) compared with the Yano-Koonin longitudinal radius \(R_t^2\) (full dots). (b) (e) (h) The BP transverse correlation length \(R_{\text{side}}^2\) (open dots) compared with the YK transverse correlation length \(R_t^2\) (full dots). (c) (f) (i) The difference of the BP transverse radii \((R_{\text{out}}^2 - R_{\text{side}}^2)\) (open dots) compared with the YK time parameter \(R_0^2\) times \(\beta_t^2\) (full dots) \([4]\). Errors on the parameters include both statistical and systematic uncertainties, added in quadrature.
As it may be seen in Figure 1, in both parameterizations the time parameter is compatible with zero, suggesting that the present technique does not allow to measure the particle emission time of the source created in $e^+e^-$ collisions.

The source velocity $v$ does not depend on $k_t$, but it is strongly correlated with the pair rapidity. The dependence of $v$ on $|Y|$ is presented, in Figure 2, in terms of the Yano-Koonin rapidity

$$Y_{YK} = \frac{1}{2} \ln \left( \frac{1 + v}{1 - v} \right)$$

as a function of the pair rapidity $|Y|$. $Y_{YK}$ measures the rapidity of the source element with respect to the centre-of-mass frame: a non-expanding source would therefore correspond to $Y_{YK} \approx 0$ for any $|Y|$. On the other hand, for a source that expands boost-invariantly the strict correlation $Y_{YK} = |Y|$ is expected. Since in a given $|Y|$ interval the parameter $v$ is almost independent of $k_t$, each $Y_{YK}$ is computed, according to Eq. (4), using the average value of $v$ over all $k_t$ in that $|Y|$ bin. A clear positive correlation between $Y_{YK}$ and $|Y|$ is observed, pointing to a pion source which is emitting particles in a nearly boost-invariant way.

2. QCD coherence and correlations of particles with restricted momenta

A fundamental property of a QCD cascade, which follows from the non-Abelian structure of QCD, is colour coherence. This induces an angular ordering of subsequent emissions in the branching process which restricts the phase space for each subsequent parton in the cascade.

According to the Local Parton-Hadron Duality (LPHD) hypothesis, parton-level QCD predictions are applicable to sufficiently inclusive hadronic observables without the need for a hadronisation phase. Hadronic spectra are proportional to those of partons if $Q_0$, the cut-off in the virtuality of the daughter partons (below which perturbative methods cease to be valid) is decreased towards a small value of the order of $\Lambda$, the QCD-scale. However, in spite of its success with single-particle inclusive spectra, the applicability of LPHD is less evident for the moments of single-particle densities and angular correlations.

Sensitive studies of colour coherence were suggested in [7]. In a QCD cascade the presence of one gluon enhances the probability for further gluon emissions, causing positive correlations. The multiplicity distribution of partons in a jet is therefore generally broader than a Poisson distribution, which corresponds to uncorrelated production. However, due to colour coherence, gluons produced with bounded transverse momenta, $p_T < p_T^{\text{cut}}$, where $p_T$ is defined with respect to the primary parton in a jet, become, for small $p_T^{\text{cut}}$, independently emitted from the primary parton, so that their multiplicity distribution becomes Poissonian.

2.1. Analysis and Results

The normalised factorial moment of order $q$ in a region of phase space of size $\Omega$ is defined as [8]

$$F_q(\Omega) = \frac{\langle n(n-1)\cdots(n-q+1) \rangle}{\langle n \rangle^q}, \quad q \geq 1.$$  

(5)

Here $n$ is the number of particles in $\Omega$ and the angle brackets $\langle \cdots \rangle$ denote the average over events. For uncorrelated particle production within $\Omega$ one has $F_q = 1$ for all $q$.

The normalised factorial moments of the multiplicity distribution of gluons which are restricted in transverse momentum $p_T < p_T^{\text{cut}}$ (cylindrically-cut phase space) are predicted to have the following qualitative behaviour [7]:

$$F_q(p_T^{\text{cut}}) \approx 1 + \frac{q(q-1)}{6} \frac{\ln(p_T^{\text{cut}}/Q_0)}{\ln(E/Q_0)} \quad \text{for} \quad p_T^{\text{cut}} \to Q_0,$$

(6)
where $E$ is the energy of the initial parton, and transverse momentum is defined with respect to its direction.

Figure 3 shows cylindrically cut factorial moments $F_q$ of order $q = 2$ to $5$ as a function of $p_T^{\text{cut}}$. With decreasing $p_T^{\text{cut}}$, the moments decrease towards a minimum at a common value of $p_T^{\text{cut}} \approx 1$ GeV but remain larger than unity. The observed deviation from the Poissonian behaviour for large $p_T^{\text{cut}}$ values agrees qualitatively with the theoretical expectation. However, for smaller $p_T^{\text{cut}}$ values the moments rise strongly, in clear disagreement with the perturbative QCD result for partons. The predicted Poisson limit for soft gluons is masked by strong hadronisation effects as $p_T^{\text{cut}} \to Q_0$ which lead to violation of LPHD for many-particle inclusive observables. The drop of the moments and the characteristic dip for $p_T^{\text{cut}} \approx 1$ GeV indicate, however, that perturbative calculations may be relevant for hadrons down to a scale of approximately 1 GeV.

The Monte Carlo model calculations which include both the parton cascade and hadronisation, largely follow the trend of the data and, in particular, reproduce the minimum around $p_T^{\text{cut}} = 1$ GeV. Differences appear for $p_T^{\text{cut}} \lesssim 1$ GeV, with HERWIG describing the data better than the models using string fragmentation. However, the dotted curves, which represent PYTHIA predictions with the inclusion of Bose-Einstein correlations, are in very good agreement with the measurements.

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