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Charged particle multiplicity distributions in e^+e^- annihilation at 29 GeV: a comparison with hadronic data

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Abstract. The charged particle multiplicity distributions for two-jet events in e^+e^- annihilation at 29 GeV have been measured using the High Resolution Spectrometer at PEP. A Poisson distribution describes the data for both the complete event and for the single jets. In addition, no correlation is observed between the multiplicities in the two jets of an event. For fixed values of the prong number of the complete event, the multiplicity sharing between the two jets is in good agreement with a binomial distribution. The rapidity gap distribution is exponential with a slope equal to the mean rapidity density. These observations, which are consistent with a picture of independent emission of single particles, are contrasted to the results from soft hadronic collisions and conclusions are drawn about the nature of clusters.

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1 Introduction

Many measurements of charged particle multiplicity distributions and correlations in soft hadronic collisions were reported following the completion of Fermilab and the CERN Intersecting Storage Rings [1, 2]. All of the data could be encompassed by the phenomenological idea that the reactions proceed through the independent emission of clusters [3]. To fit the data, the clusters had to be typically 1 GeV in mass and decay into a few stable particles, such as pions, that were subsequently observed.

In this paper we present new results on multiplicity distributions in e^+e^- annihilation at 29 GeV. The data are quite different from the hadronic results and cast new light on the nature of clusters. The experiment, which corresponds to an integrated luminosity of 185 pb^{-1}, was done using the High Resolution Spectrometer (HRS) at the e^+e^- storage ring, PEP. The storage ring was operated at a center of mass energy of 29 GeV.

2 The spectrometer

The HRS [4] is a solenoidal spectrometer that measures charged particles and electromagnetic energy over 90% of the solid angle. The tracking system consists of a vertex chamber, a central drift chamber, and an outer drift chamber. The central drift chamber has 15 layers of cylindrical drift planes, eight of which have stereo wires (± 60 mrad) in order to measure the position along the e^+e^- beam direction. The momentum of a charged particle in the 1.62 T magnetic field is measured with a resolution of 3% at 14.5 GeV. The minimum momentum for detecting tracks with good efficiency is about 200 MeV/c. The 40-module barrel shower counter system provides electromagnetic calorimetry over 62% of the solid angle with energy resolution of $\sigma_E/E = 0.16/\sqrt{E(\mathrm{GeV})}$.

The beam pipe and the inner wall of the central drift chamber are made of beryllium in order to minimize the conversion of photons into electron-positron pairs; the total material between the interaction point and the central drift chamber is less than 0.02 radiation lengths.

3 Event selection

To ensure good tracking efficiency, the thrust axis of the event was selected to be within 30° of the equatorial plane of the detector, and each track had to have an angle with respect to the e^+e^- beam direction of more than 24° and had to register in more than one-half of the drift chamber layers traversed. With these selections, the reconstruction efficiency for isolated tracks was greater than 99%. For a typical annihilation event, with several close neighboring tracks, the reconstruction efficiency per track was 80% or better.

In order to compare with the hadronic data, a two-jet data sample was selected using the sphericity (S) and aplanarity (A) variables, where the S and A values were determined from the eigenvalues of the momentum tensor. The collimated ($S<0.25$) and planar ($A<0.10$) events are called two jet since these selections remove the events with hard gluon radiation. This data sample contains 24,553 events.

The true multiplicity distribution was determined from the observed data by means of a matrix unfolding technique. If N_m^0 is the number of events observed with m tracks and N_N^T is the true number of events with N tracks (N even), we define M_{Nm} such that

$$N_N^T = \sum_m M_{Nm} N_m^0. \tag{1}$$

The matrix M_{Nm} was determined from a Monte Carlo simulation of the experiment, which includes the effects of the experimental cuts as well as the tracking inefficiencies [5].

In the initial data selection, events with $m<5$ were removed in order to exclude tau pair events. The numbers of events with $N=0$, 2 and 4 charged particles were estimated from the data themselves assuming independent fragmentation of the two jets in the event.

4 Discussion of hadronic data

The main features of the hadronic data gave rise to the cluster model were:

(i) A multiplicity distribution that broadens as the energy is increased and which becomes non-Poisson, with a tail at the higher N values, for $\sqrt{s} \geqq 12$ GeV [6].

(ii) A linear correlation between the mean number of neutral pions and the number of negative prongs [7].

(iii) Charge transfer distributions inconsistent with independent emission of single pions [8].

(iv) Rapidity gap distributions that show a break at a gap size (R) of about 1.4 units [9]. The distribution of large gaps is consistent with an exponential with a unit slope. Since the charged particle density is about two particles per unit of rapidity, this data was interpreted as giving a cluster multiplicity of two.

(v) Strong two-particle correlations in rapidity [10] with a typical range of one unit.

(vi) In addition, a long-range multiplicity correlation [11] was observed that is well described by the equation

$$\langle n_B \rangle = a + b\, n_F \tag{2}$$

where n_B and n_F are the numbers of charged particles in the two jets of the event, arbitrarily called forward (F) and backward (B). The parameter b is zero at $\sqrt{s} \sim 20$ GeV and increases as the logarithm of the energy to $b \sim 0.2$ at ISR energies.

All of these observations could be understood if the observed hadrons resulted from the decay of low mass clusters. The clusters were later identified with resonances, such as the ρ^0 meson, which were found to be copiously produced in the central region of high energy collisions [12].

More recently, these ideas have received confirmation from the measurements of 546 GeV $\bar{p}p$ collisions made by the UA5 collaboration [13]. These data show a strong $F{:}B$ correlation ($b = 0.57 \pm 0.01$ in (2)), a growth of the high N tail well above that expected from scaling the lower energy data and an $F{:}B$ split at fixed N which agrees with a binomial distribution of pairs.

All of the hadronic multiplicity data can also be well fit using the negative binomial distribution:

$$P(N,\langle N\rangle,k)=\frac{k(k+1)\ldots(k+N-1)}{N!}\cdot\left(\frac{\langle N\rangle/k}{1+\langle N\rangle/k}\right)^{N}\left(1+\frac{\langle N\rangle}{k}\right)^{k} \quad (3)$$

and various interpretations of meaning of the parameter k again lead to the idea of groupings of particles [14].

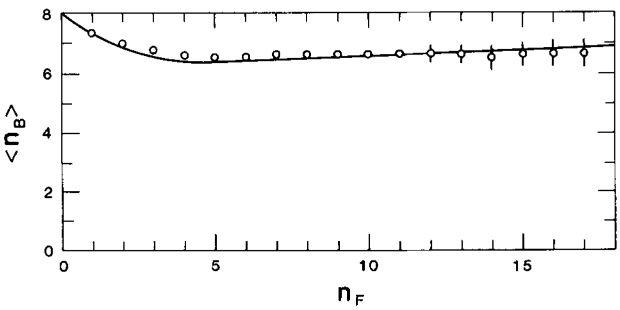

Fig. 2. Forward:backward multiplicity correlations. The errors shown are dominated by the systematic uncertainties. The line shows the result of the simple calculation described in the text

5 Results

We now compare these observations with our e^+e^- data. If the events are divided into two jets by a plane perpendicular to the thrust axis, the single jet charged particle multiplicity distribution shown as the histogram in Fig. 1a is obtained. This distribution has a mean value $\langle n\rangle=6.26\pm0.02\pm0.15$, a dispersion, $D_2=(\langle n^2\rangle-\langle n\rangle^2)^{1/2}=2.45\pm0.02\pm0.12$ and an f_2 moment, $f_2=\langle n(n-1)\rangle-\langle n\rangle^2=-0.26\pm0.03\pm0.13$: the first error is statistical and the second systematic. The full line in Fig. 1 connects values of a Poisson distribution $P(n)=\frac{\langle n\rangle^n}{n!}e^{-\langle n\rangle}$ calculated with $\langle n\rangle=6.26$. It agrees well with the data, as expected from the value of the f_2 moment which should be zero for such a distribution. The dashed line shows a Poisson in $n/2$, which might be more appropriate if pairs of oppositely charged particles were emitted [15]. This curve clearly does not agree with the data histogram.

The multiplicity distribution for the total event is shown in Fig. 1b. Again, the line connects points on a Poisson distribution with the same mean value. This data has $\langle N\rangle=2\langle n\rangle$, by definition, and a dispersion $D_2=3.48\pm0.02\pm0.17$ which is $\sqrt{2}$ times larger than $D_2=2.45\pm0.02\pm0.12$ measured for the single jets.

The variation of $\langle n_B\rangle$ with n_F, shown in Fig. 2, is flat. The slight rise at low n_F values comes from the cut at $m=5$ that excludes the low multiplicity events. The line shows the result of a simple calculation using the measured $\langle N\rangle$ values for (u, d, s), c and b quarks [16] as well as the effect of the cut

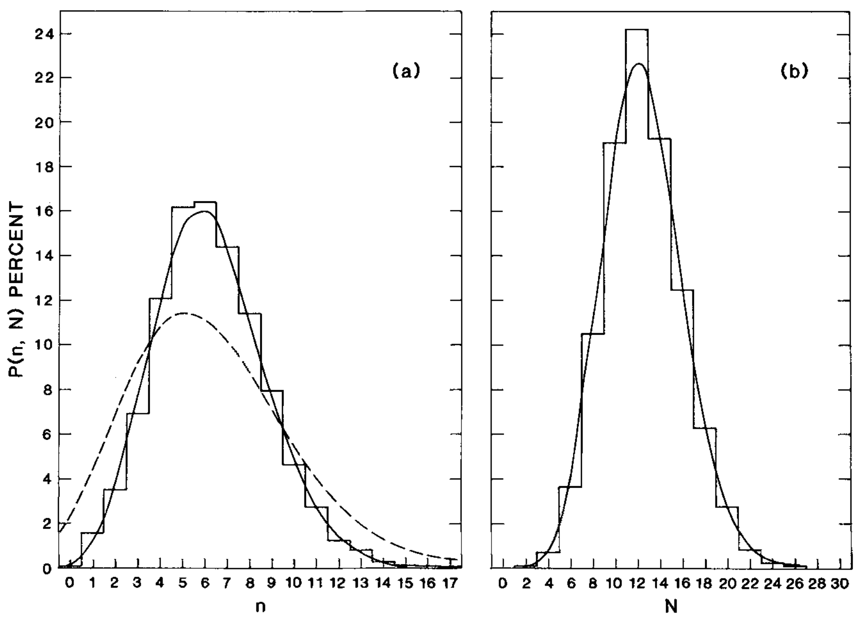

Fig. 1a, b. The histograms show the charged particle multiplicity distributions for two-jet events: **a** single jet, **b** whole event. The full lines connect points on a Poisson distribution with the same mean values. The dashed line in **a** shows a Poisson distribution of pairs

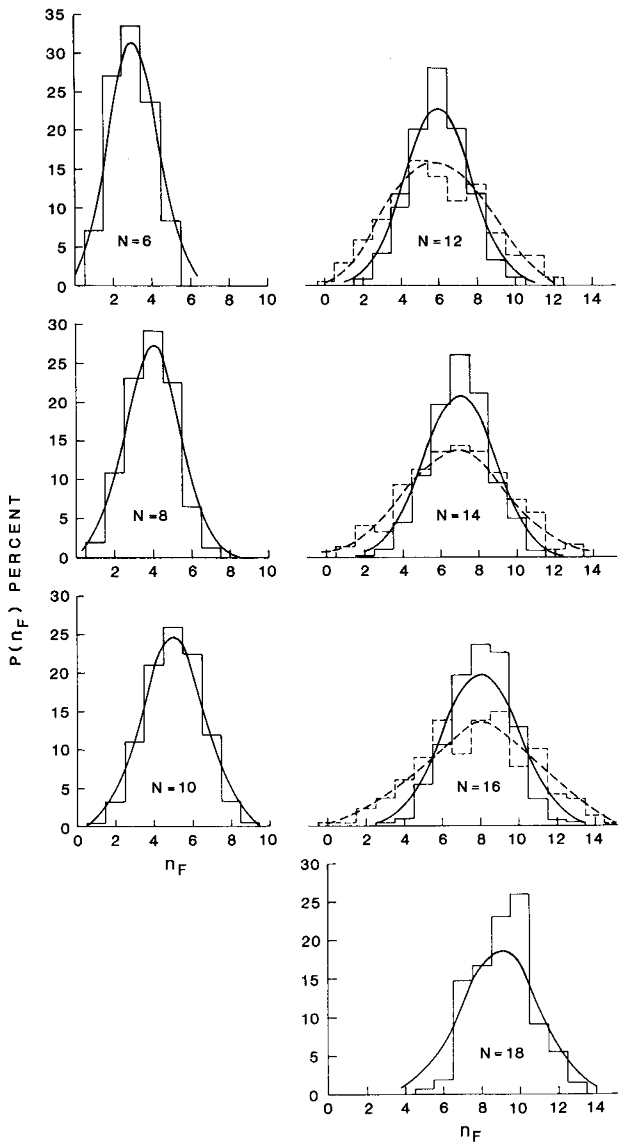

Fig. 3. The full histograms show the forward:backward charged particle multiplicity splits for fixed total multiplicity (N) for $N=6$ to $N=18$. The full lines connect points on a binomial distribution. For $N=12$, 14, 16, the dashed histograms show the results of the UA5 experiment. The dashed lines, which agree with the dashed histograms, correspond to a binomial distribution of pairs of charged particles

Table 1. Values of $\langle n_F^2 \rangle$ for various values of total multiplicity N

N	$N(N+1)/4$	$\langle n_F^2 \rangle$
6	10.5	10.1 ± 0.4
8	18.0	17.4 ± 0.4
10	27.5	27.4 ± 0.6
12	39.0	38.6 ± 0.9
14	52.5	51.3 ± 1.6
16	68.0	66.7 ± 3.4
18	85.5	85.7 ± 9.8

at $m=5$. The slight slope for the higher n_F values arises from the higher mean multiplicity values for the c and b quarks compared to the light quarks. A fit of the data of Fig. 2 with $n_F \geqq 6$ to (2) gives $b=-0.001 \pm 0.015$, consistent with zero.

The Poisson multiplicity distribution for single jets, the $\sqrt{2}$ difference between the widths of the single jet and complete multiplicity distributions, and the lack of an $F:B$ correlation support the idea of independent jet fragmentation to individual hadrons. This can be further investigated by looking at the $F:B$ split for fixed total multiplicity N. These data for $N=6$ to $N=18$ are shown as the histograms of Fig. 3. The lines, which connect the points on binomial distributions,

$$P_N(n_F)=\frac{N!}{n_B!\,n_F!}\left(\frac{1}{2}\right)^{n_B}\left(\frac{1}{2}\right)^{n_F}, \tag{4}$$

represent the histograms quite well, although the data tends to be narrower. For the binomial distribution (4), the dispersion is given by $D_2^2=\frac{N}{4}$ so that the relation $4\langle n_F^2 \rangle = N(N+1)$ holds. The values of $\langle n_F^2 \rangle$, given in Table 1, are in good agreement with this expectation.

The dashed histograms in Fig. 3 for $N=12$, 14, 16 show the results of the UA5 experiment [13]. These distributions are clearly wider than the e^+e^- data, and are well represented by the dashed lines, which correspond to binomial distributions of pairs. These hadronic distribution have been interpreted as due to charge conservation [15, 17], or to the dominance of the reactions by charge-neutral clusters [18]. Since charge conservation also holds for e^+e^- annihilation, it seems unlikely that the differences in the $F:B$ distribution at fixed N for e^+e^- and hadronic collisions arises from such effects.

6 Discussion

The most direct evidence for clusters in hadronic interactions comes from studies of rapidity correlations [1–3]; a clear effect is seen with a characteristic length in rapidity of about one unit. Correlations of similar range are also seen in the e^+e^- data [19, 20]. Since rapidity correlations are essentially momentum effects, they are certainly effected by resonances as is noted by the TASSO collaboration [19], but they may also reflect Bose-Einstein correlations between identical mesons.

An alternative technique for such investigations is to measure the distribution of rapidity gaps between the charged particles. If particles uniformly

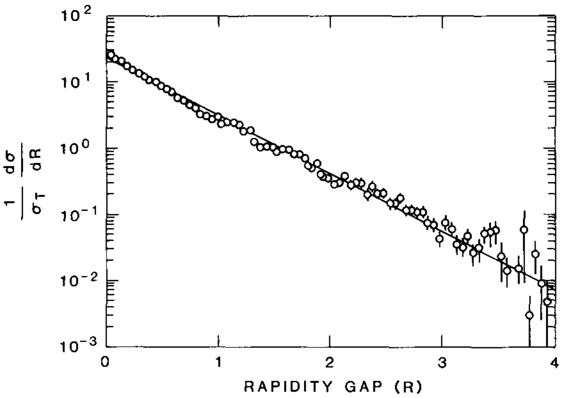

Fig. 4. Rapidity gap distribution for charged particles. The straight line is drawn with a slope of 2.07 equal to the mean rapidity density

populate the full rapidity range available (Y_T) and the multiplicity distribution is Poisson with mean $\langle N \rangle$, then the density of gaps (R) per unit of rapidity is given by [9]:

$$P(R)=\rho \exp(-\rho R) \tag{5}$$

where the mean rapidity density is $\rho=\frac{\langle N \rangle}{Y_T}$. The measured gap distribution for our e^+e^- data is shown in Fig. 4. The distribution is very close to exponential, although with a slight upward curvature. The results have been corrected for detector smearing effects as well for effects coming from misassignment of particles masses. These corrections were made using the Monte Carlo simulation.

The line, which represents the data of Fig. 4, is drawn with a slope of $\rho=2.07$; the mean rapidity density measured in this experiment [21]. This result gives further evidence for independent particle emission or alternatively for an average cluster multiplicity of one charged particle.

The e^+e^- data given here support the simplest picture of independent emission of single charged particles from the uncorrelated fragmentation of the two jets of the event. However, the e^+e^- final states, in common with the hadronic reactions, include many resonances [22] such as ρ^0, $K^*(890)$, f^0, $K^*(1420)$, etc. In pp interactions at an equivalent center of mass energy, the number of ρ^0 mesons per event is $0.5-0.6$ [12], similar to, but somewhat smaller than, the value of 0.95 ± 0.09 measured in the present experiment. In addition, 40% of the e^+e^- events contain two mesons or baryons that include the heavy quarks, c and b. These heavy quark states decay to several π and K mesons.

We are therefore faced with the interesting dilemma that the copious resonance production in e^+e^- annihilation is not manifest in the global distributions presented in this paper. This is in strong contrast to the situation in soft hadronic collisions. The rapidity correlations, however, are quite similar for the two reactions.

In view of these differences, it seems that neutral clusters decaying to two or more charged particles that provide a useful phenomenological description of most aspects of the hadronic data cannot be identified with resonances. One obvious possibility is that the effects in the hadronic data are a manifestation of multiple parton (gluon) interactions within a given hadronic collision. One specific implementation of this idea is in the dual parton model [23] where pp interactions are considered to go via the exchange of two chains.

Another qualitative difference between hadronic reactions and e^+e^- annihilation arises from the fact that hadrons are extended objects. The final states arise from superposition of reactions with different impact parameters and so inelasticities [15, 24], thus leading to the broader multiplicity distribution and the $F\!:\!B$ correlations observed in the hadronic data.

Why the resonances that are present in the e^+e^- final states are not manifest in the multiplicity correlations presented in this paper is a subject for further investigation. It is, of course, possible that the Poisson multiplicity distributions observed at $\sqrt{s}=29$ GeV are accidental. High precision data at other energies are needed to check this possibility.

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$$\langle n\rangle_c=\frac{B}{B-1}\frac{1}{\ln(1-B)},$$

where $B=\frac{\langle n\rangle}{\langle n\rangle+k}$. This equation gives $\langle n\rangle_c$ values close to one for the e^+e^- data reported by M. Derrick et al.; Phys. Lett. 168B (1986) 299
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