EVIDENCE FOR CHARGED PRIMARY PARTONS IN $e^+e^- \to 2$ JETS

TASSO Collaboration

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A study of the product of momentum-weighted jet charges in $e^+e^- \to 2$ jets as well as a detailed investigation of the charge compensation mechanism in rapidity space yield clear evidence for the presence of short range and long range charge correlations. The long range correlations show that the leading particles in one jet "know" about the charge of the leading particles in the opposite jet. If the jets are produced from initial parton pairs this observation implies that these partons are charged.

The discovery of two-jet events in the process $e^+e^- \to$ hadrons has been generally taken as evidence for an underlying $q\bar{q}$ pair creation process [1]. This interpretation is further supported by the agreement of the observed angular distribution of the jet axis with the distribution expected for massless spin 1/2 particles [1,2]. However, another expected consequence of an underlying $q\bar{q}$ pair production mechanism – the existence of a long range quantum number correlation between the quark fragmentation regions of the two jets – has never been demonstrated. In this paper we report the first observation of such a correlation between the charges of leading particles in the two jets.

We shall first establish the effect by comparing the product of momentum-weighted jet charges to that expected for a random charge distribution in each jet. Thereafter we will study charge correlations in more detail as a function of the rapidity y along the jet axis.

The experimental data used in this analysis were collected with the TASSO detector at the PETRA e^+e^- storage ring at DESY. All hadronic annihilation events with c.m. energies between 27.4 and 36.7 GeV were considered, the average energy being 33.1 GeV. The detector, trigger conditions and event selection have been described previously [3]. For the analysis charged particles were accepted within the range of polar angles $|\cos\theta| \leqslant 0.87$ and with momenta transverse to the beam direction $p_t \geqslant 0.1$ GeV/c. The momentum resolution is $\sigma_p/p = 0.02\,p$ for momenta above 1 GeV/c. The inefficiency for track reconstruction is 3%. Background tracks caused by secondary interactions in the material in front of the tracking chamber were removed by applying a cut in distance of closest approach to the interaction point. We summarize briefly the essential selection criteria for hadronic annihilation events.

To discriminate against 2γ exchange reactions the total energy carried by charged particles was required to be larger than 0.27 times the center of mass energy.

After removal of tracks that originate from γ conversion in the beam pipe only events with a charged multiplicity $\geqslant 5$ were accepted. By visual inspection of all low multiplicity events it was shown that at this stage all background from showering Bhabha events had been removed.

To reject events from $\tau^+\tau^-$ production it was demanded that in events with charged multiplicities $\leqslant 6$ the charged particles in at least one hemisphere with respect to the sphericity axis had an invariant mass greater than the τ mass when treating all particles as pions. Computer simulations showed that after these cuts the background from $\tau^+\tau^-$ events left in the hadronic data sample was negligible.

After these cuts we were left with 2773 events. Of these 2281 had a net charge $|Q| \leqslant 2$ and were used for the charge correlation study in rapidity space. Further cuts, to be discussed below, were applied when studying the product of weighted charges.

Field and Feynman [4] suggested using the momentum-weighted jet charge

$$q_{\text{jet}}(\gamma) = \sum_{i=1}^{n_{\text{jet}}} e_i x_i^{\gamma}\,, \tag{1}$$

as a measure of the charge of the parton that initiated the jet. In eq. (1) the charge of the ith particle e_i in the jet is weighted with a power γ of its fractional momentum $x_i = p_i/p_{\text{beam}}$; n_{jet} is the number of particles in the jet. According to current ideas on fragmentation a fast particle has a larger probability to contain the primary parton as a constituent than a slow one. Therefore the weighted charge $q_{\text{jet}}(\gamma)$ for positive exponents γ is expected to be more strongly correlated to the primary parton charge than the unweighted jet charge $Q_{\text{jet}} = q_{\text{jet}}(0)$.

We consider the negative average product of weighted charges

$$P(\gamma) = -\langle q_1(\gamma) q_2(\gamma) \rangle\,, \tag{2}$$

of the two jets in an event where $\langle\ \rangle$ denotes the average over the event sample. In order to discriminate against trivial correlations arising from charge conservation alone we compare $P(\gamma)$ with $P^{\rm rand}(\gamma)$ obtained by assuming that the jet charge was randomly distributed over all particles in a jet. $P^{\rm rand}(\gamma)$ is constructed from the randomized weighted jet charge

$$q_{\rm jet}^{\rm rand}(\gamma) = \frac{Q_{\rm jet}}{n_{\rm jet}} \sum_{i=1}^{n_{\rm jet}} x_i^{\gamma} . \tag{3}$$

If the fastest particles in a jet remember the charge of the primary quark better than the slower ones, $P(\gamma)$ should be greater than $P^{\rm rand}(\gamma)$ for positive exponents γ. It is convenient to take out the strong γ dependence of $P(\gamma)$ and $P^{\rm rand}(\gamma)$ by the substitution

$$q_{\rm jet}(\gamma) \to q'_{\rm jet}(\gamma) = \frac{\Sigma x_i^{\gamma}}{\Sigma x_i^{2\gamma}} q_{\rm jet}(\gamma) , \tag{4}$$

i.e. by multiplying $q_{\rm jet}$ and $q_{\rm jet}^{\rm rand}$ by a common γ dependent factor. Note that $q'_{\rm jet}(\gamma = 0)$ is equal to the unweighted jet charge while $q'_{\rm jet}(\gamma \to \infty)$ is equal to the charge of the fastest particle in the jet. In analogy to eq. (2) we define $P'(\gamma)$ and $P'^{\rm rand}(\gamma)$ using $q'_{\rm jet}$ instead of $q_{\rm jet}$.

When calculating $P'(\gamma)$ and $P'^{\rm rand}(\gamma)$ from our experimental data we have used the sphericity axis as jet axis restricting ourselves to events with sphericity $S \leqslant 0.2$ and with absolute jet charges $|Q_{\rm jet}| \leqslant 1$. Those conditions were fulfilled by 1045 events. The restriction on the jet charge increases the sensitivity of the method since cases with large $|Q_{\rm jet}|$ will exhibit only small differences between $q_{\rm jet}$ and $q_{\rm jet}^{\rm rand}$. In fig. 1 we have plotted P' and $P'^{\rm rand}$ as a function of γ, demanding that both jets of an event have at least one charged particle with fractional momentum larger than a certain value x_0. (The data points are statistically not independent, since in each plot the same data sample is used for every value of the exponent γ.) It should be emphasized that the restrictions on the jet charge and on the fractional momentum do not artificially generate long range charge correlations.

For $x_0 = 0.35$ and $\gamma = 1$ (fig. 1a) we find that P' is larger than $P'^{\rm rand}$ by 3.8 s.d., thus showing that the charge correlation between the fastest particles in opposite jets is stronger than the average charge correlation between these jets, i.e. the fastest particles in the two jets know about their relative charge. When choosing smaller x_0 values, e.g. $x_0 = 0.2$ (fig. 1b) or $x_0 = 0$ (fig. 1c), the effect is still present, although less significant.

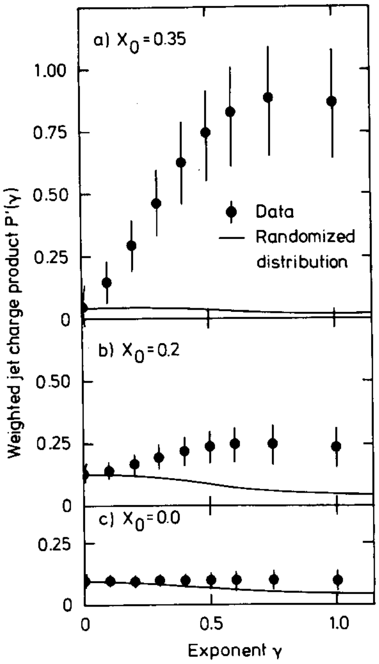

Fig. 1. Negative product of momentum-weighted jet charge $P'(\gamma)$ [eqs. (2), (4)] as a function of the exponent γ for events having in each jet at least one particle with fractional momentum $x > x_0$. The solid line shows the expectation for a charge distribution randomized in each jet. For this plot we used only events with jet charges $|Q_{\rm jet}| \leqslant 1$.

We now turn to a more detailed investigation of charge correlations in rapidity space. This will require the introduction of several quantities, leading finally to the definition of a charge compensation probability as a function of rapidity by eq. (10). Rapidity is defined as usual to be

$$y = \tfrac{1}{2} \ln[(E + p_{\parallel})/(E - p_{\parallel})] ,$$

where $p_{\parallel}$ is defined with respect to the sphericity axis of the event and E was evaluated attributing the pion mass to all charged particles.

We introduce a quantity that describes the combined probability to have a charged particle produced at y' in rapidity space and its charge compensated at y: we call it charge flow $\Phi(y, y')$, defined as

$$\Phi(y, y') = -\frac{1}{\Delta y \Delta y'} \left\langle \sum_{k=1}^{n} \sum_{i \neq k}^{n} e_i \delta_{iy} e_k \delta_{ky'} \right\rangle . \tag{5}$$

Here y and y' specify intervals of size Δy, $\Delta y'$ in rapidity space, e_i the charge of the ith particle and n the charged particle multiplicity of the event. The functions δ_{iy}, $\delta_{ky'}$ are defined such that $\delta_{iy} = 1$ throughout Δy if particle i falls into it, and zero otherwise. Considering only unit charges, charge conservation implies the normalization

$$\iint \Phi(y, y')\, \mathrm{d}y\, \mathrm{d}y' = \langle n \rangle ,$$

for events with total charge $Q = 0$. To show that Φ indeed describes the mechanism of charge compensation we consider in eq. (5) the term $-e_k \Sigma_{i \neq k} e_i \delta_{iy}$. It represents the probability distribution in y for the compensation of the charge e_k by all other charges e_i. Although allowing for negative local probabilities which correspond to anti-compensation, for events with total charge $Q = 0$ this distribution is clearly normalized to 1 because $\Sigma_{i \neq k} e_i = -e_k$. In terms of two particle density distributions

$$(1/\sigma_{\mathrm{tot}})\, \mathrm{d}\sigma^{ab}/\mathrm{d}y\, \mathrm{d}y' = \rho^{ab}(y, y'),$$

for particles of charge a and b, Φ can be expressed as

$$\Phi(y, y') = \rho^{+-}(y, y') + \rho^{-+}(y, y') - \rho^{++}(y, y') - \rho^{--}(y, y'). \qquad (6)$$

When normalizing $\Phi(y, y')$ to unity for y' fixed, we obtain as charge compensation probability for a particle produced at y':

$$\widetilde{\Phi}(y, y') = \Phi(y, y') \Big/ \int \Phi(y, y')\mathrm{d}y = \Phi(y, y')/\rho(y'), \qquad (7)$$

where $\rho(y') = (1/\sigma_{\mathrm{tot}})\mathrm{d}\sigma/\mathrm{d}y'$ is the single particle density at y'. Note that $\widetilde{\Phi}(y, y')$ is a probability density in only one variable y [‡1]. When averaging Φ over different charged multiplicities n the events enter with weights proportional to n. Thus Φ describes properties of the average particle rather than of the average event. To emphasize event properties over particle properties we prefer to equalize the multiplicity weights, considering instead of Φ the corresponding "reduced" charge flow

$$\Phi_{\mathrm{r}}(y, y') = -\frac{1}{\Delta y \Delta y'} \left\langle \frac{1}{n} \sum_{k=1}^{n} \sum_{i \neq k}^{n} e_i \delta_{iy} e_k \delta_{ky'} \right\rangle , \qquad (8)$$

with normalization $\iint \Phi_{\mathrm{r}}(y, y') = 1$. In terms of reduced two-particle densities

$$\rho_{\mathrm{r}}^{ab}(y, y') = \frac{1}{\Delta y \Delta y'} \left\langle \frac{1}{n} \sum_{k=1}^{n} \sum_{i \neq k}^{n} \delta_{iy}^{a} \delta_{ky'}^{b} \right\rangle , \qquad (9)$$

Φ_{r} can be expressed in complete analogy to eq. (6). In analogy to eq. (7) also

$$\widetilde{\Phi}_{\mathrm{r}}(y, y') = \Phi_{\mathrm{r}}(y, y') \Big/ \int \Phi_{\mathrm{r}}(y, y')\, \mathrm{d}y , \qquad (10)$$

can be interpreted as the probability for the charge of a particle produced at y' to be compensated at y if per event only one particle, chosen at random, serves as reference particle at y'.

In fig. 2 we show $\widetilde{\Phi}_{\mathrm{r}}(y, y')$ for four $|y'|$ intervals of the reference particle which are: (a) $0 \leqslant |y'| \leqslant 0.75$, (b) $0.75 \leqslant |y'| \leqslant 1.5$, (c) $1.5 \leqslant |y'| \leqslant 2.5$, (d) $2.5 \leqslant |y'| \leqslant 5.5$. The distributions shown in fig. 2 are corrected for acceptance losses. The correction was performed locally in y, y' by multiplying the observed two-particle densities by weight factors obtained from a QCD Monte Carlo calculation [6], henceforth referred to as MC($\mathrm{q\bar{q}}$ + $\mathrm{q\bar{q}g}$), whose free parameters have been determined from our data [7]. The weight factors are insensitive to the choice of fragmentation parameters.

In fig. 2 we also compare the measured values of $\widetilde{\Phi}_{\mathrm{r}}$ to those (open circles) which one would expect for the case that the charges were distributed randomly over all charged particles of an event. The corresponding random charge flow $\Phi_{\mathrm{r}}^{\mathrm{rand}}$ is obtained by averaging each event over all permutations of its charges:

$$\Phi_{\mathrm{r}}^{\mathrm{rand}}(y, y') = \frac{1}{\Delta y \Delta y'} \left\langle \frac{1}{n(n-1)} \sum_{k=1}^{n} \sum_{i \neq k}^{n} \delta_{iy} \delta_{ky'} \right\rangle . \qquad (11)$$

Comparing $\widetilde{\Phi}_{\mathrm{r}}$ to $\widetilde{\Phi}_{\mathrm{r}}^{\mathrm{rand}}$ we conclude that a random charge distribution is completely ruled out by the data. While $\widetilde{\Phi}_{\mathrm{r}}^{\mathrm{rand}}$ is a broad distribution over the full range of y, $\widetilde{\Phi}_{\mathrm{r}}$ shows a distinct peak at y values close to the y' of the reference particle. This is evidence for the presence of short range charge correlations as also

‡1 Apart from a factor of 2, $\widetilde{\Phi}(y, y')$ is for $Q = 0$ identical to the so-called associated charge density balance $\Delta q(y, y')$ as defined in ref. [5] if $\rho^{+}(y) \equiv \rho^{-}(y)$. Otherwise $\Delta q(y, y')$, when interpreted as charge compensation probability, contains a bias favouring local charge compensation.

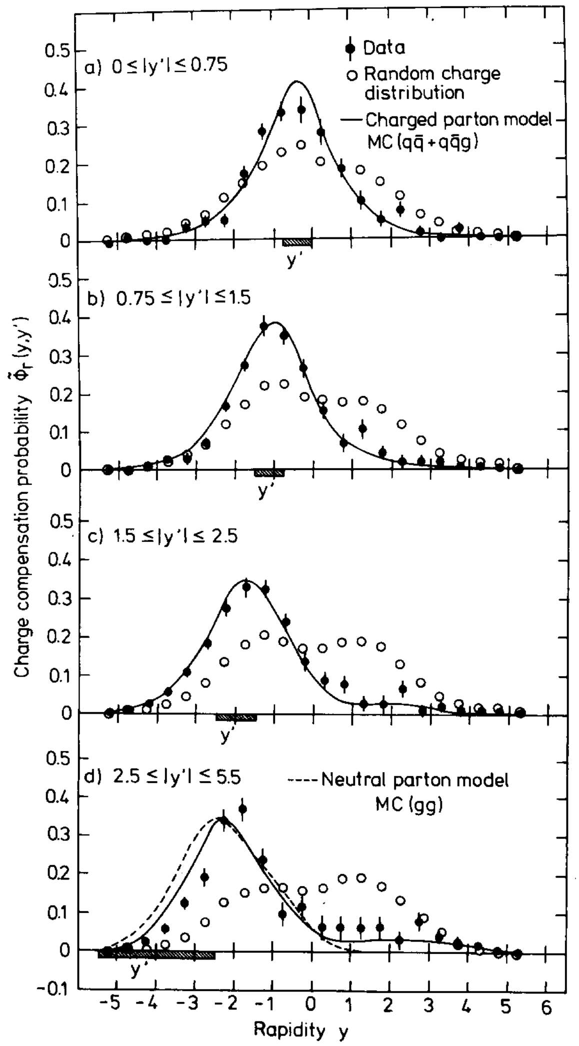

Fig. 2. Charge compensation probability $\tilde{\Phi}_r(y, y')$ [eq. (10)] as a function of rapidity y for a particle produced at y'. The open circles show the expectation for a charge distribution randomized over the whole event, $\tilde{\Phi}_r^{rand}(y, y')$ [eq. (11)]. The solid line shows the prediction of model MC($q\bar{q}$ + $q\bar{q}g$), the dashed line the prediction of a neutral parton model MC(gg).

observed in hadron–hadron collisions [5,8].

The observed strength of short range correlations implies that the charge of a particle is compensated predominantly within the same jet thus imposing a limitation on the jet charge. In fact, the average jet charge product as determined from Φ by the relation

$$\langle Q_1 Q_2 \rangle = - \int_{-\infty}^{0} \int_{0}^{\infty} \Phi(y, y')\, dy\, dy' , \qquad (12)$$

after corrections for acceptance losses, is found to be $-1.53 \pm 0.07 \pm 0.23$ (first error statistical, second systematic), whereas a random charge distribution within events (not jets) would yield for our experiment $\langle Q_1 Q_2 \rangle_{rand} = -3.23$ ‡2. The model MC($q\bar{q}$ + $q\bar{q}g$) predicts a value of -1.35, which is in agreement with our experimental results.

When moving out to higher values of $|y'|$ in fig. 2 the distribution $\tilde{\Phi}_r$ exhibits, besides the peak at $y \approx y'$, an increasing skewness, showing finally for y' interval (d) ($2.5 \leqslant |y'| \leqslant 5.5$) a long tail in y opposite to the y' of the reference particle. This demonstrates the presence of a long range correlation in addition to the short range correlation.

The curves in fig. 2 (solid lines) show the prediction of the model MC($q\bar{q}$ + $q\bar{q}g$) with the free parameters adapted to other experimental observables [7]. The model yields a good qualitative description of the data. The predicted long range correlation is somewhat weaker than that found in the experiment.

It is suggestive to consider the observed long range correlation as a direct consequence of the emission of charged primary partons in the e^+e^- annihilation. However, we have still to show that this correlation is not just the natural tail of the short range correlation which would also appear in a jet picture with neutral initial partons. We therefore consider a Monte Carlo model for jet production by two neutral initial partons. In this model, in the following referred to as MC(gg), a neutral parton (gluon) is described as a flavour neutral system composed of u, d, s quarks obeying Field–Feynman fragmentation. For $|y'| > 2.5$ the prediction of this model for $\tilde{\Phi}_r$, using as quark fragmentation parameters those determined in ref. [7], is shown as the dashed line in fig. 2d. The model predicts almost zero probability in the hemisphere opposite to the reference particle, in clear contradiction to the data. We have verified that the vanishing $\tilde{\Phi}_r$ in the high y region as predicted by MC(gg) is not due to a lack of particles at high y; in fact the predicted spectrum is even harder than the observed one.

‡2 Note that in contrast to $P'(\gamma)$ shown in fig. 1, eq. (12) was evaluated without cuts on the jet charge.

When varying the quark fragmentation parameters in MC(gg) over the full range allowed by the Field–Feynman model we find that for $y' < -2.5$ the probability integrated over $y > 1$ is smaller than 0.3% for any choice of fragmentation parameters, whereas the data show an integrated probability of (15.4 ± 2.6)%. We conclude that the observed long range correlation is due to the charge of the primary partons.

The relative strength of short and long range correlations is described by the charge flow per particle pair or charge combination asymmetry:

$$A_r(y,y') = \Phi_r(y,y')/\rho_r(y,y') = \frac{(\rho_r^{+-} + \rho_r^{-+}) - (\rho_r^{++} + \rho_r^{--})}{(\rho_r^{+-} + \rho_r^{-+}) + (\rho_r^{++} + \rho_r^{--})}. \quad (13)$$

$A_r(y,y')$, ranging between +1 and −1, measures the strength of charge compensation which acts between the average pair of particles produced at y and y', respectively. Fig. 3 shows $A_r(y,y')$ as a function of y for the y' intervals (a) to (d) as defined previously. Also shown (as dashed line) is A_r^{rand}, i.e. A_r as expected for a charge distribution randomized over the whole event. Note that for constant charged multiplicity n, $A_r^{\mathrm{rand}}(y,y') \equiv 1/(n-1)$.

Analyzing the behaviour of $A_r(y,y')$ as shown in fig. 3 we arrive at the following conclusions:

(i) The strength of local (short range) charge compensation between two particles increases strongly with increasing $|y'|$. The comparison to $A_r^{\mathrm{rand}}(y,y')$ shows that this is not a trivial consequence of the decrease of the particle density with increasing $|y'|$.

(ii) Looking at charge compensation between particles in opposite hemispheres we find for y' intervals (a) and (b) a decrease of A_r as y moves away from y' into the other hemisphere, whereas for y' intervals (c) and (d) A_r clearly rises again after having passed a minimum near $y = 1$.

We have tested the significance of the increase of A_r beyond $y = 1$ by combining the data in intervals (c) and (d) and testing the hypothesis that $A_r(y,y')$ is not rising in the y region between 1 and 5. A fit of a constant A_r gives a χ^2 of 12.7 for 3 degrees of freedom, ruling out a flat or decreasing y dependence of A_r in this region at a confidence level of 99.6%. The model MC(gg) discussed above predicts $A_r \equiv 0$ in this region. From the data one finds a completely negligible probability for this assumption.

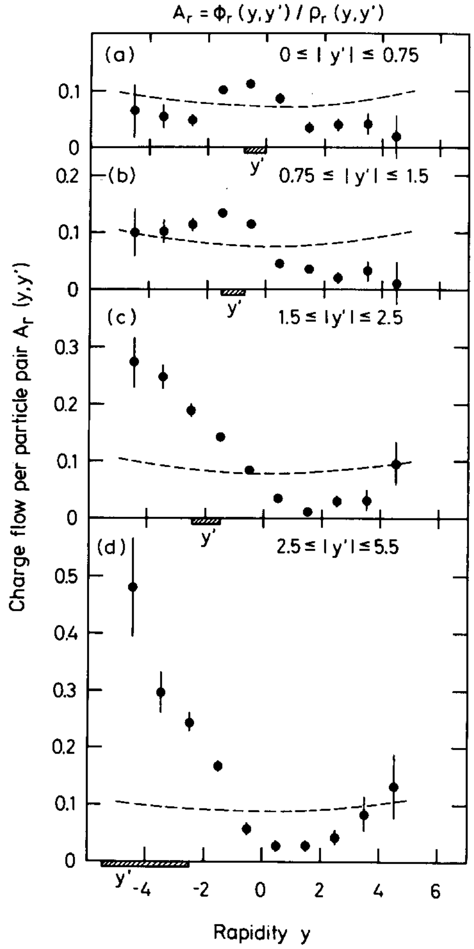

Fig. 3. Charge flow per particle pair $A_r(y,y')$ [eq. (13)] as a function of y if one particle is produced at y'. The dashed lines show the expectation for a charge distribution randomized over the whole event.

The observation that the strength of charge compensation passes through a minimum and increases again with increasing distance in rapidity clearly demonstrates the presence of two different mechanisms in charge compensation: one producing short range correlations and another one producing long range correlations. The short range correlations are expected from jet fragmentation and resonance decays. The long range correlations show that the fast particles in one jet know about the charge of the fast particles in the opposite jet. If the jets are produced from initial parton pairs our observation implies that these partons are charged.

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