DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 80/70
July 1980

TOTAL HADRONIC CROSS SECTION, MULTIPLICITY, AND INCLUSIVE PARTICLE SPECTRA FROM e^+e^- ANNIHILATION AT PETRA

by

U. Timm

NOTKESTRASSE 85 · 2 HAMBURG 52

To be sure that your preprints are promptly included in the
HIGH ENERGY PHYSICS INDEX ,
send them to the following address (if possible by air mail) :

**DESY
Bibliothek
Notkestrasse 85
2 Hamburg 52
Germany**

DESY 80/70
July 1980

TOTAL HADRONIC CROSS SECTION, MULTIPLICITY, AND INCLUSIVE PARTICLE SPECTRA FROM e^+e^- ANNIHILATION AT PETRA[†]

by

U.Timm

paper presented at the Third Warshaw Symposium on
Elementary Particle Physics, Jodlowy Dwor, Poland,
May, 1980

[†] Collaborations JADE, MARK J, PLUTO, and TASSO

ABSTRACT

The total hadronic annihilation cross section has been measured by four experiments in the range $12.0 \leq \sqrt{s} \leq 35.8$ GeV. There is no evidence for production of a sixth quark (top). The chances to measure the strong coupling constant α_s in this channel are discussed. Charged multiplicities from three experiments show a rapid rise with energy above the ln s - dependence observed for CMS energies below 10 GeV. The data are in good agreement with the multiplicities observed in hadronic collisions and confirm the scale breaking expected from hard gluon emission ($q\bar{q}g$) in e^+e^- - annihilation. In detail, there are differences to the multiplicities from pp. The inclusive spectra display scaling for $x > 0.2$ up to $\sqrt{s} = 35.8$ GeV within the experimental errors, but the accuracy is not sufficient to show the predicted violation of scaling ($\simeq 10\%$ of the slope).

1. The total hadronic annihilation cross section

One of the most important quantities in the study of multihadron production from e^+e^- initial states is the ratio R of the total hadronic cross section to the pointlike cross section for producing muon pairs. Experimental data on this quantity are now available from the four exper= iments at PETRA (JADE, MARK J, PLUTO, TASSO) up to $\sqrt{s} \simeq 35.8$ GeV. Following the quark-parton model with first and second order QCD corrections, the cross section has the very simple form $^{1)}$

$$\frac{\sigma^{tot}_{had}}{\sigma_{\mu\mu}} \equiv R = N_c \cdot \sum_{(i)} Q_i^2 \left\{ 1 + \frac{\alpha_s}{\pi} + (1.98 - 0.12 N_f)\left(\frac{\alpha_s}{\pi}\right)^2 \right\} \tag{1}$$

where N_c is the number of color freedom, Q_i the electric charge of the quark q_i, $\alpha_s = 12\pi / \{(33 - 2N_f)\cdot \ln s/\Lambda^2\}$ the strong coupling constant, $\Lambda \simeq 0.5$ GeV a free parameter, and N_f the number of free flavors that can be produced up to $\sqrt{s}$ in pairs $M\bar{M}$, with $M = (q_i, \bar{q}_{N_f})$, $i < N_f$. The ratio R is a powerful experimental tool, because : (1) it tests the pointlike nature of quarks when the ratio $\sigma^{tot}_{had} / \sigma_{\mu\mu}$ is found to be constant, (2) it measures the quark charges Q_i by the observation of thresholds due to a new term $Q_i^2\ \{1 + \cdots\cdots\}$ when $\sqrt{s}$ rises, (3) by counting thresholds it also counts the number of flavors N_f, (4) it counts the number of colors N_c by comparing with $\sigma_{\mu\mu}$, and (5) it measures the strong coupling constant.

This report concentrates on the evidence for the existance of a sixth quark flavor (top or truth), and on the chances to measure α_s from the total hadronic cross section.

In view of the small cross sections ($\sigma_{\mu\mu} = 0.096$ nb at $\sqrt{s} = 30$ GeV) the most economical way for detecting new flavor is to measure R at the highest energy available, in order to check for a new threshold. For PETRA the highest energy was $\sqrt{s} = 31.6$ GeV (1979) and 35.8 GeV (1980), after installation of more cavities (32 → 64) and RF-power. The measurements at these energies, all four experiments combined, yielded $\overline{R} = 3.96 \pm 0.28$ (1979) and 4.17 ± 0.44 (1980, preliminary). Thus the value expected from equ. (1), for $\Lambda = 0.5$ and $Q_6 = 2/3$, namely $R = 5.36$, is missed by 5 and 3 standart deviations respectively. No conclusions can be drawn if $Q_6 = 1/3$ ($R = 4.29$ expected).

The next step is then a search for $(t\bar{t})$ resonances in the region ≃ 1 GeV below the maximum energy. The result of such a scan in the energy region $29.90 \leq \sqrt{s} \leq 31.46$ GeV (1979) is shown for the combined data 2-5) in fig.1, with the result that no such resonance was detected. A similar scan was performed this year in the range $35.00 \leq \sqrt{s} \leq 35.42$ GeV. The result was not fully evaluated up to June 1980, but a similar negative evidence is very likely. The present, but preliminary conclusion is that no top quark with charge 2/3 was found in e^+e^-- collisions for energies $\sqrt{s} \leq 35.8$ GeV.

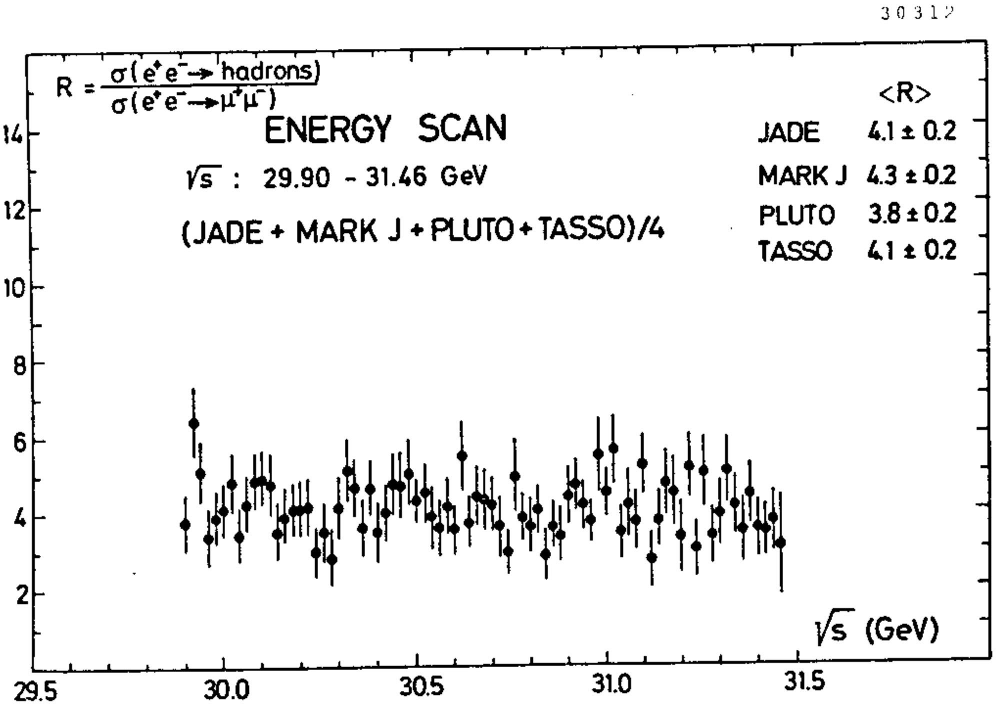

Fig.1 Search for a $(t\bar{t})$ resonance at PETRA, scan 1979 30).

The total hadronic cross section is in principle an ideal place to measure the strong coupling constant α_s, but - as we will see - the present statistical and systematic errors still prevent an accurate determination. The data on R from the four experiments at PETRA [2-14] are listed in table 1 with their statistical errors. All the data have been corrected for the contribution from the two-photon channel and $\tau\bar{\tau}$ - production, and for acceptance and radiative effects. For the data above $\sqrt{s}$ = 20 GeV the systematic errors quoted are 8% for JADE, and $\simeq$ 10% for the other experiments. The last column in the table contains the statistical average per energy for the four experiments. These combined data are displayed in fig.2 together with the prediction, equ. (1), between the limits $0.2 \leq \Lambda \leq 1.0$ GeV. Data from various experiments below $\sqrt{s}$ = 10 GeV are also shown.

Are these data useful to determine α_s ? The present answer is certainly no, not only because of the large systematic errors, also the

Table 1 R = $\sigma_{had}^{tot} / \sigma_{\mu\mu}$ from PETRA experiments (scan 1979 †, 1980 ††), the data above 31.6 GeV are preliminary

$\sqrt{s}$ (GeV)	JADE	MARK J	PLUTO	TASSO	average
12.0	4.1 ± .3	4.03 ± .28	4.27 ± .27	4.0 ± .4	4.12 ± .15
13.0		4.1 ± .5	5.0 ± .5	5.4 ± .8	4.69 ± .32
17.0		4.4 ± .6	4.3 ± .5	3.1 ± .6	3.98 ± .32
22.0	2.9 ± .7	4.7 ± .7	3.41 ± .73	3.2 ± .8	3.58 ± .36
27.6	4.0 ± .5	3.8 ± .3	3.64 ± .31	3.9 ± .4	3.79 ± .18
30.0	4.6 ± .4	4.2 ± .3	4.38 ± .37	4.0 ± .2	4.11 ± .08
30.7	4.1 ± .2	4.40 ± .16	3.8 ± .2	3.7 ± .3	
† 31.6	4.2 ± .6	4.0 ± .5	3.59 ± .52		
33.0	3.9 ± .8	3.3 ± .6		3.98 ± .81	3.64 ± .41
35.0	4.0 ± .3			4.18 ± .42	4.03 ± .16
††35.28		4.00 ± .21			
35.8	3.3 ± .7	4.7 ± .7		4.76 ± .92	4.17 ± .44
average >20 GeV	4.05 ± .14	4.17 ± .10	3.82 ± .14	3.94 ± .14	4.03 ± .06

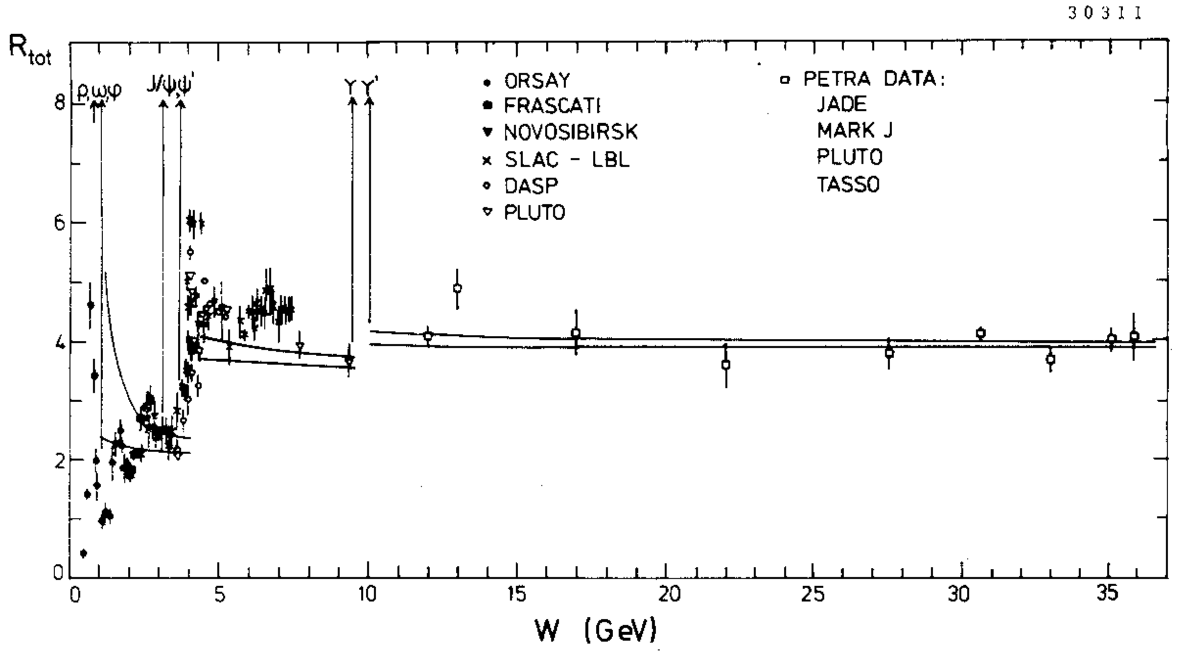

Fig. 2

The normalized total cross section R = $\sigma_{had}^{tot}/\sigma_{\mu\mu}$ for CMS energies $W \leqq 35.8$ GeV from the combined PETRA experiments. The lines indicate the prediction from equ.(1) between the limits Λ = 1.0/0.2 (upper/lower line). Data below 10 GeV are shown for comparison.

statistics are not sufficient. We now show, what the data yield for α_s, without regard of those big systematic errors quoted. They have their main sources in acceptance corrections from the Monte Carlo models used (≃5%), and in the luminosity measurements. (≃5%).

An inspection of fig.2 shows that there is very little variation in the data, except for the region near the b-threshold, where we expect resonances. If we exclude the region below, say $\sqrt{s} \leq 20$ GeV, there is a large range up to 36 GeV where R varies very little (≃ 1.2%) and α_s is constant within ≃ 12%. Using all the statistics in this energy range we find for the error weighted average of the combined data above $\sqrt{s} = 20$ GeV the value $\overline{R} = 4.03 \pm 0.06$ (see table 1). It is based on ≃ 3200 events and has a relative statistical error of 1.6%. The error is not small enough to mearure Λ with any precision in view of the fact that R varies about 2.7% between the limits of Λ=0.2/1.0, which is a likely range for that parameter. In order to get a feeling for the systematic error we can make use of having four independent experiments.

The average $\overline{R}_i$ per experiment is found in table 1, last line. In view of the systematic errors quoted earlier, it is a surprise to find for their distribution a rather low value, $\sigma_{R_i} = 0.15$ which represents a spread around the mean of 3.75%. Comparing this with the individual errors of $2 \cdot 1.6 = 3.2\%$, the systematic error after the average is of the order of 2%. This observation may be accidental, due to the small sample, or it may be due dominantly to cancellation of individual systematic errors, indicating that these are randomly distributed, or it may indicate that all systematic errors work essentially in the same direction, which is the least probable case. At any rate, the result calls for a more careful study of systematic errors in the experiments.

Using equ.(1) with the mean value from the four PETRA experiments in the range $22 \leq \sqrt{s} \leq 35.8$ GeV, $\overline{R} = 4.03 \pm 0.06$, we obtain for the strong coupling constant $\overline{\alpha}_s = 0.28 \pm 0.04 \pm (0.07?)$, where the first error is statistical, the second is the tentative systematic error of 2% with a question mark. The prediction from the same formula, properly averaged and weighted over the energy range, is $\overline{R} = 3.92 \pm 0.06$ and $\overline{\alpha}_s = 0.20 \pm 0.04$, taking Λ at $0.5\,^{+0.5}_{-0.3}$ GeV. The experimental value agrees reasonably well to the expectation, but this has as yet little weight due to the size and uncertainty of systematic errors. A caution must also be observed with concern to the use of equ.(1). Following M.Dine and J.Sapirstein [1] this simple representation neglects vacuum polarization from leptons and hadrons, mass corrections for c and b quarks, and the inclusion of the effect of two-loop β functions. At $\sqrt{s} = 6$ GeV these corrections add 3.8% to the value for R taken from equ.(1).

2. Multiplicities and multiplicity distributions

Multiplicity is experimentally a fairly well defined quantity for charged particles, but not so for neutrals. This report therefore deals only with charged multiplicities. We know from the "low" energy data in e^+e^- annihilation that the mean charged multiplicity, $\langle n_{CH} \rangle$, increases logarithmically with energy like

$$(2) \qquad \langle n_{CH} \rangle = a + b \cdot \ln s \quad , \qquad 1.4 < \sqrt{s} < 7 \text{ GeV},$$

and this behaviour is in agreement with what we expect from the Feynman scaling hypothesis[15].

The first evidence from e^+e^- experiments at PETRA energies for a much faster than logarithmic increase came from TASSO [16]. A fit to these data to the equ. (2) in the low and high energy region yields two incompatible sets of constants : a = 2.67, b = 0.48 for $\sqrt{s} < 7$ GeV; a = -6.1, b = 2.79 for $\sqrt{s} > 7$ GeV, which is a clear indication of scale breaking. The observed fast rise in $\langle n_{CH} \rangle$ cannot be due to $b\bar{b}$ production above threshold, from where an increase $\Delta\langle n_{CH} \rangle \simeq 0.2$ is expected. However, we have good reasons from perturbative QCD calculations to expect a larger rise due to additional gluon fragmentation at higher energies. E.g. a fit of the TASSO data to the analytic form

$$(3) \qquad \langle n_{CH} \rangle = a + b \cdot \exp\left(c \cdot \sqrt{\ln(s/\Lambda^2)}\right) ,$$

which was proposed for heavy quarks [17], determines the constants a = 2.92 ± 0.04, b = 0.003 ± 0.001, c = 2.85 ± 0.07. More recent data from JADE [18] and PLUTO [19] continue to confirm the rapid groth of $\langle n_{CH} \rangle$ beyond 10 GeV. All the data presently available from PETRA experiments are listed in table 2 with their statistical errors. The systematic errors quoted are 14% for JADE, and 7% for the PLUTO and TASSO data. The mean multiplicities are shown with their combined statistical and systematic errors in fig.3 together with earlier data below 10 GeV [20].

Table 2 Mean charged multiplicity from PETRA

$\sqrt{s}$ (GeV)	JADE	PLUTO	TASSO
12		7.8 ± 0.1	
13		8.3 ± 0.3	9.0 ± 0.4
17		8.2 ± 0.3	10.7 ± 0.6
22	10.1 ± 0.7	10.5 ± 0.9	11.2 ± 0.7
27.6	11.6 ± 0.5	11.6 ± 0.3	12.1 ± 0.3
30	11.7 ± 0.5		
30.25		11.4 ± 0.1	
30.3			13.4 ± 0.2
30.75		11.5 ± 0.3	
31.2			13.1 ± 0.3
31.25		11.7 ± 0.3	
31.6	10.9 ± 0.6		

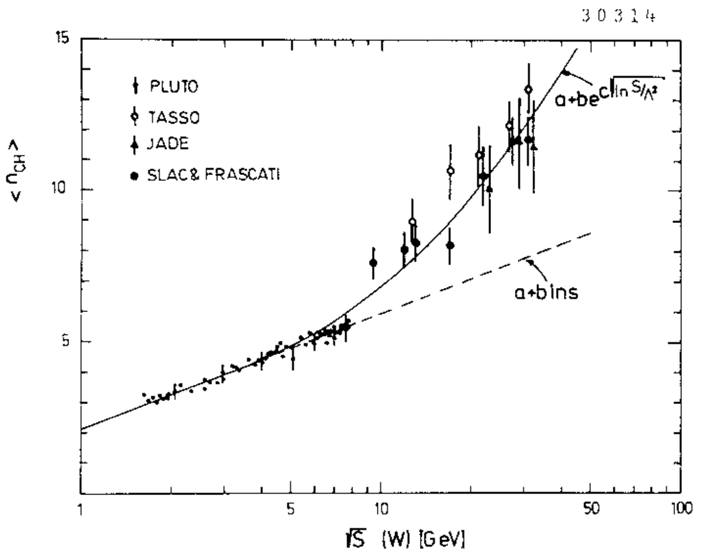

Fig.3
Mean charged multiplicity from PETRA experiments, and earlier data below 12 GeV.
full line 19):
$a = 2.38 \pm 0.09$
$b = 0.04 \pm 0.01$
$c = 1.92 \pm 0.07$
$\chi^2/N_{DF} = 1.3$
dotted line 24):
$a = 2.1$, $b = 0.85$

A reasonable fit to these data, using equ. (3), is obtained for $\Lambda = 0.5$ with the parameters given in the figure caption, but simpler functions fit the data equally well, e.g.:

$\langle n_{CH}\rangle = a + b\cdot(\ln s)^2$, $a = 2.96 \pm 0.03$, $b = 0.18 \pm 0.01$, $\chi^2/N_{DF} = 1.5$
$\langle n_{CH}\rangle = a + s^b$, $a = 1.73 \pm 0.03$, $b = 0.34 \pm 0.01$, $\chi^2/N_{DF} = 1.3$

For a proper comparison with multiplicities from other types of interaction we first subtract the contribution $K_S^0 \to \pi^+\pi^-$, which brings the data down by ≃ 0.7 units. The result of this subtraction is plotted for the

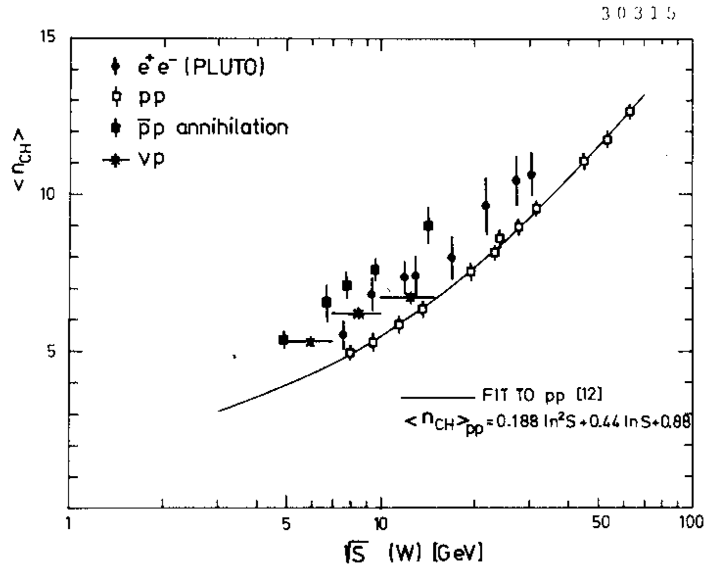

Fig.4
Comparison of mean charged multiplicities observed in e^+e^- annihilation (PLUTO, $K_S^0 \to \pi^+\pi^-$ subtracted)21), $\bar{p}p$ annihilation 22), and νp interactions 23).

PLUTO data in fig. 4, which also shows mean multiplicities from pp,$p\bar{p}$ and νp collisions $^{21,22,23)}$. The general rise is very similar for all reactions, but the pp data lie systematically below the data from e^+e^- by 1 unit, above 5 GeV. The multiplicities from $p\bar{p}$, which agree well with e^+e^- data at low energies$^{20,24)}$, seem to be 1 unit higher above 5 GeV. The few high energy νp points fall on the e^+e^- data.

We learn more about multiplicities if we investigate the distributions, which are available now for the PLUTO data. The second moment of the distribution, the dispersion $D_{CH} = \sqrt{(<n_{CH}^2>-<n_{CH}>^2)}$ increases at the same rate as the mean multiplicity. Thus the ratio $<n_{CH}>/D_{CH}$ is constant within the experimental accuracy. This ratio is shown in fig.5 and compared to the same ratio from pp collisions$^{21)}$, which lies systematically below the e^+e^- data.

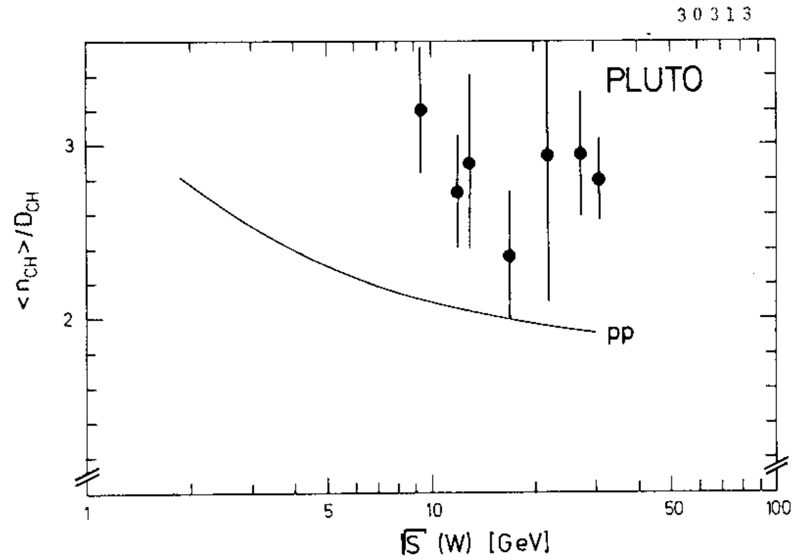

Fig. 5
Energy dependence of the ratio $<n_{CH}>/D_{CH}$ for e^+e^- (PLUTO, $K_s^0 \to \pi^+\pi^-$ subtracted), and for pp interactions(full line)

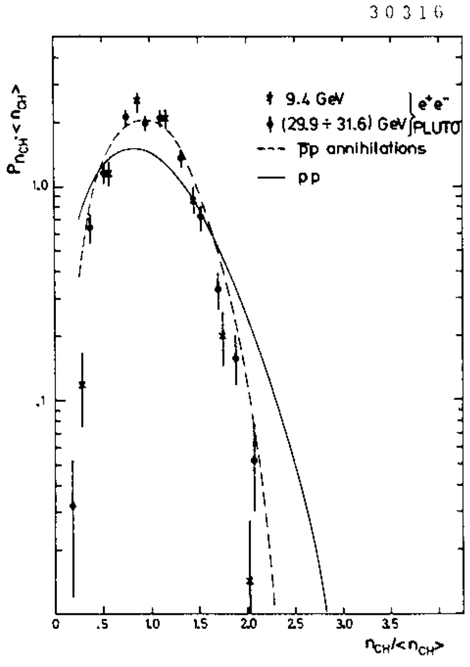

Fig.6 KNO plot for e^+e^- data at 9.4 and 30.7 GeV (PLUTO, $K_s^0 \to \pi^+\pi^-$ subtracted). The dashed curve is a fit to $p\bar{p}$ annihilation$^{22)}$(lower energies), the full curve results from high energy pp collisions.

The full multiplicity distribution is shown for the two energies $\sqrt{s}$ = 9.4 and 30.8 GeV in fig.6 in a normalized plot, $\langle n_{CH}\rangle \cdot P_{n_{CH}}$ versus $n_{CH}/\langle n_{CH}\rangle$ (P=probability), also known as Koba-Nielsen-Olesen (KNO) plot[25]. Following the KNO hypothesis, distributions for different energies should coincide in this representation, which is in fact found for the two energies as far apart as 20 GeV. The shape of the distribution is rather more similar to that found in $p\bar{p}$ than that for pp collisions.

3. Inclusive particle spectra from e^+e^- annihilation

Apart from a factor s, inclusive particle spectra are defined as the differential cross section for producing a hadron h with the fractional momentum $x = p/E_{beam}$. From the hypothesis of quark fragmentation, these spectra are expected to scale with s, because, at energies large enough to neglect particle masses, the number of hadrons h which are produced with fractional energy x by a quark q_i, $D^h_{q_i}(x)$, is independent of s. And

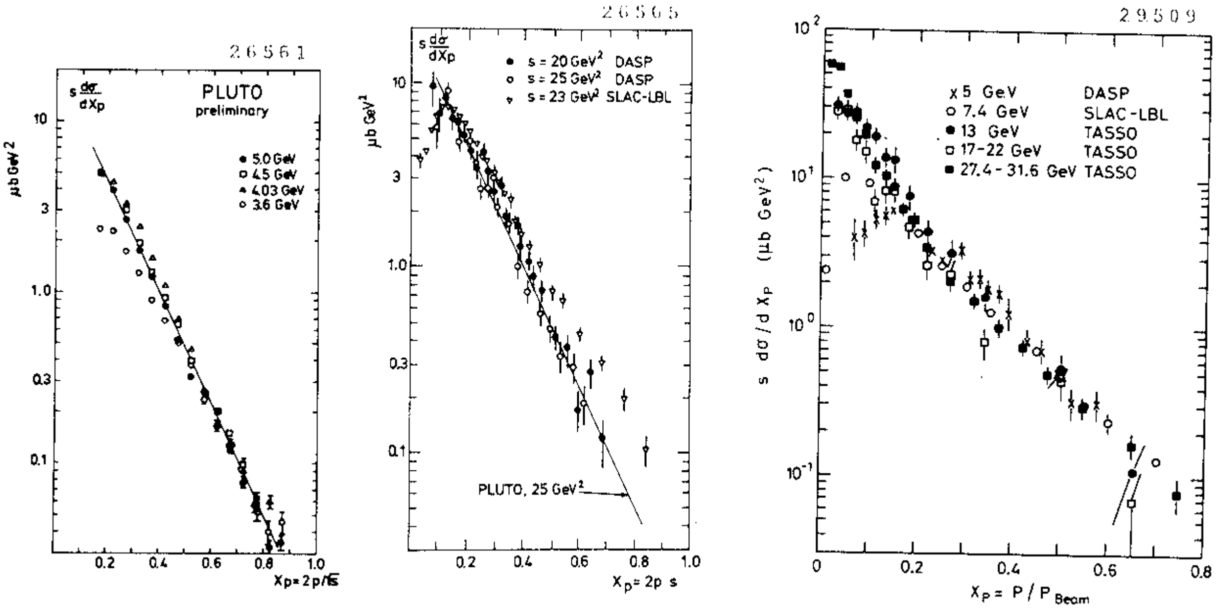

Fig.7 Inclusive particle spectra for (a) $3.6 \leq \sqrt{s} \leq 5.0$ GeV (PLUTO)[26] (b) $4.5 \leq \sqrt{s} \leq 5.0$ GeV (DASP, SLAC-LBL)[27], and (c) $5.0 \leq \sqrt{s} \leq 31.6$ GeV (DASP, SLAC-LBL, TASSO)[16,28]. The full line is drawn for $s \cdot d\sigma/dx = 20 \cdot \exp(-7.5 \cdot x)$ µb GeV².

this function enters in the differential cross section,

$$\frac{d\sigma}{dx}(e^+e^- \to q_i\bar{q}_i \to h) = \sigma_{q_i\bar{q}_i} \cdot 2\, D^h_{q_i}(x) = \frac{4\pi\alpha^2}{s} Q_i^2 \cdot 2\, D^h_{q_i}(x) \tag{4}$$

so that $s \cdot d\sigma/dx$ is a function of x only. Fig.7 shows, that in fact the data scale for $x > 0.2$ at all energies between 3.6 and 31.6 GeV within errors. However, at low x values, the particle yield grows rapidly with increasing energy due to the rapid rise of multiplicity. Gluon emission must lead to scale breaking effects: the primary momentum is then shared by gluon and quark, which favours the yield at low momenta and disfavours the yield at high momenta. The resulting change for the slope of the distribution is expected 29) to be about +10% at $\sqrt{s}$ = 30 GeV, much too small to be detected by the present measurements. We conclude that the inclusive particle spectra in e^+e^- annihilation are not a good place to detect scale breaking effects.

References

1. see e.g. M.Dine, J.Sapirstein, Phys.Rev.Lett.43,668(1979)
2. JADE-Collaboration, W.Bartel et al., Phys.Lett.91B,152(1980)
3. MARK J-Collaboration, D.P.Barber et al., MIT-report 110(1980)
4. PLUTO-Collaboration, Ch.Berger et al., Phys.Lett. 91B,140(1980)
5. TASSO-Collaboration, R.Brandelik et al., Phys.Lett.88B,199(1979)
6. JADE-Collaboration, W.Bartel et al., Phys.Lett.88B,171(1979)
7. W.Bartel, private communication on preliminary data
8. S.Orito, Proc.Int.Sympos. on Lepton and Hadron Interactions 1979,p.52
9. PLUTO-Collaboration, Ch.Berger et al., Phys.Lett.81B,410(1979)
10. PLUTO-Collaboration, Ch.Berger et al., Phys.Lett.86B,413(1979)
11. MARK J-Collaboration, D.P.Barber et al., Phys.Rev.Lett.42,1113(1979)
12. Mark J-Collaboration, D.P.Barber et al., Phys.Lett.85B,463(1979) and P.Duinker, private communication on most recent data
13. TASSO-Collaboration, R.Brandelik et al., Phys.Lett.83B,261(1979)
14. TASSO-Collaboration, R.Brandelik et al., Z.Phys.C4,87(1980)
15. R.P.Feynman, Phys.Rev.Lett.23,1415(1969)
16. TASSO-Collaboration, R.Brandelik et al., Phys.Lett.89B,418(1980)
17. W.Furmanski, S.Pokorski, Nucl.Phys.B155,253(1979), A.Bassetto, M.Ciafoloni,G.Marchesini, Phys.Lett.83B,207(1978), K.Konoshi, Rutherford Preprint RL 79-035 T 241 (1979).

18. JADE-Collaboration, W.Bartel et al., Phys.Lett.88B,171(1979)
19. PLUTO-Collaboration, Ch.Berger et al., to be published, DESY 69/80
20. C.Bacci et al., Phys.Lett.86B,234(1979), J.L.Siegrist, Ph.D.Thesis SLAC-225 UC-34d(1980)
21. pp interactions: E. de Wolf et al., Nucl.Phys.87B,325(1975), E.Albini et al., Il Nuovo Cim.32A,101(1976), W.Thome, Ph.D.Thesis, Aachen Preprint PITHA 80/4 (1980), P.Slattery, Phys.Rev.Lett.29, 1624(1972) and Phys.Rev.D7,2073(1973).
22. $p\bar{p}$ annihilations: R.Stenbacka et al., Il Nuovo Cim.51A,63(1979), P.D.Gall, Ph.D.Thesis, DESY F1 76/02 (1976), F.T. Das et al., Phys. Lett.51B,505(1974), L.N.Abesalashvili et al.,Phys.Lett.52B,236(1974), M.A.Jabiol et al., Nucl.Phys.127B,365(1977), R.M.Robertson et al., Purdue Preprint PU-79-485 (1979), J.Rushbrooke et al., Phys.Lett.59B, 303(1975).
23. νp interactions: N.Schmitz, Int.Symp. on Lepton and Photon Interac= tions at High Energies, FNAL (1979), p.359, MPI Preprint MPI-PAE/Exp. EL 80 (1979).
24. J.Salava, V.Simak, Nucl.Phys.69B,15(1974)
25. Z.Koba, H.B.Nielsen, P.Olesen, Nucl.Phys.B40,317(1972)
26. U.Timm, European Conf. on Particle Physics, Budapest 1977, p.729
27. DASP-Collaboration, R.Brandelik et al., Phys.Lett.67B,358(1977)
28. DASP-Collaboration, R.Brandelik et al., Nucl.Phys.B148,189(1979) G.J.Feldmann, M.L.Pearl, Phys. Report 33,285(1977)
29. R.Bauer, J.Engels, B.Peterson, Z.Phys.C79,265(1979)
30. W.Bartel, Report at the XXth Rencontre de Moriond, 1980