Recent L3 Results (and Questions) on BEC at LEP

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Abstract

Results of two recent studies of Bose-Einstein correlations (BEC) in hadronic Z decays are reported. The first finds that a good description of the two-pion correlation function is achieved using a Lévy stable distribution in conjunction with a hadronization model having highly correlated configuration and momentum space, the τ-model. Using the results of this parametrization, the space-time source function is reconstructed. The second investigates the question of the existence of inter-string BEC, unfortunately without clear conclusions.

1 Introduction

We study BEC in hadronic Z decay using data collected by the L3 detector at an $\mathrm{e^+e^-}$ center-of-mass energy of $\sqrt{s} \simeq 91.2$ GeV. Approximately 36 million like-sign pairs of well-measured charged tracks from about 0.8 million hadronic Z decays are used [1]. Events are classified as two- or three-jet events using calorimeter clusters with the Durham jet algorithm. To determine the thrust axis of the event we also use calorimeter clusters.

The two-particle correlation function of two particles with four-momenta p_1 and p_2 is given by the ratio of the two-particle number density, $\rho_2(p_1, p_2)$, to the product of the two single-particle densities, $\rho_1(p_1)\rho_1(p_2)$. Since we are interested only in the correlation, R_2, due to Bose-Einstein interference, the product of single-particle densities is replaced by $\rho_0(p_1, p_2)$, the two-particle density that would occur in the absence of BEC: $R_2(p_1, p_2) = \frac{\rho_2(p_1,p_2)}{\rho_0(p_1,p_2)}$. An event mixing technique is used to construct ρ_0.

Since the mass of the identical particles of the pair is fixed, R_2 is defined in six-dimensional momentum space, which is often reduced to a single dimension, the four-momentum difference $Q = \sqrt{-(p_1 - p_2)^2}$. But there is no reason to expect the hadron source to be spherically symmetric in jet fragmentation. In fact, the source is found to be elongated along the jet axis [2], but only by about 25%, which suggests that a parametrization in terms of the single variable Q, may be a good approximation. This is confirmed by studies of various decompositions of Q [1, 3].

2 Parametrizations of BEC

With a few assumptions [4], R_2 is related to the Fourier transform, $\tilde{f}(Q)$, of the (configuration space) density distribution of the source, $f(x)$:

$$R_2(p_1, p_2) = \gamma \left[1 + \lambda |\tilde{f}(Q)|^2\right] (1 + \delta Q) \ . \tag{1}$$

The parameter γ and the $(1 + \delta Q)$ term are introduced to parametrize possible long-range correlations not adequately accounted for in ρ_0, and λ to account for several factors, such as lack of complete incoherence of particle production and presence of long-lived resonance decays.

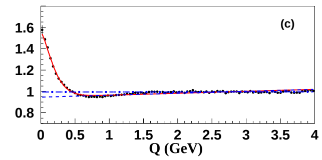

Fig. 1: The Bose-Einstein correlation function R_2 for two-jet events. The curve corresponds to a fit of the Lévy parametrization (2). The dashed line represents the long-range part of the fit, *i.e.*, $\gamma(1+\delta Q)$. The dot-dashed line represents a linear fit in the region $Q > 1.5\,\mathrm{GeV}$.

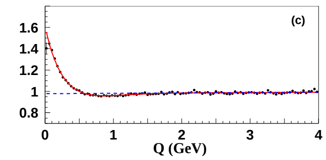

Fig. 2: The Bose-Einstein correlation function R_2 for two-jet events. The curve corresponds to the fit of the one-sided Lévy parametrization, (3), as described in the text. The dashed line represents the long-range part of the fit, *i.e.*, $\gamma(1+\delta Q)$.

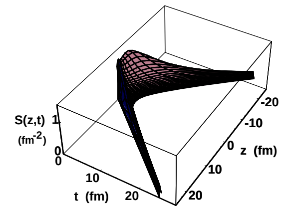

Fig. 3: The temporal-longitudinal part of the source function normalized to the average number of pions per event.

2.1 Static parametrizations

A model-independent way to study deviations from the Gaussian is to use [5] the Edgeworth expansion about a Gaussian. Another way is to replace it in configuration space by a symmetric Lévy distribution. These parametrizations lead to

$$R_2(Q) = \gamma \left(1 + \lambda \exp\left(-(RQ)^\alpha\right) \left[1 + \frac{\kappa}{3!} H_3(RQ)\right]\right) (1 + \delta Q) \ , \qquad (2)$$

where $\alpha = 2$ for the Gaussian and Edgeworth parametrizations; $0 < \alpha \leq 2$ for the Lévy parametrization; and $\kappa = 0$ except in the Edgeworth case where κ is the third-order cumulant moment and $H_3(RQ) \equiv (\sqrt{2}RQ)^3 - 3\sqrt{2}RQ$ is the third-order Hermite polynomial.

The Edgeworth and Lévy parametrizations indeed fit the low-Q peak much better than the purely Gaussian parametrizations, yielding, respectively, $\kappa = 0.71 \pm 0.06$ and $\alpha = 1.34 \pm 0.04$. However, the χ^2 are still poor. Both the symmetric Lévy (Fig. 1) and the Edgeworth parametrizations do a fair job of describing the region $Q < 0.6\,\mathrm{GeV}$, but fail at higher Q, particularly the region 0.6–1.5 GeV where R_2 dips below unity, indicative of an anti-correlation. This is clearly seen in Fig. 1 by comparing the data in this region to an extrapolation of a linear fit, (2) with $\lambda = 0$, in the region $Q \geq 1.5\,\mathrm{GeV}$. The inability to describe this dip in R_2 is the primary reason for the failure of both parametrizations.

2.2 Time dependence of the source

The parametrizations discussed so far all assume a static source. The parameter R, representing the size of the source as seen in the rest frame of the pion pair, is a constant. It has, however, been observed that R depends on the transverse mass, $m_\mathrm{t} = \sqrt{m^2 + p_\mathrm{t}^2}$, of the pions [6].

In the previous section we have seen that BEC depend, at least approximately, only on Q and not on its components separately. Further, we have seen that R_2 in the region 0.6–1.5 GeV dips below its values at higher Q. A model which predicts such Q-dependence as well as an m_t-dependence is the τ-model [7], in which it is assumed that the average production point in the overall center-of-mass system, $\overline{x} = (\overline{t}, \overline{r}_x, \overline{r}_y, \overline{r}_z)$, of particles with a given four-momentum k is given by $\overline{x}^\mu(k^\mu) = a\tau k^\mu$. In the case of two-jet events, $a = 1/m_\mathrm{t}$, where m_t is the transverse mass and $\tau = \sqrt{\overline{t}^2 - \overline{r}_z^2}$ is the longitudinal proper time. For isotropically distributed particle production, τ is, instead, the proper time, and the transverse mass is replaced by the mass, while for the case of three-jet events the relation is more complicated. The second assumption is that the distribution of $x^\mu(k^\mu)$ about its average, $\delta_\Delta(x^\mu(k^\mu) - \overline{x}^\mu(k^\mu))$, is narrower than the proper-time distribution. Then R_2 is found [8] to depend only on Q, the values of a of the two pions, and $\widetilde{H}$, the Fourier transform of the distribution of τ, $H(\tau)$. Since there is no particle production before the onset of the collision, $H(\tau)$ should be a one-sided distribution. We choose a one-sided Lévy distribution, which is characterized by three parameters: the index of stability α, the proper time of the start of particle emission τ_0, and $\Delta\tau$, which is a measure of the width of $H(\tau)$. Replacing the individual values of a of the two pions by their average results then (suppressing the normalization and long-range correlations) in [8]

$$R_2(Q,\bar{a}) = 1 + \cos\left[\bar{a}\tau_0 Q^2 + \tan\left(\frac{\alpha\pi}{2}\right)\left(\frac{\bar{a}\Delta\tau Q^2}{2}\right)^\alpha\right]\exp\left[-\left(\frac{\bar{a}\Delta\tau Q^2}{2}\right)^\alpha\right] . \quad (3)$$

Before proceeding to fits of (3), we first consider a simplification obtained by assuming an average $\bar{a}$-dependence, which is implemented in an approximate way by defining an effective radius, $R = \sqrt{\bar{a}\Delta\tau/2}$. This results in

$$R_2(Q) = \gamma\left[1 + \lambda\cos\left[\bar{a}\tau_0 Q^2 + (R_\mathrm{a} Q)^{2\alpha}\right]\exp\left(-(RQ)^{2\alpha}\right)\right](1+\delta Q) , \quad (4)$$

where R_a is related to R by

$$R_\mathrm{a}^{2\alpha} = \tan\left(\frac{\alpha\pi}{2}\right) R^{2\alpha} . \quad (5)$$

For two-jet events (Durham, $y_\mathrm{cut} = 0.006$) a good fit (χ^2/dof = 97/95), shown in Fig. 2, is achieved with the additonal assumption $\tau_0 = 0$. However, for three-jet events it is necessary to relax (5), *i.e.*, regard R_a as a free parameter, while keeping $\tau_0 = 0$ (χ^2/dof = 102/94). Alternatively, (5) can be kept but $\bar{a}\tau_0$ made a free parameter, although the description is somewhat worse (χ^2/dof = 127/94). The fits describe well the dip in the 0.6–1.5 GeV region, as well as the low-Q peak. We speculate that the need for an additional free parameter for three-jet events could be that the replacement of the individual values of a by their average is less valid than for two-jet events or that the onset of particle production might be somewhat later for three-jet events than for two-jet events. Whatever the reason, we now turn our attention exclusively to two-jet events

Fits of (3) to the two-jet data are performed in several m_t intervals. The quality of the fits is acceptable and the fitted values of the parameters, α, τ_0 and $\Delta\tau$, are stable and within errors independent of m_t, as expected in the τ-model. Their values (weighted averages of the values found in the four m_t intervals) are $\tau_0 = 0 \pm 0.01$ fm, $\alpha = 0.43 \pm 0.03$ and $\Delta\tau = 1.8 \pm 0.4$ fm. Using these values we reconstruct the space-time picture of the emitting process for two-jet events.

Given the symmetry of two-jet events, the emission function (in cylindrical coordinates) in the τ-model is [8]

$$S_\mathrm{x}(r,z,t) = H(\tau)P(r,\eta) = H(\tau)\left(\frac{m_\mathrm{t}}{\tau}\right)^3 \rho_{\mathrm{p_t}}(r m_\mathrm{t}/\tau)\rho_\mathrm{y}(\eta) , \quad (6)$$

where η is the space-time rapidity, y the rapidity, p_t the transverse momentum, and $\rho_{\mathrm{p_t}}$ and ρ_y are the inclusive single particle p_t and y distributions and where we have assumed that $P(r,\eta)$ can be factorized.

Using $H(\tau)$ as obtained from the BEC fits of (3) together with the inclusive rapidity and p_t distributions [1], the full emission function is reconstructed. Its integral over the transverse distribution (Fig. 3.) exhibits a "boomerang" shape with a maximum at low t and z and tails extending to very large values of t and z, a feature also observed in hadron-hadron [9] and heavy ion collisions [10]. The transverse part, obtained by integrating over z and azimuthal angle, is shown in Fig. 4 for various proper times. Particle production starts immediately, increases rapidly and decreases slowly forming an expanding ring-like structure.

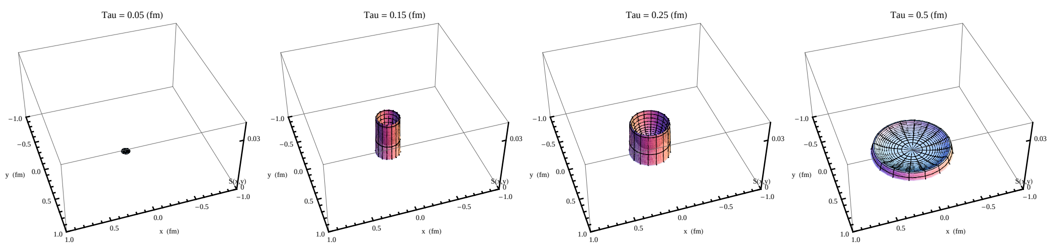

Fig. 4: The transverse source function normalized to the average number of pions per event for various proper times.

3 Inter-string BEC

The question of the existence of inter-string BEC rose to prominence during the measurement at LEP of the mass of the W boson. Uncertainty as to its existence and how to model it was one of the largest, along with the question of color reconnection, contributions to the systematic uncertainty on the mass measured in the channel $\mathrm{e^+e^-\to W^+W^-\to q\bar{q}q\bar{q}}$. No evidence of inter-string BEC was found [11], but the significance of the result was limited by poor statistics. Here we examine another channel involving two strings: $\mathrm{e^+e^-\to qg\bar{q}}$ where the gluon is connected to the quark by one string and to the anti-quark by another. This channel has been studied briefly in DELPHI data [12], with no definite conclusion. Here we present new results with L3 data [13].

The influence of inter-string BEC on R_2 depends on the amount of 'overlap', both in momentum- and configuration-space. Full momentum-overlap means that the distribution of $\vec{p}$ for pions from string 1 is the same as that for pions from string 2. If there is no overlap in momentum space, inter-string BEC can not take place, and the BEC parameters for two strings (λ_2 and r_2) will be the same as those for one string (λ_1 and r_1). If there is full overlap in momentum space, the expectations are:

	no spatial overlap	full spatial overlap
Inter-string BEC	$\lambda_2=\lambda_1 \quad r_2>r_1$	$\lambda_2=\lambda_1 \quad r_2=r_1$ (HBT) $\quad r_2>r_1$ (Lund)
No inter-string BEC	$\lambda_2<\lambda_1 \quad r_2=r_1$	$\lambda_2<\lambda_1 \quad r_2=r_1$

where the expectation for r in the case of full spatial overlap and inter-string BEC depends on whether r is measured along the color field (Lund) or directly (HBT).

A comparison of BEC in 2-jet (1-string) and 3-jet (2-string) events finds very weak dependence of λ and r on y_{cut}. The value of λ_1 is somewhat larger than λ_2, which might suggest an absence of inter-string BEC. However, r_2 is somewhat larger than r_1, suggesting the opposite.

Samples of single jets are defined based on jet configuration and on b-tagging. The gluon content of the various samples varies from zero to 75%. There is no evidence for a dependence of λ or r on the gluon fraction, suggesting the presence of inter-string BEC *à la* HBT.

The degree of overlap should be greatest in the tip of the gluon jet. Therefore, BEC are measured in various intervals of $x = E/E_{\mathrm{jet}}$ and of rapidity with respect to the jet direction. The value of λ is found to decrease with increasing x or rapidity, but this occurs in quark jets as well as in gluon jets suggesting that it is not an inter-string effect. The value of r does not decrease with increasing x or rapidity in contradiction to the expectation of inter-string BEC *à la* HBT.

The results are thus inconclusive. Inter-string BEC remains an open question.

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