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BOSE-EINSTEIN CORRELATIONS IN e^+e^- ANNIHILATION IN THE $\Upsilon(1S)$ AND CONTINUUM

Budker INP 95-8

НОВОСИБИРСК

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ABSTRACT

Bose-Einstein correlations in direct $\Upsilon(1S)$ decays and continuum in the energy region $\sqrt{s} = 7.2 - 10.3$ GeV have been studied using data taken with the MD-1 detector at VEPP-4 storage ring. Assuming gaussian density of the pion source the data indicate the radius of the source $\mathcal{R} = 0.69 \pm 0.09 \pm 0.04$ fm for direct $\Upsilon(1S)$ decays and $\mathcal{R} = 0.80 \pm 0.22 \pm 0.05$ fm for the continuum. The correlation strengths for both data samples also are similar. Thus Bose-Einstein correlations do not reveal a noticable difference between quark and gluon fragmentation.

1. Introduction

An enhancement in the production of pairs of pions of the same charge and similar momenta was first observed in $p\bar{p}$ annihilation and attributed to Bose-Einstein statistics appropriate to identical pion pairs [1]. Later this phenomenon has been proposed [2-4] as a tool to study the space-time structure of particle sources in high-energy reactions. Since then Bose-Einstein (BE) correlations have been extensively studied in various reactions. A comprehensive review has been given in [5].

e^+e^- annihilation is one of the most favorable processes for a quantitative study of BE correlations. It is due to fixed energy of the reaction, a simple parton configuration of the final state and existence of phenomenological models [21] satisfactory describing main features of this process. Results have been presented from the data taken at PEP [8, 11], CESR [9], PETRA [10], SPEAR [11], TRISTAN [12] and LEP [13–15] in the energy region $\sqrt{s} = 3 - 91$ GeV.

In this paper we present a new measurements of BE correlations in direct $\Upsilon(1S)$ decays and nearby continuum. The experiment was performed using the MD-1 detector at VEPP-4 storage ring. Multihadron final states in the continuum are produced via quark and antiquark fragmentation, those from direct $\Upsilon(1S)$ decays originate from hadronization of $3g$ and γgg states. Thus data from these processes allow us to compare space-time properties of quark and gluon fragmentation.

The paper is organized as follows. Section 2 summarises the theory of BE correlations and provides the analysis techniques used to study the correlations. Section 3 describes the data sample and details of the event and track selection. In Section 4 the problem of finding a correlation-free reference sample is addressed. Corrections for residual differences of the data and simulation are described in Section 5. Section 6 presents results and estimation of the systematic errors. Effects of non-pion tracks contamination, long-lived particles and final-state interaction are discussed in Section 7. Comparison with previous experiments is a subject of Section 8. The final section contains a summary and conclusions.

2. Theoretical overview

Description of the theoretical basis for BE correlations can be found in a number of sources [2–7]; only a brief review will be given here.

For a pair of identical bosons, the quantum mechanical wave-function must be symmetric under particle exchange. If $\rho(x)$ is the space-time distribution of the chaotic source of bosons, this requirement enhances the two-particle differential cross section by a factor [2–7]

$$r(k_1, k_2) = 1 + |\hat{\rho}(k_1 - k_2)|^2, \tag{1}$$

where k_1, k_2 are particle four-momenta and $\hat{\rho}(k_1 - k_2)$ is the Fourier transform of $\rho(x)$ with respect to $k_1 - k_2$, normalized to unity as $k_1 = k_2$. Thus one can measure the space-time distribution of the pion source by studying the correlations of the momenta of pions. It follows from (1) that identical bosons tended to be emitted close to each other in phase space and for chaotic source the enhancement factor tends towards a maximum of 2 as $k_1 \to k_2$.

Study of BE correlations as a function of four-momenta difference allows to obtain more complete information on the space-time structure of the source. However, our data are insufficient to support such an investigation. Quite general arguments based on dynamics of color string show [16–18] that BE correlations in e^+e^- annihilation are almost independent on the total momentum of the pair and depend mainly on the momentum transfer in the pair rest frame. Therefore we shall study r as a function of the single Lorentz invariant variable $Q^2 = -(k_1 - k_2)^2$. The quantity Q is equivalent to twice the momentum of a particle in the rest frame of the pair. Taking both particles as pions $Q^2 = M^2_{\pi\pi} - 4 \cdot m^2_{\pi}$, where $M_{\pi\pi}$ is the invariant mass of the pair. This variable was first introduced in this context in ref.[1].

Assuming gaussian distribution of the pion source density in the pair rest frame ($\rho(x) \sim \exp(-x^2/2\mathcal{R}^2)$), the BE correlation function can be

parametrized as

$$r(Q^2) = 1 + \lambda \cdot \exp(-\mathcal{R}^2 \cdot Q^2), \tag{2}$$

where $\mathcal{R}$ is the radius of the pion source and the parameter λ measures the strength of the correlations between pions. As was mentioned above, a chaotic source of identical bosons is expected to produce $r(Q^2 \to 0) = 2$. The corresponding value of the parameter λ is thus 1. However experiments have reported values of λ between 0 and 1 [8–15]. Some factors responsible for it will be discussed in Sec.7.

The BE correlation function is usually determined as

$$r(Q^2) = P(Q^2)/P_o(Q^2), \tag{3}$$

where $P(Q^2)$ is the measured two-particle density for a like-charged pairs, and $P_0(Q^2)$ denotes the two-particle density for a "reference sample" , which, ideally, resembles the data in all respects except for the BE correlations. Several techniques, used to obtain such sample, will be described in Sec.4.

An expression slightly different from (2) is often used in the literature to analyze the experimental data:

$$r(Q^2) = N \cdot (1 + \delta \cdot Q) \cdot (1 + \lambda \cdot \exp(-\mathcal{R}^2 \cdot Q^2)), \tag{4}$$

where the factor $(1 + \delta \cdot Q)$ is introduced to take into account possible long-scale difference between $P(Q^2)$ and $P_0(Q^2)$, and N is a normalization factor. Although this expression is purely empirical, it has been shown to describe e^+e^- annihilation data well over a wide range of energies [8–15].

3. Detector, data sample and track selection

The MD-1 detector has been described in detail elsewhere [19]. Here we give a brief description of the systems relevant to this analysis.

In the MD-1 detection of charged particles and momentum reconstruction are provided by 38 proportional chambers. In a solid angle $0.4 \cdot 4\pi$ sr the momentum resolution of the tracking system is $\sigma_p/p = (5-7)\% \cdot p$ (GeV/c). The central part of the detector comprises also 24 scintillation counters, 8 gas Cherenkov counters and 14 units of the shower-range system (sandwiches of proportional chambers and stainless steel plates). The magnetic field of the detector is transverse to the beam orbit plane and equals 11.3 kG at the $\Upsilon(1S)$.

The trigger information comes from the scintillation counters, shower-range and tracking systems. At least two particles in an event were required. The efficiency of the trigger was 97.9% for the $\Upsilon(1S)$ hadronic decays.

The used event sample corresponds to the integrated luminosity of 6.6 pb^{-1} on the $\Upsilon(1S)$ resonance and 19.1 pb^{-1} in the continuum in the energy region $\sqrt{s} = 7.2 - 10.3$ GeV. For comparison of the $\Upsilon(1S)$ and continuum results and for subtraction of the continuum contribution from the $\Upsilon(1S)$ we used a reduced continuum sample centered at the $\Upsilon(1S)$ energy. This sample corresponds to the integrated luminosity of 15.6 pb^{-1} in the energy region $\sqrt{s} = 8.7 - 10.3$ GeV.

The event selection procedure was described in ref.[20]. The total number of selected continuum events is 39200. The total number of selected events in the $\Upsilon(1S)$ sample is 59300. It transforms to 48700 after background and continuum subtraction. After correction for electromagnetic $q\bar{q}$-decays of the $\Upsilon(1S)$, the number of direct decays is 44600.

We have used also direct $\Upsilon(1S)$ decays and $q\bar{q}$ events generated by the JETSET 6.3 Monte Carlo generator [21]. The passage of particles through the detector was simulated by means of detailed detector simulation Monte Carlo program UNIMOD [22]. All events were subsequently processed with the same reconstruction and analysis chain as the real data.

Pairs of tracks are selected according to the following criteria:

1. The particle trajectories are required to be consistent with the event vertex. This cut suppresses decay products of long-lived particles.

2. The particle momenta are required to be in the range 0.2–1.6 GeV/c. The lower cut eliminates particles that spiral around in the track chamber and the upper one reduces correlations arised from the energy-momentum conservation.

3. Overlapping pairs of tracks were not taken into analysis in view of potential problems in reconstruction.

4. The interactions of particles with a beam pipe are suppressed by the requirement that the distance between tracks on the surface of the beam pipe must be greater than 12 mm.

The resulting samples of like-sign pairs are used for calculation of the two-particle probability densities $P(Q^2)$ assuming all particles to be pions.

4. The reference sample

To evaluate the correlation function r, a "reference" density $P_0(Q^2)$ is required. The choice of an appropriate reference sample from which $P_0(Q^2)$ can be obtained is a central problem in the experimental study of BE correlations. Some often used methods are discussed below.

One of the simplest ways to obtain a reference sample is to use the unlike-sign pairs in the events. Their distribution contains much of the same physics as the like-signed distribution (i.e. phase space, momentum and angular distributions), but does not contain BE correlations. Differences exist, however, due to resonance decays, detector effects and some other phenomena.

Another method of obtaining a reference sample uses the technique of event mixing. Pairs of pions are formed by combining a pion from the event under study with pions from previous events. For this method to work well, the events must be isotropic or the jet axes must be oriented in the same direction. It restricts use of this method in the Υ decays where events are neither completely isotropic nor extremely jetlike.

Finally, a reference sample can be produced by the Monte Carlo simulation that does not contain the BE effect. However, the Monte Carlo event generators are not usually tuned to two-particle effects in the fragmentation, and they may not give satisfactory results.

Tests of reference samples based on unlike-sign pairs and event mixing technique on the MC events show significant deviation of $r_{MC}(Q^2)$ from constant though our MC generators does not contain BE correlations. It confirms that neither of the reference samples used is perfect. To the extent that the failings of the reference sample are correctly simulated by the Monte Carlo, one can overcome them by dividing the data by the Monte Carlo, i.e. studying the double ratio:

$$R = r_{Data}/r_{MC}. \tag{5}$$

As most other recent analyses [10, 12–15] we follow this procedure. It allows to cancel differences between like- and unlike-sign samples due to resonance decays and detector effects. Therefore we shall use the unlike-sign pairs as our basic reference sample. The Q^2 distributions of like- (L) and unlike-sign (U) pairs for Monte Carlo events are calculated using the same cuts as for the real data. The correlation function is then evaluated as a double ratio:

$$R = (L_{Data}/U_{Data})/(L_{MC}/U_{MC}) \tag{6}$$

5. Corrections to R for residual differences between the data and simulation

Besides the absence of BE correlations, our simulation has also some other differences from the data which can affect the parameters of correlation function (6). In particular, it is not tuned to two-particle effects. Fortunately, it is canceled in the first order in the ratio of the like- and unlike-sign pair distributions. Corrections to R for some others differences between the data and simulation are described below.

Due to the pair selection criteria number 3 and acceptance limitations of the MD-1, the ratio of acceptances of the like- and unlike-sign pairs in our analysis substantially depends on Q^2 and momentum of the pair. The effective acceptance of the MD-1 depends also on track finding and selection efficiencies of the tracking system. For cancellation of these effects in the (Data/MC)-ratio a precise simulation of the momentum spectra and the detector response is required. Though JETSET 6.3 MC generator [21] and UNIMOD codes [22] do it reasonably well, correction for residual differences is desirable.

This correction is obtained by calculation of the double ratio (6) for "mixed" samples, i.e. for pairs formed by combining particles from different events and passed through the same cuts. These pairs obviously do not have any dynamic correlations, however their spectra and acceptances are similar to the ordinary pairs. The correlation function is then divided by this correction:

$$C_1 = (L^{mix}_{Data}/U^{mix}_{Data})/(L^{mix}_{MC}/U^{mix}_{MC}). \quad (7)$$

Resulting fourfold ratio can be re-written as:

$$R/C_1 = ((L_{Data}/L^{mix}_{Data})/(U_{Data}/U^{mix}_{Data}))/((L_{MC}/L^{mix}_{MC})/(U_{MC}/U^{mix}_{MC})),$$

showing, that this correction can be applied also separately to the data and MC samples before taking of their ratios.

For calculation of the C_1 correction for direct $\Upsilon(1S)$ decays, a pure sample of "mixed" $(\Upsilon_{dir} \cdot \Upsilon_{dir})$ pairs is required. The symbol $(\Upsilon_{dir} \cdot \Upsilon_{dir})$ means that both particles of the pair are originated in direct $\Upsilon(1S)$ decays. Our $\Upsilon(1S)$ sample contains 74% of direct $\Upsilon(1S)$ decays and 26% of the $q\bar{q}$ events. A calculation shows that the sample of "mixed" $\Upsilon(1S)$ pairs consists of 58% $(\Upsilon_{dir} \cdot \Upsilon_{dir})$, 36% $(\Upsilon_{dir} \cdot q\bar{q})$ and 6% $(q\bar{q} \cdot q\bar{q})$ pairs. Assuming that Q^2-distribution of $(\Upsilon_{dir} \cdot q\bar{q})$ pairs is average of $(\Upsilon_{dir} \cdot \Upsilon_{dir})$ and $(q\bar{q} \cdot q\bar{q})$ ones, purification is done by subtraction from the "mixed" $\Upsilon(1S)$ sample the continuum one taken with the appropriate weight. The Monte Carlo simulation of this procedure for the mixture of $3g$- and $q\bar{q}$-events shows that it works well.

Another residual difference between the data and simulation concerns the production of resonances. The recent measurements of ARGUS [23–25] show

that JETSET 6.3 MC overestimates production rates of most resonances. Therefore normalization to (L_{MC}/U_{MC})-ratio actually overcompensates contribution of resonances. It is of a primary importance for the η and η' mesons because their measured production rates are significantly lower than gives the simulation and pairs from their decays are situated in the region of the correlation peak. The ARGUS measurements also show that energy spectra of resonances in direct $\Upsilon(1S)$ decays are harder than in the simulation. Correction of resonance multiplicities and spectra to measured values is obtained by weighting of pairs from their decays with the weights equal to the ratio of measured and simulated spectra of resonances. The correlation function is then divided by the double ratio

$$C_2 = (L^{wght}_{MC}/U^{wght}_{MC})/(L_{MC}/U_{MC}). \quad (8)$$

This correction was calculated through simplified simulation ignoring efficiency of the MD-1 tracking system.

It was also shown using the above mentioned procedure that (L_{MC}/U_{MC})-ratio without contribution of resonances has for $3g$ events 15% decrease in the $M_{\pi\pi}$ interval 0.6–2.0 GeV/c^2. The similar ratio for the $\Upsilon(1S)$ data is consistent with constant in this region. Thus this decrease is probably artifact of the Monte Carlo model. Though this inconsistency is situated outside the region of the BE enhancement it can affect the parameters of the correlation peak. For cancellation of this effect the correlation function is multiplied by the $(L^{nr}_{MC}/U^{nr}_{MC})$-ratio, where L^{nr}_{MC} and U^{nr}_{MC} are the like- and unlike-sign MC pairs of non-resonant origin.

The last but not the least difference concerns a $\pi\pi$ final-state interaction which is ignored in the JETSET MC simulation. Since hadronic final-state interaction is poorly known R can not be corrected for it. This point will be discussed in Sec.7.

6. Results and systematic errors

After applying of all above mentioned corrections, the correlation functions R are shown as a function of $M_{\pi\pi}$ for direct $\Upsilon(1S)$ decays and continuum in Figs.1a,b respectively. Fits to these spectra by parametrization (4) yield the following parameters:

$\Upsilon(1S)_{dir}$: $\lambda = 0.52 \pm 0.10$, $\mathcal{R} = 0.69 \pm 0.10$ fm, $\delta = 0.07 \pm 0.07$ (GeV/c)$^{-1}$,

continuum: $\lambda = 0.37 \pm 0.13$, $\mathcal{R} = 0.82 \pm 0.22$ fm, $\delta = 0.03 \pm 0.07$(GeV/c)$^{-1}$, The region of $0.46 < M_{\pi\pi} < 0.535$ GeV/c^2 was excluded from the fits to remove sensitivity to the production rate of K_s. The results of the fits are superimposed over Fig.1. The fact that both δ are consistent with zero indicates a good reliability of corrections. Several sources of systematic uncertainties involved in this study are discussed below.

The finite momentum resolution could, in principle, lead to systematic effects by broadening and reducing the observed BE enhancement. However, the MC simulation shows that for $\mathcal{R} = 0.8$ fm the systematic error introduced by this factor does not exceed 1%.

Another source of systematic errors is the uncertainty of the coefficients of the continuum subtraction used for generation of "pure" samples of direct $\Upsilon(1S)$ decays and $(\Upsilon_{dir} \cdot \Upsilon_{dir})$-pairs (see Sec.5). A conservative estimate of these uncertainties gives 5% for the former and 10% for the later cases. Varying subtraction coefficients by these numbers, the systematic errors of 0.01 and 0.005 fm are obtained for λ and $\mathcal{R}$ respectively.

The correlation function may be distorted also by the errors in production rates of resonances [23–25] used for calculation of the correction C_2. Related systematic error is estimated by re-calculation of C_2 for the rates shifted from the measured values by one standard deviation. Combining resulting changes of parameters quadratically over all resonances, a systematic errors of λ and $\mathcal{R}$ equal to 0.04 and 0.03 fm for direct $\Upsilon(1S)$ decays and 0.05 and 0.05 fm for the continuum are obtained.

Taking $1 + \epsilon \cdot Q^2$ instead of $1 + \delta \cdot Q$ for parametrization of the long-range correlations, we obtain variations of λ and $\mathcal{R}$ equal to -0.04 and 0.02 fm for direct $\Upsilon(1S)$ decays and 0.02 and 0.01 fm for the continuum.

Combining all these errors quadratically, the systematic errors of λ and $\mathcal{R}$ equal to 0.06 and 0.04 fm for direct $\Upsilon(1S)$ decays and 0.06 and 0.05 fm for the continuum were obtained.

Derived parameters of the pion source depend also on assumption about their space-time distribution $\rho(x)$, i.e. from the choice of parametrization of $R(Q) = 1 + \lambda \cdot |\tilde{\rho}(Q)|^2$. Related effects are estimated through the fits to $R(Q)$ by several parametrizations corresponding to different hypotheses about shape of $\rho(x)$:

1) $\rho(x) \sim \theta(\mathcal{R} - x)$ — tailless distribution,
2) $\rho(x) \sim \exp(-x^2/2\mathcal{R}^2)$ — gaussian tail,
3) $\rho(x) \sim \exp(-x/\mathcal{R})$ — exponential tail,
4) $\rho(x) \sim (1 + (x/\mathcal{R})^2)^{-3}$ — polynomial tail.

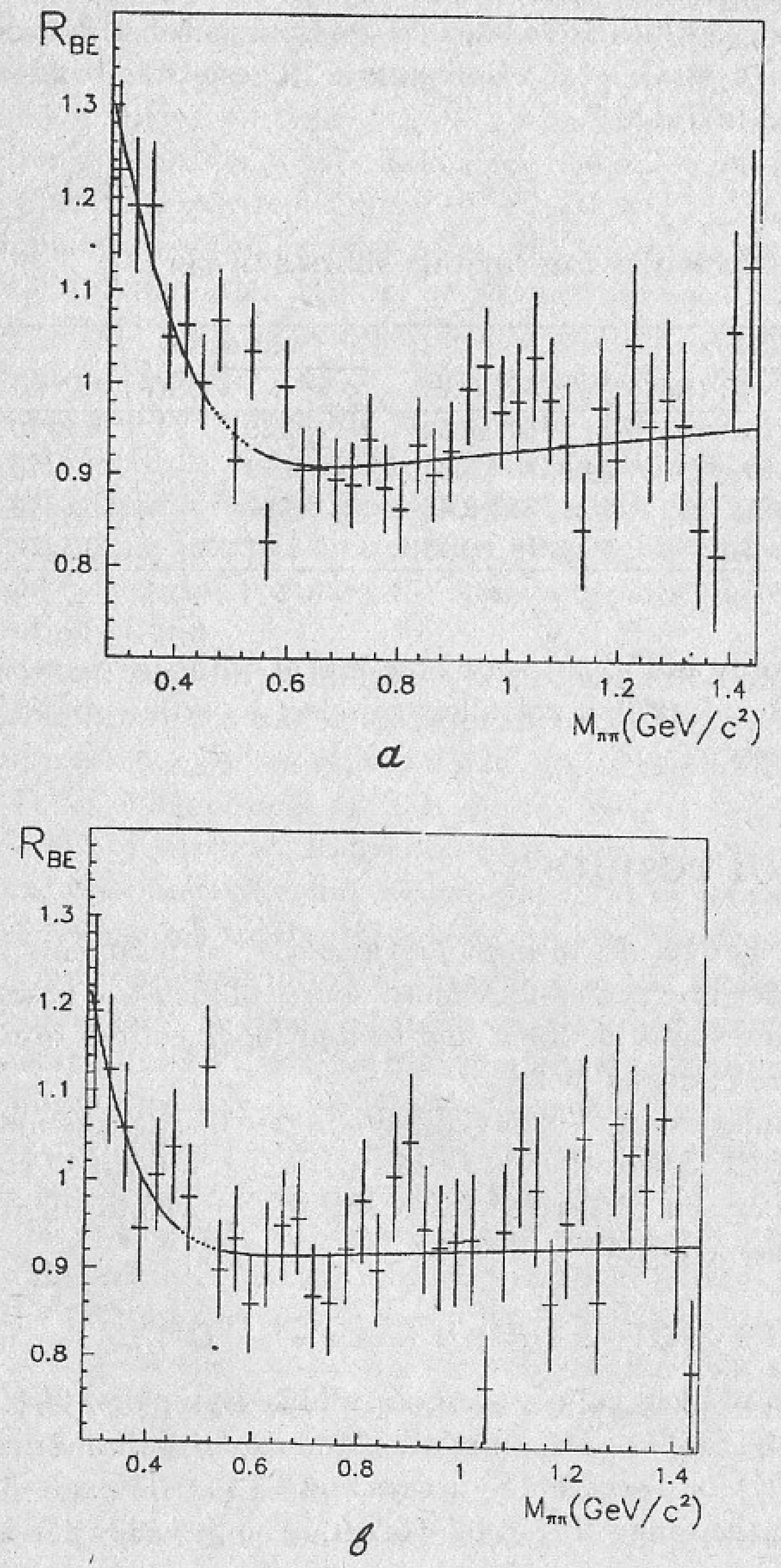

Fig. 1. r_{Data}/r_{MC}, fully corrected: *a* $\Upsilon(1S)_{dir}$, *b* continuum.

While λ can be compared directly, dimensional parameter for comparison is taken as $\sqrt{<x^2>/3}$, which is equal to $\mathcal{R}$ for gaussian distribution. $\hat{\rho}(Q) = 1 - <x^2> \cdot Q^2/6$ as $Q \to 0$. Comparison of results for various parametrizations is shown in Table 1.

Table 1.

Comparison of results for various shapes of $\rho(x)$.

Parametrization	$\Upsilon(1S)_{dir}$ λ	$\sqrt{<x^2>/3}$ (fm)	χ^2/NDF	Continuum λ	$\sqrt{<x^2>/3}$ (fm)	χ^2/NDF
1	0.48	0.63	53.8/70	0.32	0.68	70.9/70
2	0.52	0.69	54.3/70	0.37	0.82	70.8/70
3	0.57	0.75	55.4/70	0.43	0.97	70.6/70
4	0.62	1.02	56.1/70	0.47	1.31	70.5/70

Thus derived values of λ and $<x^2>$ become higher with increasing of assumed tails of $\rho(x)$. Our data don not allow to select a certain shape of $\rho(x)$ through the χ^2 criteria.

7. Discussion of results

Our values of λ as well as results of most previous e^+e^- experiments [8-15] are below of unity which is expected for chaotic source of identical bosons (see Sec.2). Some factors responsible for it and related modifications of the correlation parameters are discussed below.

The first factor is admixture of unidentical pairs in our like-sign sample. Assuming the absence of BE correlations for these pairs, parameters of correlations for identical pions can be derived by fitting $R(Q^2)$ with a slightly modified version of (4), namely [12]

$$R(Q^2) = N \cdot (1 + \delta \cdot Q) \cdot (1 + P_\pi(Q) \cdot \lambda \exp(-\mathcal{R}^2 \cdot Q^2)), \qquad (9)$$

where $P_\pi(Q)$ is a fraction of identical pions among all like-sign pairs. $P_\pi(Q)$ was obtained using the JETSET 6.3 MC simulation and can be parametrized as $0.74 + 0.03 \cdot \exp(-41 \cdot Q^2)$ for direct $\Upsilon(1S)$ decays and $0.72 + 0.07 \cdot \exp(-31 \cdot Q^2)$ for the continuum in the range of $Q < 0.5$ GeV/c. The fit yields parameters of:

$\lambda = 0.68 \pm 0.14$, $\mathcal{R} = 0.69 \pm 0.09$ fm for direct $\Upsilon(1S)$ decays and
$\lambda = 0.48 \pm 0.17$, $\mathcal{R} = 0.80 \pm 0.22$ fm for the continuum.

Since $P_\pi(Q)$ is a slowly varied function of Q, $\mathcal{R}$ remains almost unchanged.

Another λ-decreasing factor is the final-state pions originated from decays of long-lived particles. BE enhancement for pairs separated by decay-lengths of weakly decaying particles (e.g. K_s, Λ, c-hadrons) is unobservably narrow. Therefore parameters of correlations for remaining pairs can be derived similarly to previous case replacing in (9) $P_\pi(Q)$ by $P_\pi^{near}(Q)$, which is a fraction of such pairs among all like-sign pairs. $P_\pi^{near}(Q)$ was obtained using the JETSET 6.3 MC simulation and can be parametrized as $0.65 + 0.04 \cdot \exp(-31 \cdot Q^2)$ for direct $\Upsilon(1S)$ decays and $0.45 + 0.03 \cdot \exp(-31 \cdot Q^2)$ for the continuum in the range of $Q < 0.5$ GeV/c. In the continuum $P_\pi^{near}(Q)$ is lower due to contribution of $c\bar{c}$-events. Fit to $R(Q)$ yields parameters of:

$\lambda = 0.77 \pm 0.16$, $\mathcal{R} = 0.69 \pm 0.09$ fm for direct $\Upsilon(1S)$ decays and
$\lambda = 0.79 \pm 0.28$, $\mathcal{R} = 0.80 \pm 0.22$ fm for the continuum.

Thus taking into account λ-decreasing contributions of unidentic pairs and weakly decaying particles, for remaining pairs λ is close to the theoretical expectation of unity.

However, according to analysis [26] contribution of the final-state pions, originated from decays of some resonances, to observed BE enhancement is also suppressed. For pairs, separated by the decay-lenght of resonanse of width Γ BE enhancement appears mainly at $Q < \Gamma/c$ [26]. Therefore pions from decays of "narrow" resonances (e.g. η, η', ω) will give no visible contribution to the observed enhancement and effective contribution of pions from broader resonances will be suppressed by a factor dependent on a resonance width. Accurate description of this effect in the multihadron production is absent up to now. A rough estimate was obtained from analysis of the string fragmentation in JETSET 6.3 MC simulation, assuming that pions are effectively interfering only if the distance between their production points does not exceed the decay-length of ρ-mesons. It is motivated by the fact that ρ-mesons are the only resonances included in the JETSET 6.3 MC simulation whose decay-length in the rest frame of the daughter pion ($\gamma c\tau \simeq 3$ fm) is comparable with the measured size of the pion source. Similarly to previous cases the fractions of such pairs $P(Q) = 0.20$ for direct $\Upsilon(1S)$ decays and $P(Q) = 0.13$ for the continuum were obtained, which gives $\lambda = 2.6$ and 2.8 respectively. Thus account for "narrow" resonances would increase λ significantly above unity. A similar conclusions were done in refs. [11, 13]. This effect needs a further study.

The BE correlation function is altered also by the final-state interaction which is ignored by simulation. While hadronic final-state interaction is poorly known [27] the Coulomb interaction according to ref. [6] alters the distribution $R(Q^2)$ by a factor $\exp(-2\pi\alpha m_\pi/Q)$ and related correction can be applied as:

$$R(Q^2) \to R(Q^2) \cdot \exp(2\pi\alpha m_\pi/Q). \quad (10)$$

This correction is about 6.6% at a Q^2 value of 0.01 $(\mathrm{GeV/c})^2$. However the final-state interaction is absent for pairs produced far apart and is reduced for pairs produced at intermediate distances [28]. Since many pairs in e^+e^- annihilation are of such origin, naive using of (10) leads to overcompensation of Coulomb effect. Therefore we shall use slightly modified version of (10), namely:

$$R(Q^2) \to R(Q^2) \cdot (1 - P^{cul}(Q^2) + P^{cul}(Q^2) \cdot \exp(2\pi\alpha m_\pi/Q)), \quad (11)$$

where $P^{cul}(Q^2)$ is the fraction of pairs which contain two particles of identic type produced closely enough for substantial modification of their wave function by Coulomb interaction. Identicity is required here since as calculated $Q^2 \to 0$, a real Q^2 of unidentic type pairs remains large suppressing Coulomb correction. P^{cul} can be estimated as $\lambda < P^{cul} < P_\pi^{near}$. Taking their average, $P^{cul} = 0.58 \pm 0.07$ for direct $\Upsilon(1S)$ decays and $P^{cul} = 0.41 \pm 0.05$ for the continuum were obtained. Related correction to λ is equal to $+(8 \pm 1)\%$, while $\mathcal{R}$ remains almost unchanged.

Testing consistency of the data and simulation, we have studied the ratio of the unlike-sign samples U_{Data}/U_{MC}, corrected for all factors mentioned in Sec.5. Since the unlike-sign pairs do not exhibit BE correlations, this ratio should be equal to unity if all other features of the data are correctly simulated. For direct $\Upsilon(1S)$ decays this ratio is shown as a function of $M_{\pi\pi}$ in Fig. 2. A wide bump around $M_{\pi\pi} = 0.6$ GeV/c^2 and some dip at low $M_{\pi\pi}$ are seen. Continuum data show a similar picture with a more pronounced low $M_{\pi\pi}$ dip. A similar effect has been seen also in Z^0 decays [14]. Our estimation shows that observed structure can not be produced by residual errors in resonance production rates. Discrepancy may results from a poor tuning of the MC event generators to two-particle effects in the fragmentation. In this case it is canceled in the first order in the (L_{MC}/U_{MC})-ratio and weakly affects the parameters of BE correlations.

Another potential source of observed discrepancy is a poorly known hadronic final-state interaction [27]. If this interaction or other effects different for like- and unlike-sign pairs are dominant sources of discrepancy than normalization to unlike-sign pairs in (6) lead only to additional systematic errors and more adequate formula is:

$$R = L_{Data}/L_{MC} \quad (12)$$

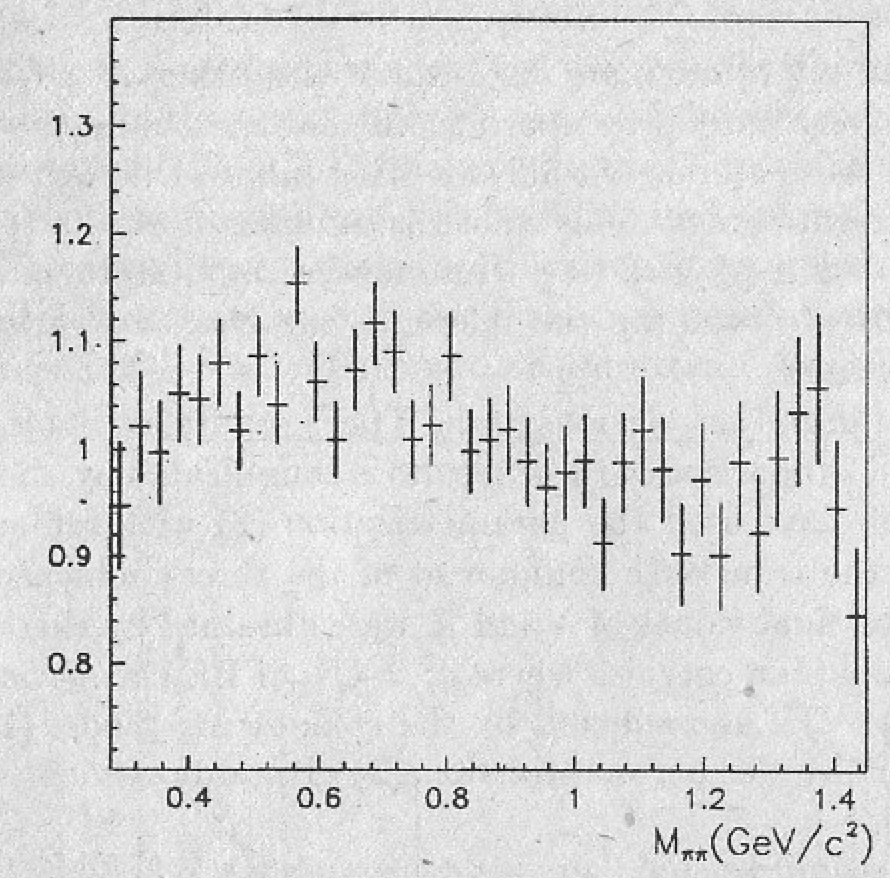

Fig.2. $\Upsilon(1S)_{dir}$: U_{Data}/U_{MC}, fully corrected.

Formula (12) does not suffers from inadequate simulation of the unlike-sign pairs, however is unprotected from a poor tuning of the MC event generator to two-particle effects. The fit to (12), corrected for the factors mentioned in Sec.5, by parametrization (4) yields for direct $\Upsilon(1S)$ decays parameters of $\lambda = 0.34 \pm 0.07$, $\mathcal{R} = 0.52 \pm 0.07$ fm, which can be compared with $\lambda = 0.52 \pm 0.10$, $\mathcal{R} = 0.69 \pm 0.10$ fm obtained from (6). In other analyses non unlike-sign reference samples usually also give lower values of λ and $\mathcal{R}$ [14, 15]. The exception is the result of the MARK II [11], which does not use Monte Carlo normalization. Since our study shows substantial dependence of λ and $\mathcal{R}$ obtained from (12) on parameters of fragmentation we do not consider it as alternative measurement of BE correlations.

Thus interpretation of observed $\pi\pi$-correlations in terms of BE interference suffers mainly from the poor knowledge of effects of hadronic final-state interaction and resonances. To clarify this additional theoretical and experimental studies are desirable. Some light on combination of these effects can shed study of the like- and unlike-sign $\pi\pi$-distributions in the process $\tau \to 3\pi\nu_\tau$, where 3π-state is produced via $\rho\pi$ channel in very clean conditions. The ARGUS analysis [29] shows a significant deviation of the data from the model ignoring these effects.

8. Comparison with previous experiments

In this section we shall try to compare our results with others e^+e^- experiments. One must be very careful comparing different measurements of BE correlations, because the methods of analyses often differ. Different experiments correct for different things. This concerns of detector effects (e.g. identification of particles) and physics (e.g. resonances, final state interaction). Various methods of obtaining the reference samples and various parametrizations of R are used.

The only measurement of BE correlations in the $\Upsilon(1S)$ decays available so far is one from CLEO [9]. Comparison of these results is complicated by above mentioned factors. Ref.[9] have used the parametrization (2) with replacement of Q^2 to square of the transverse component of the three-momentum difference q_t^2. However, the final values of λ and $\mathcal{R}$ were obtained by extrapolation to the limit of equal pion energies where $q_t^2 = Q^2$. If BE correlations actually depend mainly on Q^2, as predicted by the color string model [16–18], this procedure and fit by the parametrization (2) give almost identical results.

Similarly to our analysis unlike-sign pairs have been used in ref. [9] as the basic reference sample. However, their result was not corrected for contribution of resonances in the (L_{Data}/U_{Data})-ratio except of excluding of the K_s- and ρ-meson regions from the fit. According to JETSET 6.3 MC in the region below ρ-meson the part of unlike-sign pairs originating from decays of various resonances is 9–17% for direct $\Upsilon(1S)$ decays and 12–22% for the continuum. It can be compared with $\lambda = 0.38$ for raw CLEO data (Tab.II of ref.[9]). Therefore though JETSET 6.3 MC overestimates resonance production rates [23–25], their contribution is substantial.

In view of this we can not compare these measurements directly. Testing their consistency we have repeated our analysis without correction for contribution of resonances, i.e. turning off the Monte Carlo normalization. Resulting expression for r is:

$$r = (L_{Data}/U_{Data})/(L^{mix}_{Data}/U^{mix}_{Data}),$$

where normalization to (L^{mix}/U^{mix})-ratio is done for cancellation of difference of acceptances of like- and unlike-sign pairs (see Sec.5). For direct $\Upsilon(1S)$ decays the value of r is shown as a function of $M_{\pi\pi}$ in Fig. 3. A fit to this spectrum by parametrization (2) yields $\lambda = 0.49 \pm 0.10$, $\mathcal{R} = 0.84 \pm 0.13$ fm. Similarly to ref.[9] the regions of $0.46 < M_{\pi\pi} < 0.535$ GeV/c^2 and $M_{\pi\pi} > 0.68$ GeV/c^2 are excluded from the fit to remove sensitivity to K_s- and ρ-production. The result of the fit is superimposed over Fig.3. Distortion of

the BE correlations, when correction for resonances is turned off, is relatively small. It is a consequence of the uniform distribution of the resonance contributions in the region below ρ-meson if the measured production rates [23–25] are taken. The CLEO paper [9] gave $\lambda = 0.50 \pm 0.09$, $\mathcal{R} = 0.99 \pm 0.14$ fm. Even these results can not be compared directly because in this paper the efficiency of the particle identification is not given. However, we can see from Sec.7 that related correction can not significantly change $\mathcal{R}$ and does not exceed 30% for λ. Thus two measurements are well-consistent.

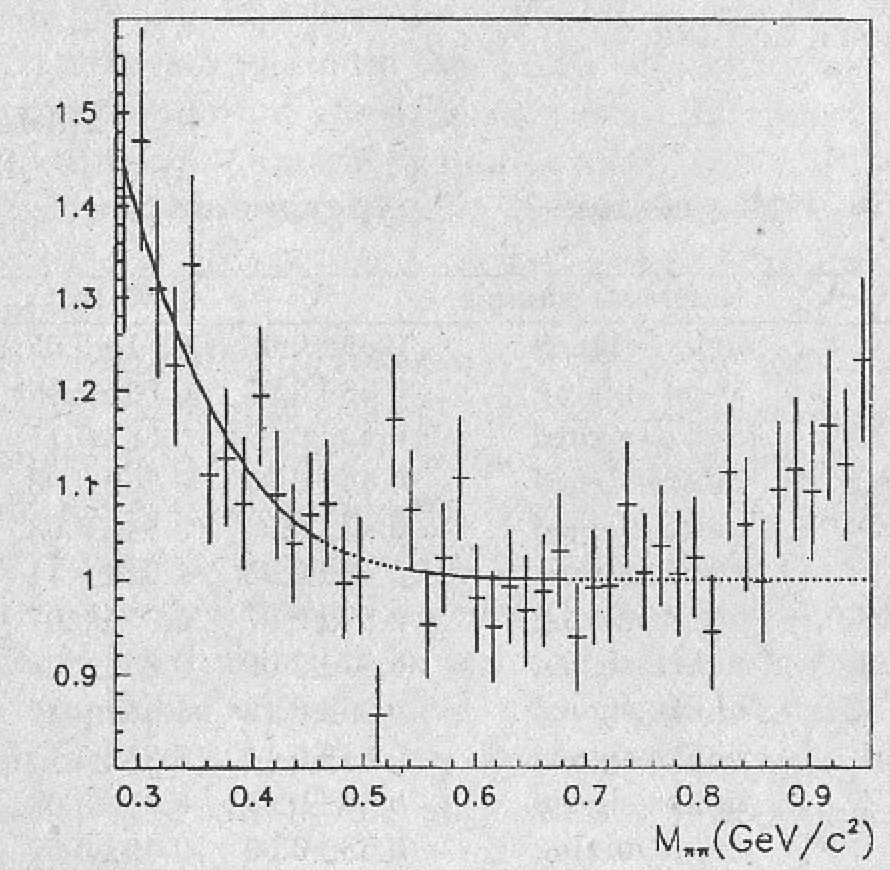

Fig.3. $\Upsilon(1S)_{dir}$: L_{Data}/U_{Data}, acceptance corrected.

The same procedure for our continuum data at the average $\sqrt{s} = 9.46$ GeV gives $\lambda = 0.46 \pm 0.11$, $\mathcal{R} = 0.85 \pm 0.16$ fm, which can be compared with $\lambda = 0.43 \pm 0.07$, $\mathcal{R} = 0.86 \pm 0.15$ fm obtained by CLEO [9] at the average $\sqrt{s} = 10.5$ GeV. Another measurement of BE correlations without correction for contribution of resonances in the (L/U)-ratio was done by MARK II [11] in the energy region $\sqrt{s} = 4.1 - 6.7$ GeV. Without additional corrections they have obtained $\lambda = 0.46 \pm 0.04$, $\mathcal{R} = 0.63 \pm 0.06$ fm.

There are also several other measurements of BE correlations in the continuum between $\sqrt{s} = 4$ and 91 GeV [8–15]. Comparison of these results also is complicated by reasons mentioned in the beginning of this section. To remove experiment-dependent effects it is desirable to use the corrected parameters. However various experiments use different sets of corrections. Most papers contain corrections for non-pion track contamination and Coulomb effect but no corrections for contribution of long-lived particles. Therefore we shall take where it is possible results corrected only for first two effects. In previous analyses the Coulomb correction was applied according to (10) which lead to overcompensation of this effect (see Sec.7). Since this correction weakly depends on experiment it was recalculated according to (11). After these corrections our data give $\lambda = 0.73 \pm 0.16$, $\mathcal{R} = 0.69 \pm 0.10$ fm for direct $\Upsilon(1S)$ decays and $\lambda = 0.52 \pm 0.19$, $\mathcal{R} = 0.80 \pm 0.22$ fm for the continuum, where the statistical and systematic errors were combined quadratically. A summary of results is shown in Table 2.

Table 2.

Comparison with previous e^+e^- experiments

Experiment	$\sqrt{s}$(GeV)	Reference sample	λ	$\mathcal{R}$(fm)
MARK II [11]	4.1-6.7	unlike-signed	0.59±0.06	0.71±0.05
		event mixing	0.68±0.07	0.78±0.06
CLEO [12]	10.5	unlike-signed	0.46±0.07	0.86±0.15
	10.8	unlike-signed	0.44±0.04	0.86±0.08
MARK II [11]	29	unlike-signed	0.47±0.05	0.84±0.08
		event mixing	0.43±0.05	1.01±0.11
TPC [8]	29	event mixing	0.57±0.07	0.65±0.07
TASSO [10]	34	unlike-signed	0.57±0.09	0.80±0.06
AMY [12]	57.2	unlike-signed	0.56±0.12	1.18±0.17
OPAL [13]	91	unlike-signed	0.84±0.14	0.93±0.15
ALEPH [14]	91	unlike-signed	0.58±0.04	0.81±0.04
		event mixing	0.38±0.02	0.49±0.02
DELPHI [15]	91	unlike-signed	0.41±0.03	0.82±0.03
		event mixing	0.33±0.03	0.42±0.04
This exp-t	7.2-10.3	unlike-signed	0.52±0.19	0.80±0.22
MARK II [11]	$J/\psi(3.1)$	unlike-signed	0.98±0.09	0.81±0.05
		event mixing	0.95±0.09	0.79±0.05
CLEO [12]	$\Upsilon(9.46)$	unlike-signed	0.54±0.10	0.99±0.14
This exp-t	$\Upsilon(9.46)$	unlike-signed	0.73±0.16	0.69±0.10

There is no evidence of variation of the BE correlation parameters in the continuum in the energy range of Tab.2. The constancy of $\mathcal{R}$ confirms statement of the color string model [16–18] that $\mathcal{R}$ represents the size of the local region responsible for production of pions of similar momenta rather than the size of the entire source. Variation of λ in the continuum arised from

variation of contamination by long-lived particles does not exceed the errors. Lower contamination of quarkonium decays by these particles accounts for somewhat higher values of their λ (see Sec.7). In other respects BE correlations do not show difference between the hadronization of quarks and gluons. Results of our experiment are consistent with previous measurements.

9. Conclusions

BE correlations have been studied using the MD-1 detector in direct $\Upsilon(1S)$ decays and continuum in the energy region $\sqrt{s} = 7.2 - 10.3$ GeV. Correlations do not reveal a noticeble difference between quark and gluon fragmentation. Assuming gaussian distribution of the pion source density in the pair rest frame the radius of the source $\mathcal{R} = 0.69 \pm 0.09 \pm 0.04$ fm for direct $\Upsilon(1S)$ decays and $\mathcal{R} = 0.80 \pm 0.22 \pm 0.05$ fm for the continuum was obtained.

If λ-decreasing contributions of non-pion tracks and weakly decaying particles are taken into account, the correlation strength λ for remaining pairs becomes close to unity. Account for contribution of "narrow" resonances would increase λ significantly above unity. A substantial contribution may arise, however, also from hadronic final-state interaction between pions. A poor knowledge of these two effects is a main problem in interpretation of observed $\pi\pi$-correlations in terms of BE interference.

Comparison with previous e^+e^- experiments does not show substantial variations of BE correlation parameters in the energy region $\sqrt{s} = 4-91$ GeV. Parameters of correlations obtained in this paper agree with those from other experiments.

Acknowledgements. The authors express their sincere gratitude to the staffs of MD-1, VEPP-4 and Computer Division whose efforts allowed us to perform this experiment. This work was supported in part by a Russian Foundation of Fundamental Research.

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Bose-Einstein Correlations in e^+e^- Annihilation in the $\Upsilon(1S)$ and Continuum

Budker INP 95-8

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Бозе-Эйнштейновские корреляции в e^+e^- аннигиляции в $\Upsilon(1S)$ и континууме

Ответственный за выпуск С.Г. Попов
Работа поступила 24 февраля 1995 г.

Сдано в набор 24 февраля 1995 г.
Подписано в печать 24 февраля 1995 г.
Формат бумаги 60×90 1/16 Объем 1.8 печ.л., 1.5 уч.-изд.л.
Тираж 290 экз. Бесплатно. Заказ N° 8

Обработано на IBM PC и отпечатано на
ротапринте ГНЦ РФ "ИЯФ им. Г.И. Будкера СО РАН",
Новосибирск, 630090, пр. академика Лаврентьева, 11.