SCALE BREAKING IN INCLUSIVE CHARGED PARTICLE PRODUCTION BY e^+e^- ANNIHILATION

TASSO Collaboration

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The scaled cross section $s\mathrm{d}\sigma/\mathrm{d}x_p$ for inclusive charged-particle production in e^+e^- annihilation has been studied for c.m. energies W between 12.0 and 36.7 GeV. Scale breaking is observed. For $x_p > 0.2$ the cross section decreases by ~20% when W increases from 14 to 35 GeV. The production angular distribution was used to separate the longitudinal and transverse cross-section contributions and to determine the ratio of the structure functions $m\overline{W}_1$ and $\nu\overline{W}_2$.

There is overwhelming experimental evidence that e^+e^- annihilation into hadrons at high energies proceeds predominantly through production of a pair of quarks. Hadrons are created in the colour field of the separating quarks. In the quark–parton model the fragmentation functions of the quarks are expected to depend only on the fractional energy, $x = 2E/W$ (W = total c.m. energy) carried by the hadron. This scale invariance is broken by gluon emission which as W increases leads to a depletion of the high-x region and to an increase of the particle yield at low x. There is a close relationship between the e^+e^- process $e^+e^- \to$ hadrons + anything at high energies and deep inelastic lepton–nucleon scattering, $\ell N \to \ell'$ + anything. In QCD, the scale-breaking effects predicted for the two processes and established experimentally for the latter [1] have a similar origin.

Recently we have investigated the scaling behaviour of inclusive π^0 and $\pi^\pm$ production and have found indications for scale breaking [2,3]. In this paper, to gain in statistical sensitivity, we study inclusive charged-particle production without particle separation, i.e. we sum over $\pi^\pm$, $K^\pm$, $p, \bar{p}$. Approximately 16 000 hadronic annihilation events were collected with the TASSO detector at the DESY storage ring PETRA at c.m. energies W between 12.0 and 36.7 GeV. A precise measurement of the total hadronic annihilation cross section, σ_{tot}, obtained with these data was presented in a recent paper [4].

The track and event selection was described in ref. [4]. For convenience we repeat the track selection criteria. To be accepted a charged track had to be reconstructed in three dimensions, the distance of closest approach to the origin in the x, y plane (perpendicular to the beam) had to be $d_0 < 5$ cm, the momentum component perpendicular to the beam had to be $p_{xy} > 0.1$ GeV/c, the polar angle θ with respect to the beam direction had to satisfy $|\cos\theta| < 0.87$, the distance along the beam direction (= z axis) between the track and the event vertex had to be $|z - z_v| < 20$ cm. The overall track-finding efficiency was 97%. The r.m.s. momentum resolution including multiple scattering was $\sigma_p/p = 0.017\,(1 + p^2)^{1/2}$, p in GeV/c. The measured momentum was corrected for energy loss in the material in front of the tracking chamber assuming the particle to be a pion.

The inclusive charged-particle cross sections presented below are corrected so as to include all charged particles produced directly in the annihilation process or by decay of produced particles with lifetime $< 3 \times 10^{-10}$ s. Thus, e.g. the charged particles from K_s^0 or Λ decay are included, irrespective of how far away from the interaction point the decay occurs, while the charged particles from K_L^0 are not included.

In order to determine the cross sections defined in this way the Monte Carlo technique described in ref. [4] was used. Events were generated [5] according to $e^+e^- \to q\bar{q}$ and $e^+e^- \to q\bar{q}g$ (q = u, d, s, c, b) using Field–Feynman fragmentation functions [6] ‡1,2. Baryon production was also included [8]. The produced particles were followed through the detector. The generated events were passed through the track reconstruction and acceptance programs used for the

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‡1 For the c and b quarks the same fragmentation functions were used as for the light quarks.

‡2 The branching ratios for B mesons were taken from ref. [7].

real data. Using the Monte Carlo results, the measured cross sections were corrected for background, acceptance, detection and track-reconstruction efficiency, for interactions in the material in the front of the tracking chamber (energy loss, multiple scattering, photon conversion, nuclear interactions), for momentum resolution and for radiative effects. The data were analyzed in terms of the fractional momentum $x_p = 2p/W$. Corrections were made for contamination [4] from $\gamma\gamma$ scattering [$(1.6 \pm 0.8)\%$ of all events] which produces preferentially low-momentum particles, and from τ pair production [$(1.5 \pm 1.5)\%$ of all events at $W \leqslant 15$ GeV and $(1.2 \pm 1.2)\%$ for $W \geqslant 15$ GeV] which accounts for $(5 \pm 5)\%$ of accepted particles at high x_p ($x_p \gtrsim 0.4$). The high-momentum region is affected by smearing corrections for the finite momentum resolution, by uncertainties in the model and in the radiative corrections, leading e.g. to a systematic uncertainty of 11% for the x_p interval 0.6 – 0.8 at $W = 34$ GeV. At very low x_p values, $x_p < 0.05$, the subtraction of the electrons from photon conversion represents the largest correction. According to the Monte Carlo study at 0.2 GeV/c 30% of all accepted charged particles are electrons from photon conversion decreasing to below 5% above 0.5 GeV/c. The Monte Carlo prediction was cross-checked up to 0.25 GeV/c against the yield of electrons identified by the inner time-of-flight counters. Good agreement was observed. Apart from an overall (i.e. independent of W and x_p) normalization uncertainty of 4.5% we estimate the systematic errors at $W = 34$ GeV to be typically 5% for $x_p < 0.05$, 4% for $0.05 < x_p < 0.5$ and 11% for $0.5 < x_p < 0.8$.

The differential cross section for producing a particle h with mass m, momentum p, energy E and angle θ relative to the beam axis can be expressed [9] in terms of two structure functions $\overline{W}_1$ and $\overline{W}_2$:

$$d^2\sigma/dx\, d\Omega = (\alpha^2/s)\beta x(m\overline{W}_1 + \tfrac{1}{4}\beta^2 x\nu \overline{W}_2 \sin^2\theta), \qquad (1)$$

where $s = W^2$, $\beta = p/E$ and ν is the energy of the virtual photon as seen in the h rest system, $\nu = (E/m)\sqrt{s}$. At particle energies $E \gg m$, x can be replaced by x_p:

$$d^2\sigma/dx_p\, d\Omega \simeq (\alpha^2/s)x_p(m\overline{W}_1 + \tfrac{1}{4}x_p \nu \overline{W}_2 \sin^2\theta), \qquad (2)$$

and

$$s\, d\sigma/dx_p \simeq 4\pi\alpha^2 x_p(m\overline{W}_1 + \tfrac{1}{6}x_p \nu\overline{W}_2). \qquad (3)$$

The functions $m\overline{W}_1$ and $\nu\overline{W}_2$ in general depend on x_p and s. If scale invariance holds they are functions of x_p alone and $s\, d\sigma/dx_p$ is energy independent (for $E \gg m$). The contributions from the two structure functions can be separated by measuring the angular dependence of the particle yield. The angular dependence can be written in the form

$$d^2\sigma/dx\, d\Omega \sim 1 + [(\sigma_T - \sigma_L)/(\sigma_T + \sigma_L)] \cos^2\theta, \qquad (4)$$

where σ_T and σ_L are the cross-section contributions from transverse and longitudinal photons as seen in the h rest system. Defining $A = (\sigma_T - \sigma_L)/(\sigma_T + \sigma_L)$ the ratio of the structure functions is given by

$$-\nu\overline{W}_2/m\overline{W}_1 = 4/x)A/(1 + A). \qquad (5)$$

In fig. 1 the corrected scaled particle cross sections $s\, d\sigma/dx_p$ are presented for c.m. energies of 14, 22 and 34 (= average over 30.0–36.7)GeV. The error bars shown include the statistical as well as the systematic errors except for the overall normalization uncertainty of 4.5%, which is common to all cross-section data. The cross sections decrease steeply as a function of x_p. The c.m. energy dependence is more clearly seen in fig. 2a where $s\, d\sigma/dx_p$ is plotted for fixed x_p inter-

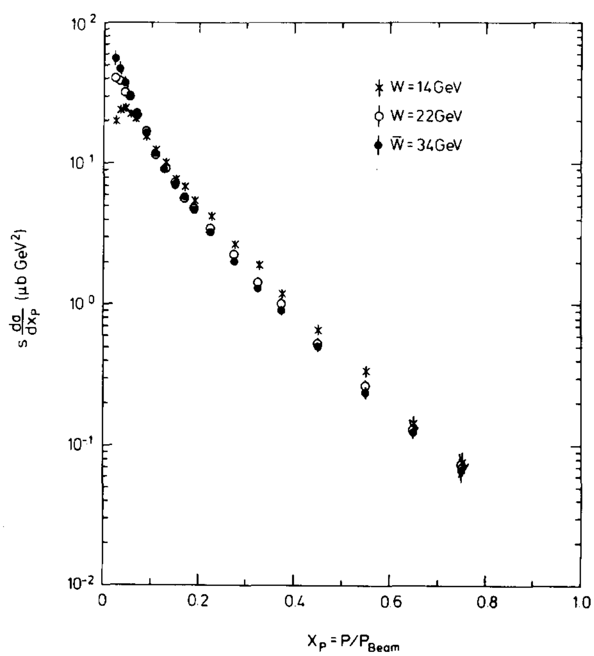

Fig. 1. The scaled cross section $s\, d\sigma/dx_p$ ($x_p = 2p/W$) for inclusive charged-particle production measured at $W = 14$, 22 and 34 GeV. The errors shown include the statistical as well as the systematic uncertainties except for an overall normalization uncertainty of 4.5%.

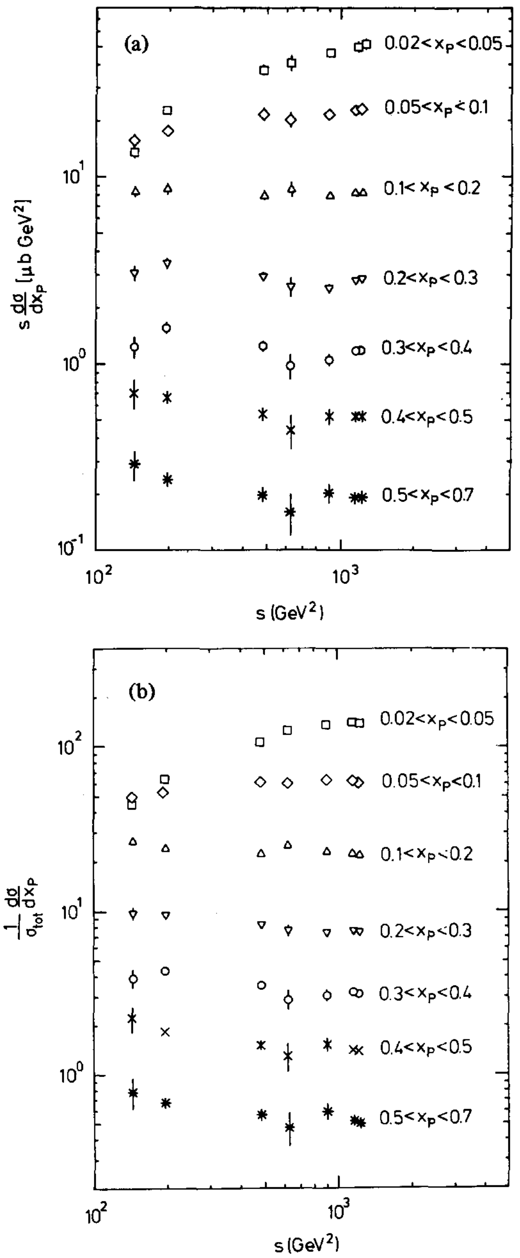

Fig. 2. Inclusive charged particle production. (a) The scaled cross section $s\,d\sigma/dx_p$ versus the square of the c.m. energy $s = W^2$. The errors shown include the statistical as well as the systematic uncertainties except for an overall normalization uncertainty of 4.5%. (b) The normalized cross section $(1/\sigma_{tot})d\sigma/dx_p$ versus s. The errors shown include the statistical as well as the systematic uncertainties.

vals as a function of s. At small x_p, $x_p \leqslant 0.1$, a rapid rise is seen with s which is responsible for the observed growth of the charged-particle multiplicity with s. For $x_p \geqslant 0.2$ the data show a slow significant decrease with s [‡3]. In fig. 2b instead of $s\,d\sigma/dx_p$ the normalized cross section $(1/\sigma_{tot})d\sigma/dx_p$ is plotted. The normalized cross section has smaller systematic errors, and a possible contribution from the weak neutral current (expected [4] to change σ_{tot} at $W = 35$ GeV by 2–3%) is taken care of. The s dependence observed is similar to that for the scaled cross section. The observed type of scaling violation is in agreement with preliminary data presented in ref. [10]. In order to quantify the amount of scale breaking we fitted our cross-section data between $W = 12.0$ and 36.7 GeV to a form suggested by QCD [11]:

$$s\,d\sigma/dx_p = b[1 + c_1 \ln(s/s_0)]$$

and

$$(1/\sigma_{tot})d\sigma/dx_p = d[1 + c_2 \ln(s/s_0)],$$

where $s_0 = 1$ GeV^2. The fits yielded the results shown in table 1. In each one of the four x_p intervals above $x_p = 0.2$ the observed scale breaking is at the level of a 4 to 10 s.d. effect. Going from $W = 14$ to $W = 35$ GeV $s\,d\sigma/dx_p$ on the average is reduced by ~20%.

In the quark–parton model scale invariance is expected, strictly speaking, for the parent particles e.g. D, D*, produced directly in the fragmentation process, while we measure mostly the daughter particles resulting from the decay (chain) of the parents. We have studied in the Monte Carlo model mentioned before charm and bottom quark production, $e^+e^- \to c\bar{c}$ and $e^+e^- \to b\bar{b}$ without perturbative QCD effects, using Field–Feynman fragmentation functions [6], and including the charmed and bottom meson decays [7]. In both cases the resulting $s\,d\sigma/dx_p$ for inclusive charged-particle production increases slightly with in-

‡3 This decrease is not a consequence of the fact that at $W = 12$ GeV and low x_p ($x_p = 0.2$) kaons and protons are not yet fully relativistic. We have used our data on $\pi^\pm$ production (ref. [3]) and our preliminary data on $K^\pm$ and p, $\bar{p}$ production and determined $(s/\beta)d\sigma/dx$ summed over all charged particles as a function of x. We found that at $W = 12$ GeV and $x = 0.2$ $(s/\beta)d\sigma/dx$ is approximately 20% larger than $s\,d\sigma/dx_p$ at $x_p = 0.2$ with the difference rapidly decreasing as x increases, while at $W = 35$ GeV and $x = 0.2$ the difference is only ≈ 2%. Hence, we expect for $(s/\beta)d\sigma/dx$ and $x > 0.2$ an even larger decrease with s.

Table 1

x_p	b (μb GeV^2)	c_1	d	c_2
0.1–0.2	8.6 ± 1.3	−0.008 ± 0.020	28.7 ± 1.5	−0.033 ± 0.007
0.2–0.3	4.3 ± 0.6	−0.053 ± 0.013	15.1 ± 0.8	−0.071 ± 0.005
0.3–0.4	2.1 ± 0.3	−0.063 ± 0.013	7.3 ± 0.6	−0.081 ± 0.006
0.4–0.5	0.96 ± 0.18	−0.065 ± 0.016	3.0 ± 0.4	−0.075 ± 0.010
0.5–0.7	0.37 ± 0.07	−0.069 ± 0.017	1.1 ± 0.2	−0.074 ± 0.013

creasing energy for $x_p > 0.3$ in contradistinction to the data.

Hence, the observed scale breaking in the data seems not to be attributable to the decay of heavy particles. The observed amount of scale breaking appears to be larger than the prediction of first-order perturbative QCD. For instance in the Monte Carlo model mentioned before [‡4] [which includes only first-order QCD effects and assumes α_s (s = 1000 GeV^2) = 0.19] we find for $0.2 < x_p < 0.7$ the cross section to decrease by less than 10% between 14 and 35 GeV. Leading-logarithm calculations can give stronger scale breaking [11,12]. This depends on the value of the QCD parameter Λ.

‡4 This model uses a thrust cut-off T_0 to separate the perturbative from the nonperturbative region. For T_0 we used $T_0 = 1 - 0.63\ W^{-3/4}$, W in GeV.

In order to determine the ratio $(\sigma_T - \sigma_L)/(\sigma_T + \sigma_L)$ the corrected angular distributions were fitted to eq. (4). In fig. 3a $A = (\sigma_T - \sigma_L)/(\sigma_T + \sigma_L)$ is plotted as a function of x_p for W = 14, 22 and 34 GeV. The ratio A tends to go to zero, i.e. $\sigma_L \approx \sigma_T$, as $x_p \to 0$ and approaches unity for $x_p > 0.2$ in agreement with a previous measurement [13]. The approach to unity is faster the higher the c.m. energy W is. If A is plotted instead as a function of the particle momentum p all three energies fall on top of each other (see fig. 3b). The behaviour of $(\sigma_T - \sigma_L)/(\sigma_T + \sigma_L)$ can be understood in the quark–parton model. The production angular distribution of the primary $q\bar{q}$ pairs is $\sim(1 + \cos^2\theta)$. Since the hadrons are emitted with small transverse momenta relative to the quark direction, high-momentum particles follow closely the primary quark direction. Emission of low-momentum particles, on the other hand, is almost independent of

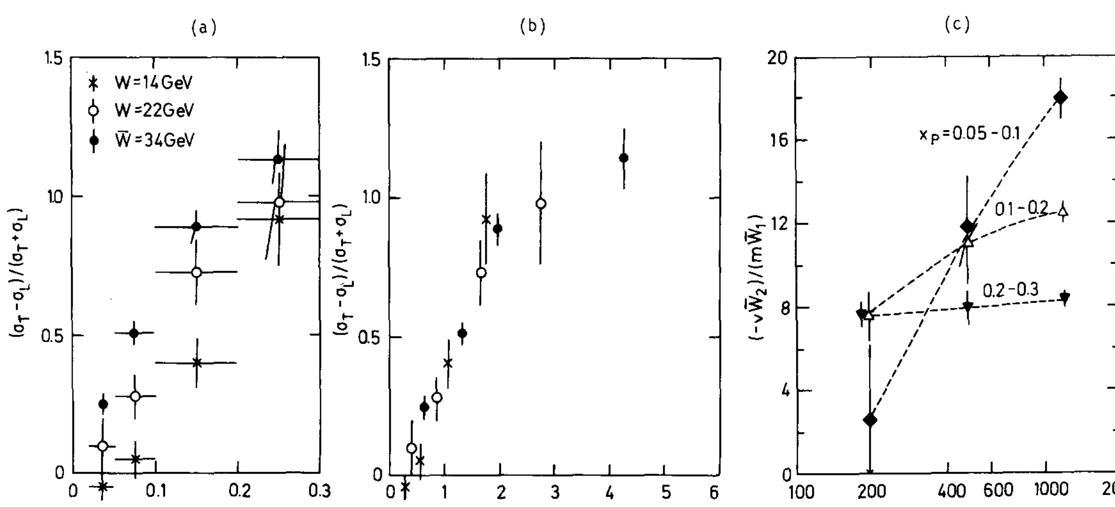

Fig. 3. (a,b) Inclusive charged-particle production. The ratio $(\sigma_T - \sigma_L)/(\sigma_T + \sigma_L)$ for W = 14, 22 and 34 GeV as a function of the fractional momentum x_p (a) and of the momentum p (b). (c) The ratio of the structure functions $(-\nu\bar{W}_2)/(m\bar{W}_1)$ for the x_p intervals 0.05–0.1, 0.1–0.2 and 0.2–0.3 as a function of the square of the c.m. energy, $s = W^2$. The dashed lines are drawn to guide the eye.

the quark direction and therefore $A \to 0$ as $p \to 0$.

In fig. 3c the ratio of the structure functions $(-\nu\overline{W}_2)/(m\overline{W}_1)$ as determined from A is displayed as a function of s. Strong s dependence is observed for $x_p < 0.2$ while for $0.2 < x_p < 0.3$ the ratio is s independent within errors (in agreement with fig. 3a).

In conclusion, the scaled cross section $s\,d\sigma/dx_p$ for inclusive charged-particle production exhibits scale breaking. For $0.2 < x_p < 0.7$ the cross section decreases by ~20% when W increases from 14 to 35 GeV. The measured scaling violation is stronger than expected in a quark–parton model modified by the effect of hard gluon bremsstrahlung with α_s (s = 1000 GeV^2) = 0.10. The longitudinal and transverse cross-section contributions σ_L and σ_T were separated with the help of the angular distribution. For x_p close to zero $\sigma_L \approx \sigma_T$ while for $x_p > 0.2$ $\sigma_L \ll \sigma_T$. The ratio $(\sigma_T - \sigma_L)/(\sigma_T + \sigma_L)$ when plotted as a function of x_p is strongly s dependent while no s dependence is found when analyzed as a function of particle momentum. The ratio of the structure functions $(-\nu\overline{W}_2)/(m\overline{W}_1)$ shows strong s dependence for $x_p < 0.2$ and no s dependence within errors for $0.2 < x_p < 0.3$.

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