Bose-Einstein study of position-momentum correlations of charged pions in hadronic Z^0 decays

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Abstract

Bose-Einstein correlations in pairs of identically charged pions produced in e^+e^- annihilations at Z^0 peak are studied for the first time assuming a dynamic emitting source. The correlation functions are analyzed in intervals of average pair transverse momentum and pair rapidity, to investigate correlations between pion production points and momenta. The Yano-Koonin and Bertsch-Pratt parameterizations are used to estimate the source parameters and the velocity of source elements with respect to the centre-of-mass frame. The source rapidity scales with pair rapidity, and both longitudinal and transverse dimensions decrease for increasing average pair transverse momenta, in agreement with an expanding source.

1 Using BEC to obtain informations on particle source created in interactions

The space-time structure and evolution of a source emitting particles can be probed using intensity interferometry. Bose-Einstein correlations (BEC) in pairs of identical bosons have been analysed extensively for different energies and initial states, evolving from studies with one-dimensional correlation function and static source hypothesis to dynamic source and multi-dimensional refined investigations.

In the case of a dynamic source, the expansion leads to correlations between particle emission points and 4-momenta (position-momentum correlations). The correlation function depends on both the relative 4-momentum q and the average 4-momentum K of the pair: $C(p_1, p_2) = C(q, K)$ where $q = (p_1 - p_2)$ and $K = (p_1 + p_2)/2$. The measured radii correspond to regions of homogeneity in K (effective source elements) from which pions are emitted with momenta similar enough to interfere and contribute to the correlation function.

2 Analysis procedure and correlation functions

Bose-Einstein correlation are analyzed to investigate dynamical features of the pion emitting source created after e^+e^- annihilation at centre-of-mass energy of about 91 GeV. Results are based on the high statistics data obtained with the OPAL detector at LEP. All details of the analysis can be found in [1]. Three-dimensional correlations are measured as functions of two different sets of components of the pair 4-momentum difference q, in two suitable frames, to be fitted by two parametrizations of interest. The first set, $(Q_\ell, Q_{\mathrm{t_{side}}}, Q_{\mathrm{t_{out}}})$, is evaluated in the Longitudinally CoMoving System (LCMS) [2] and the second set, $(q_\mathrm{t}, q_\ell, q_0)$, in the center-of-mass frame (CMS). Experimentally, the correlation functions C are defined, in a small phase space volume

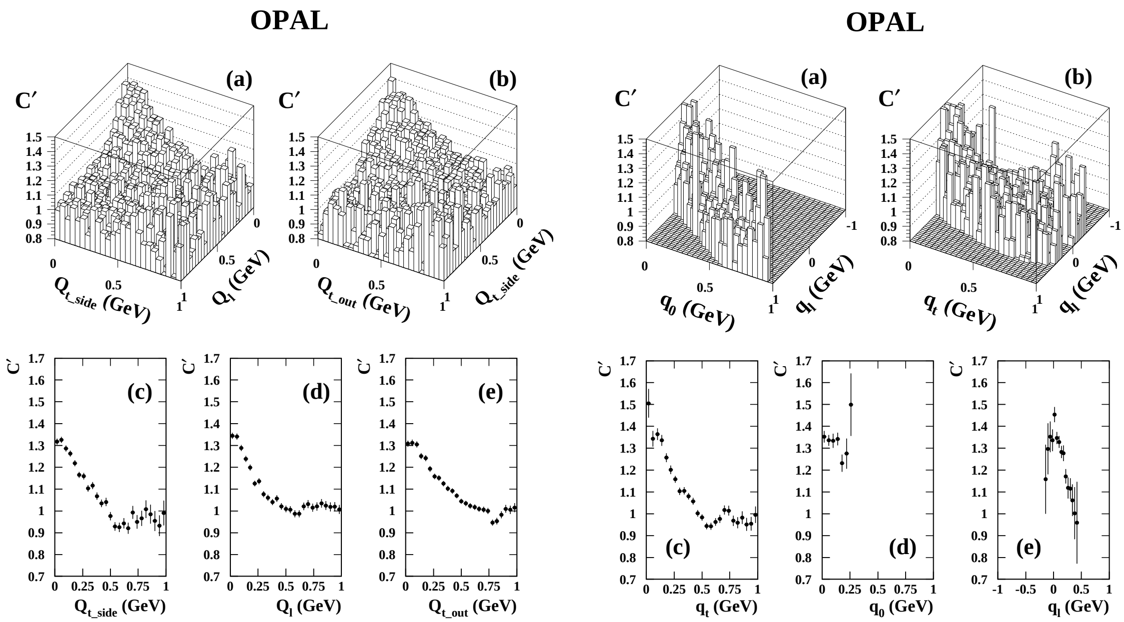

Fig. 1: Projections of correlation functions $C'(Q_\ell, Q_{\mathrm{t_{side}}}, Q_{\mathrm{t_{out}}})$ (left) and $C'(q_{\mathrm{t}}, q_\ell, q_0)$ (right) in bin 0.8 $\leq |Y| <$ 1.6 and 0.3 GeV $\leq k_{\mathrm{t}} <$ 0.4 GeV, obtained for low values ($<$ 0.2 GeV) of the remaining variables.

around each triplet of variables, as number of like-charge pairs divided by number of unlike-charge pairs. To reduce distorsions due to long-range correlations and pions from resonance decays, the double ratio C' of C in data and in a sample of Monte Carlo events without BEC, $C' = C^{\mathrm{DATA}}/C^{\mathrm{MC}}$, is introduced. The dependence of $C'(Q_\ell, Q_{\mathrm{t_{side}}}, Q_{\mathrm{t_{out}}})$ and $C'(q_{\mathrm{t}}, q_\ell, q_0)$ on K is analyzed by selecting pions in intervals of two components of K, the pair rapidity and the pair average transverse momentum with respect to the event thrust direction:

$$|Y| = \frac{1}{2}\ln\left[\frac{(E_1+E_2)+(p_{\ell,1}+p_{\ell,2})}{(E_1+E_2)-(p_{\ell,1}+p_{\ell,2})}\right] \qquad k_{\mathrm{t}} = \frac{1}{2}\left|(\vec{p}_{\mathrm{t},1}+\vec{p}_{\mathrm{t},2})\right| \tag{1}$$

Two-dimensional and one-dimensional projections of the correlation functions are shown in Fig.1, where cuts ($<$ 0.2 GeV) are applied on other variables. Central bin corresponding to pair rapidities and transverse momenta in the intervals $0.8 \leq |Y| < 1.6$ and 0.3 GeV $\leq k_{\mathrm{t}} < 0.4$ GeV is chosen. BEC enhancements are visible in data at low Q_ℓ, $Q_{\mathrm{t_{side}}}$ and $Q_{\mathrm{t_{out}}}$ as q_ℓ and q_{t}. The range available to the variable q_0 instead is quite restricted, and no BEC peak can be observed. The condition: $[(q_{\mathrm{t}}^2 + q_\ell^2) - q_0^2]$ invariant > 0, and the bound on pair rapidity constrain the correlation function to be different from zero only in a limited region of (q_ℓ, q_0) plane.

3 Results from BP and YK parametrizations

Two parameterizations are used to extract source dimensions. The Bertsch-Pratt (BP) [3]

$C'(Q_\ell, Q_{\mathrm{t_{side}}}, Q_{\mathrm{t_{out}}}) =$

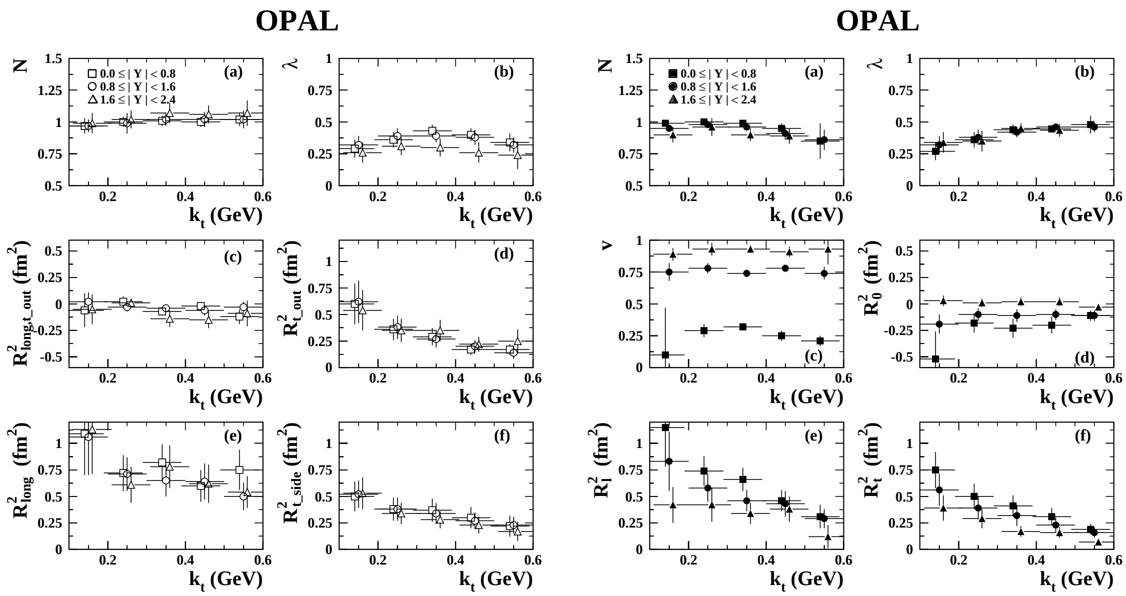

Fig. 2: Best-fit parameters of Bertsch-Pratt parameterization to correlation function $C'(Q_\ell, Q_{\mathrm{t_{side}}}, Q_{\mathrm{t_{out}}})$ (left) and of Yano-Koonin to $C'(q_\mathrm{t}, q_\ell, q_0)$ (right), as a function of k_t, for different intervals of rapidity $|Y|$. Horizontal bars represent bin widths and vertical bars include statistical and systematic errors, added in quadrature.

$$N[1+\lambda \mathrm{e}^{-(Q_\ell^2 R_{\mathrm{long}}^2 + Q_{\mathrm{t_{side}}}^2 R_{\mathrm{t_{side}}}^2 + Q_{\mathrm{t_{out}}}^2 R_{\mathrm{t_{out}}}^2 + 2 Q_\ell Q_{\mathrm{t_{out}}} R_{\mathrm{long,t_{out}}}^2)}] F(Q_\ell, Q_{\mathrm{t_{side}}}, Q_{\mathrm{t_{out}}}) \qquad (2)$$

and Yano-Koonin (YK) [4]

$$C'(q_\mathrm{t}, q_\ell, q_0) = N\{1+\lambda \mathrm{e}^{-[q_\mathrm{t}^2 R_\mathrm{t}^2 + \gamma^2 (q_\ell - v q_0)^2 R_\ell^2 + \gamma^2 (q_0 - v q_\ell)^2 R_0^2]}\} F(q_\mathrm{t}, q_\ell, q_0) \qquad (3)$$

In both parameterizations, N is a normalization factor and λ measures the degree of incoherence (related to fraction of pairs that interfere). The functions $F(Q_\ell, Q_{\mathrm{t_{side}}}, Q_{\mathrm{t_{out}}}) = (1 + \epsilon_{\mathrm{long}} Q_\ell + \epsilon_{\mathrm{t_{side}}} Q_{\mathrm{t_{side}}} + \epsilon_{\mathrm{t_{out}}} Q_{\mathrm{t_{out}}})$ and $F(q_\mathrm{t}, q_\ell, q_0) = (1 + \delta_\mathrm{t} q_\mathrm{t} + \delta_\ell q_\ell + \delta_0 q_0)$, where ϵ_i and δ_i are free parameters, take into account residual long-range correlations, due to energy and charge conservation. In Eq.2, $R_{\mathrm{t_{side}}}$ and R_{long} are transverse and longitudinal radii in LCMS, $R_{\mathrm{t_{out}}}$ and the cross-term $R_{\mathrm{long,t_{out}}}$ are a combination of both spatial and temporal extentions of the source. The difference $R_{\mathrm{t_{out}}}^2 - R_{\mathrm{t_{side}}}^2$ is proportional to the duration of particle emission process. In Eq.3, where $\gamma = 1/\sqrt{1-v^2}$ and $c = 1$, v is the longitudinal velocity of the source element in CMS frame, R_0 measure the duration of particle emission process, R_t and R_ℓ are transverse and longitudinal radii.

Best-fit parameters of BP and YK parametrizations to $C'(Q_\ell, Q_{\mathrm{t_{side}}}, Q_{\mathrm{t_{out}}})$ and $C'(q_\mathrm{t}, q_\ell, q_0)$ in the different $|Y|$ and k_t intervals are shown in Fig.2. BP parameters show a minor dependence on rapidity while depend on k_t. $R_{\mathrm{t_{side}}}^2$, $R_{\mathrm{t_{out}}}^2$ and, less markedly, R_{long}^2 decrease with increasing k_t. The presence of correlations between particle production points and momenta indicates that source expands during emission process. R_{long}^2 is larger than $R_{\mathrm{t_{side}}}^2$, in agreement with a source elongated in the direction of the event thrust axis [5]. The cross-term parameter $R_{\mathrm{long,t_{out}}}^2$ is compatible with zero, apart from a few bins at the highest rapidity interval. The difference

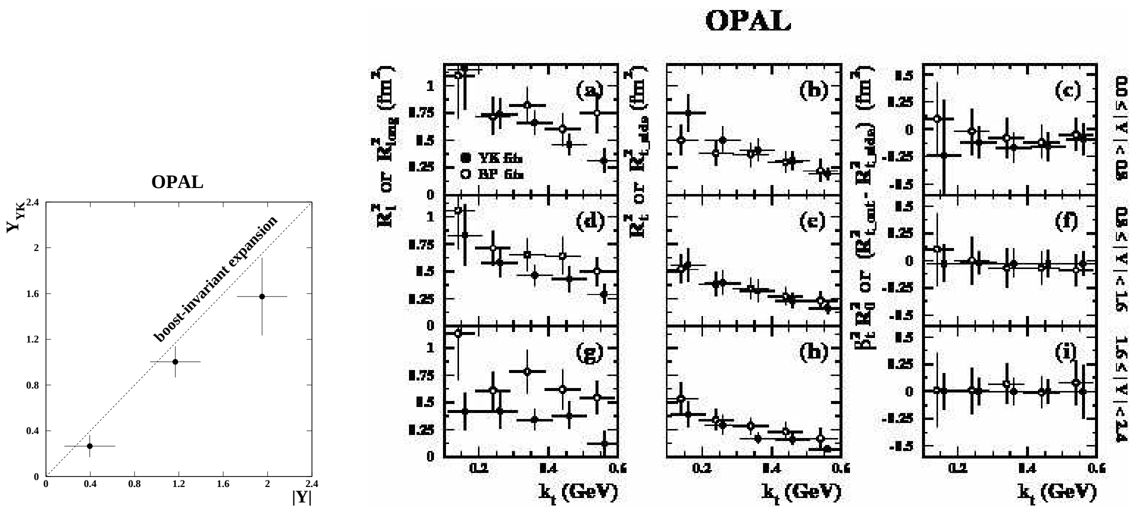

Fig. 3: Left: Yano-Koonin rapidity $Y_{\rm YK}$ as a function of pair rapidity $|Y|$. Right: BP parameters (open dots) compared with YK parameters (full dots): longitudinal radius, transverse radius and duration of emission process. Errors include statistical and systematic uncertainties, added in quadrature.

$R^2_{\rm t_{out}} - R^2_{\rm t_{side}}$ for $|Y| < 1.6$ is positive at low $k_{\rm t}$, then decreases and becomes negative for $k_{\rm t} \geq$ 0.3 GeV, while in the interval $1.6 \leq |Y| < 2.4$ is compatible with zero for all $k_{\rm t}$. As a consequence, it is not possible to estimate the particle emission duration from $R^2_{\rm t_{out}} - R^2_{\rm t_{side}}$. YK parameters show dependence on both Y and $k_{\rm t}$. Both $R^2_{\rm t}$ and R^2_ℓ decrease with increasing $k_{\rm t}$ and $|Y|$ and R^2_ℓ are larger than $R^2_{\rm t}$. This agrees again with an expanding, longitudinally elongated source. R^2_0 is compatible with zero at high rapidities, and assumes negative values for $|Y| < 1.6$. This excludes an interpretation in terms of duration of particle emission process. Difficulties in achieving reliable results for R^2_0 parameter in YK fits are reported in literature [6], due to the limited phase-space available in $\gamma^2(q_0 - vq_\ell)^2$. The source velocity v does not depend on $k_{\rm t}$, but it is strongly correlated with pair rapidity. The dependence of v on $|Y|$ is presented in terms of Yano-Koonin rapidity

$$Y_{\rm YK} = \frac{1}{2}\ln\left(\frac{1+v}{1-v}\right) \tag{4}$$

as a function of pair rapidity $|Y|$, in Fig.3 (left). $Y_{\rm YK}$ measures the rapidity of the source element with respect to the centre-of-mass frame: a static source would correspond to $Y_{\rm YK} \approx 0$ for any $|Y|$ while for a boost-invariant expanding source the strict correlation $Y_{\rm YK} = |Y|$ is expected. A clear positive correlation between $Y_{\rm YK}$ and $|Y|$ is observed, even if $Y_{\rm YK} < |Y|$ at the largest pair rapidities, in agreement with a source which is emitting in a nearly boost-invariant way.

4 Comparison between BP and YK parameters

The following relations should hold between BP and YK parameters measured in LCMS and CMS frames, respectively [7]:

$$R^2_{\mathrm{t_{side}}} = R^2_{\mathrm{t}} \tag{5}$$
$$R^2_{\mathrm{long}} = \gamma^2_{\mathrm{LCMS}}(R^2_\ell + \beta^2_{\mathrm{LCMS}} R^2_0) = R^2_\ell \tag{6}$$
$$R^2_{\mathrm{t_{out}}} - R^2_{\mathrm{t_{side}}} = \beta^2_{\mathrm{t}}\gamma^2_{\mathrm{LCMS}}(R^2_0 + \beta^2_{\mathrm{LCMS}} R^2_\ell) = \beta^2_{\mathrm{t}} R^2_0 \tag{7}$$

where β_{LCMS} is the velocity of the source element measured in LCMS, $\gamma_{\mathrm{LCMS}} = 1/\sqrt{1-\beta^2_{\mathrm{LCMS}}}$ and $\beta^2_{\mathrm{t}} = \left\langle \frac{2k_{\mathrm{t}}}{E_1+E_2} \right\rangle^2$, where brackets stand for the average over all pairs in given $|Y|$ and k_{t} interval. For a boost-invariant source, $\beta_{\mathrm{LCMS}} = 0$. In Fig.3 (right), the BP parameters R^2_{long}, $R^2_{\mathrm{t_{side}}}$ and $R^2_{\mathrm{t_{out}}} - R^2_{\mathrm{t_{side}}}$ are compared with the YK parameters R^2_ℓ, R^2_{t} and $\beta^2_{\mathrm{t}}\mathrm{R}^2_0$. R^2_{long} is systematically larger than R^2_ℓ in all rapidity intervals in agreement with a source whose expansion is not exactly boost-invariant. $R^2_{\mathrm{t_{side}}} = R^2_{\mathrm{t}}$ within errors, with possible deviations at low k_{t}. The negative values of R^2_0 and $R^2_{\mathrm{t_{out}}} - R^2_{\mathrm{t_{side}}}$ appearing in the two first rapidity intervals prevent an interpretation in terms of the duration of particle emission process.

5 Conclusion and discussion

An analysis of BEC in e^+e^- annihilation events at Z^0 peak performed in bins of average 4-momentum of the pair, K, is presented for the first time and dynamic features of the pion emitting source are investigated. Transverse and longitudinal radii decrease for increasing k_{t}, indicating the presence of correlations between particle production points and momenta. The Yano-Koonin rapidity scales approximately with pair rapidity, in agreement with a nearly boost-invariant expansion of the source. Limitations in the available phase space did not allow measurement of the duration of particle emission process.

Similar results are observed in more complex systems from pp and heavy-ion collisions. Negative values of R^2_0 are suggested as indicators for source opacity, i.e. surface dominated emission [8]. A similar dependence of $R^2_{\mathrm{t_{out}}} - R^2_{\mathrm{t_{side}}}$ on k_{t} is reported in heavy-ion collision experiments [9] [see Florkowski in these proceedings]. The τ model, based on Bjorken-Gottfried condition [10] predict expansion ring in transverse direction [see Csörgő and Metzger in these proceedings].

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