RECENT RESULTS FROM PETRA

Michel Davier
Laboratoire de l'Accélérateur Linéaire
Université Paris-Sud - 91405 Orsay, France

Abstract

Recent physics results from the experiments at PETRA are presented. Emphasis is not on completeness but rather to give a broad view of the impact of PETRA e^+e^- results in the context of the standard model : QCD and the electro-weak theory. Finally the potential for finding new phenomena outside the standard model will be discussed. Positive experimental indications are scarce, however.

1. PETRA RUNNING

Since PETRA turn-on in 1979, the emphasis has always been to run at the highest energies. While this effort was originally organized to track down the t-quark, it was also justified by the possible occurence of new phenomena at high energy. This strategy has conditioned the running of PETRA with a priority of energy over luminosity, with the exception of the data-taking in 1981-82 at 35 GeV centre-of-mass energy. Such a state of affairs is clearly visible on Fig. 1, showing the total luminosity logged by a typical experiment over the years. Most of the quantitative work results from the $\sim$ 80 pb^{-1} accumulated at $\sqrt{s} \sim 34.5$ GeV for JADE, Mark J and TASSO. Unfortunately, since they were mutually exclusive, PLUTO could only take $\sim$ 40 pb^{-1} at that energy and CELLO a miserable 11 pb^{-1}.

In Spring '84, PETRA reached its maximum beam energy of 23.4 GeV and a continuous scanning from $\sqrt{s}$ = 40 GeV to 46.8 GeV could be completed in 30-MeV steps, comparable to the energy resolution of the ring. At $\sqrt{s}$ = 44 GeV, where an extensive running period is underway, the maximum achieved luminosity so far is 250 nb^{-1}/day, still a far cry from the value of 750 nb^{-1}/day obtained at $\sqrt{s}$ = 34.5 GeV in 1982. However the potential for a new discovery in e^+e^- physics relies mostly on energy, and this loss of luminosity can be considered reasonable.

Running two years later, PEP has been operated with a different philosophy : a fixed beam energy of 14.5 GeV and large luminosities, up to 1500 nb^{-1}/day. The data samples of the PEP experiments are therefore significantly larger, by a factor 3 to 4. What was the best choice, running for energy or luminosity ? Only the future will tell.

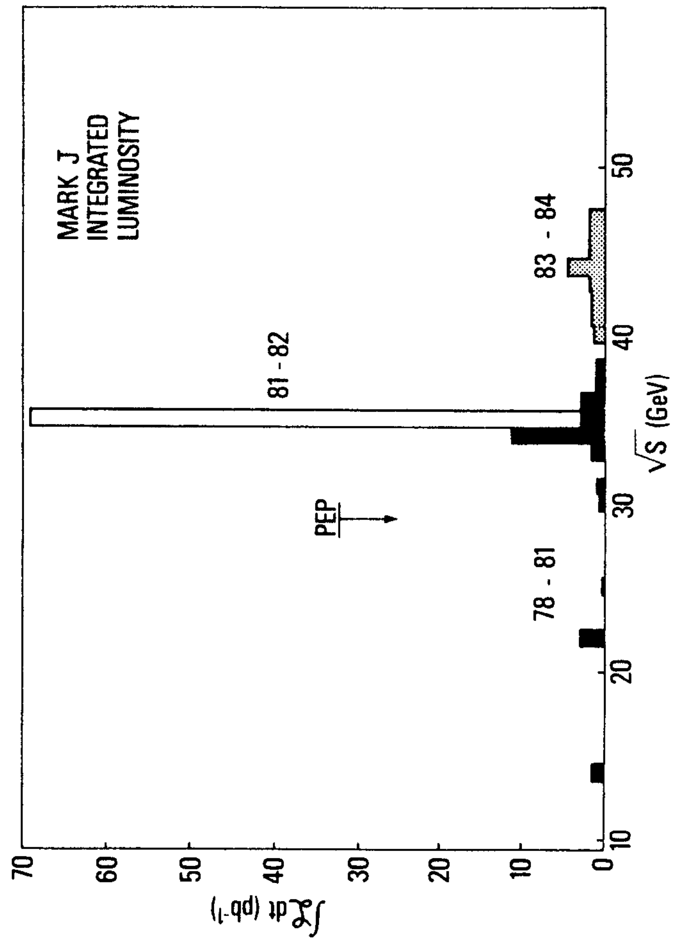

FIG. 1 - Integrated luminosity per experiment at PETRA (Mark J).

2. TESTING THE STANDARD MODEL : QCD

2.1. Quark jet fragmentation

Despite the fast discovery of gluon jets in e^+e^- annihilation, progress in this area has been hampered by the fact that the jet-parton correspondence is not unique at these energies. Therefore any quantitative study of QCD has to rely on the best possible knowledge of the fragmentation propêrties of the partons - the quarks to start with. The inclusive production of hadrons will teach us a lot about the cascade process from the quarks to the observed hadrons. In a second step, such information can be readily used to constrain the existing flexibility within the Monte-Carlo simulations which are used in the studies of QCD.

New results have been obtained by JADE[1] and TASSO[2] on the inclusive production of vector mesons : ρ° and K^{*}. This production plays a major role in current Monte-Carlo generators characterized by a ratio

$$r = \frac{PS}{PS + V}$$

describing the rate of pseudoscalar and vector particles. With the parametrization of the fragmentation function

$$F(z) \sim (1-z)^{\alpha}$$

α and r are related by the constraint of the overall multiplicity and therefore the data restrict the range of these parameters (Fig. 2). At 35 GeV, the analysis of JADE yields

$$(.98 \pm .09 \pm .15) \quad \rho^{\circ}/\text{event}$$

and $$(.87 \pm .16 \pm .08) \quad K^{*\pm}/\text{event} \; .$$

Another interest of studying jet fragmentation lies in the ability to discover or confirm the existence of heavy particles, since c and b quarks are copiously produced in e^+e^- annihilation and therefore their fragmentation should lead to heavy mesons or baryons. An example of this approach is given in Fig. 3 from an investigation done by TASSO[3] in order to look for F mesons through the $\phi\pi$ mode as reported by the CLEO group[4]

$$F^{\pm} \to \phi \; \pi^{\pm}$$
$$\quad \hookrightarrow K^+K^- \; .$$

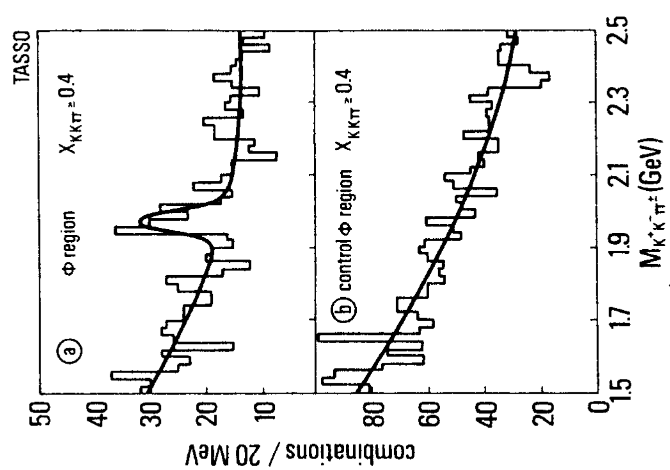

Fig. 3 - The $K^+K^-\pi$ mass spectrum showing evidence for $F \to \phi\pi$ (data from TASSO[3]).

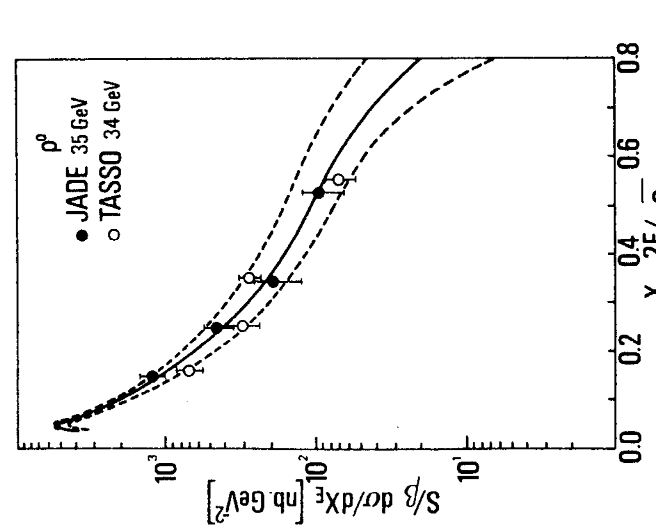

Fig. 2 - The ρ° inclusive cross section compared to a fragmentation function of the form $F(z) \sim (1-z)^{\alpha}$; r is the fraction of pseudoscalar meson production in the Lund Monte Carlo generator (data from TASSO[2] and JADE[1]).

TASSO finds a mass

$$M_F = (1975 \pm 9 \pm 10) \text{ MeV}$$

in agreement with CLEO (1975 ± 5) and recent determinations by the ARGUS (1967 ± 4) and ACCMOR (1975 ± 4) collaborations.[5,6] Some discrepancy shows up, however, as far as the total F yield from a c quark is concerned. For the quantity

$$R(e^+e^- \to F + \text{anything}) \times BR\ (F \to \phi\pi)$$

TASSO finds (.061 ± .012 ± .018), whereas CLEO and ARGUS measure only ∿ .02. The production of F mesons by b quarks could explain a small part of the difference.

2.2. QCD description of the annihilation into 2-and 3-jet final states

It was established in 1982 by the CELLO collaboration[7] that a proper description of the jet final state had to incorporate a 2nd order QCD calculation and that uncertainties related to the fragmentation model were rather large. These uncertainties in fact are presently the limiting factor to measure the $q\bar{q}g$ running coupling constant $\alpha_s(Q^2)$. Although not immediately appreciated, these facts have now been confirmed in 1983 by TASSO[8] and in 1984 by JADE.[9] Although all experiments agree on the relevance of the 2nd order corrections, the fragmentation dependence seems not to be seen in the analysis of the MARK J group,[10] contrary to the other analyses.

Many problems plague this a priori beautiful laboratory of QCD : i) The 2nd order calculations in QCD are not unique : ERT,[11] AB[12] and FKSS.[13] The corrections are numerically different but they refer to a different treatment of soft gluons.

ii) The fragmentation is still considered in two extreme (?) ways : string fragmentation (SF, Lund model)[14] or independent fragmentation (IF).[15]

iii) Several versions exist for the gluon fragmentation function with no clear-cut preference.

iv) Finally the IF scheme does not automatically insure energy-momentum conservation and some contortion of the model has to be imagined to achieve this. This is not done in a unique way.

The analysis of CELLO[7] is summarized in Fig. 4(a) : the asymmetry of the energy-weighted angular correlations (EWAC) yield different values of α_s when the SF or the IF schemes are used. The same conclusion was reached on the 3-jet fraction (Fig. 4(b)). The present situation from the PETRA experiments is presented in Table I : except for MARK J, the experiments see a significant systematic shift of α_s depending on the fragmentation scheme used. This shift, about .05, is considerably larger than the statistical accuracy (.01 ; .02 for CELLO) and therefore the present knowledge of α_s is truly limited by our relative ignorance of the fragmentation process. It is therefore crucial to improve the situation by independent studies aiming at reducing the flexibility still existing at that level. The recent analysis of JADE[9] of the EWAC asymmetry shows a better overall description with the SF (Fig. 5(a) and (b)). Using only charged particles, the TASSO analysis[8] does not discriminate between the two possible schemes. Progress would be welcome both from more refined analyses and better phenomenological treatments.

2.3. Hard scattering of 2 photons into 2 jets

Study of the crossed Compton process

$$\gamma\gamma \to q\bar{q}$$

is a well-known test of the charge of the quarks in the naive quark-parton model (QPM), since its rate is proportional to $\sum_q e_q^4$ and therefore can distinguish between quark models giving the same $\sum_q e_q^2$ in the e^+e^- annihilation rate. Results have been available recently both for untagged photons ($Q^2 \sim 0$) by TASSO[17] and CELLO[18] and tagged photons ($\langle Q^2 \rangle > .35$ GeV^2) by PLUTO.[19] The first situation has the advantage of higher statistics but suffers from 1γ-annihilation background which has to be carefully subtracted out. The second method is cleaner and provides more information through the Q^2 dependence of the rate.

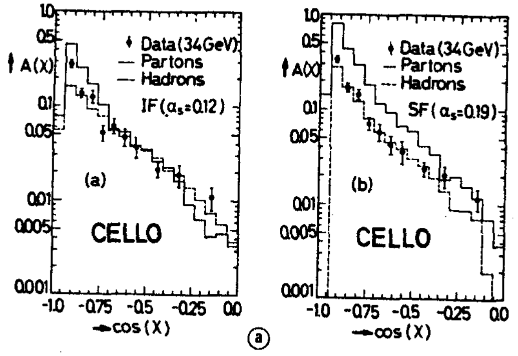

Fig. 4.a - The asymmetry of the energy-weighted angular correlations compared to the predictions of the independent fragmentation (IF) model and the string fragmentation (SF) model in 2nd order QCD. Values for α_s defer markedly in the two analyses (CELLO[7]).

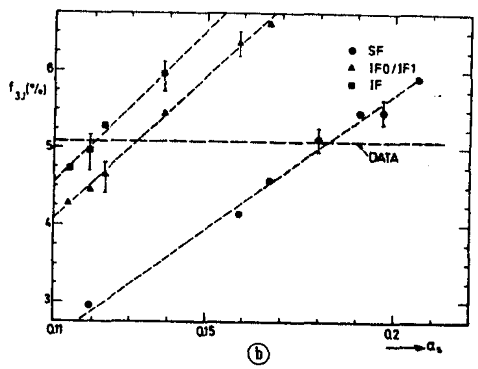

Fig. 4.b - The fraction of 3-jet events as a function of α_s for the IF and SF models ; IF0 and IF1 correspond to different ways to implement $(E, \vec{p})$ conservation (CELLO[7]).

Table I

Results on α_s from EWAC asymmetry in 2nd order QCD

Experiment	SF	IF	QCD* **
CELLO	.19	.12 → .15	FKSS y_m = .03
MARK J	.14	.12	ERT + AB ε = 0.2, δ = 26°
TASSO	.19	.11 → .14	FKSS + corrections ε = 0.2
	.16	.12	ERT + AB δ = 40°
JADE	.165	.11 → .12	FKSS y_m = .0125

* 2 partons i,j are counted as 2 separate jets if $y = \frac{m_{ij}^2}{s} > y_m$ where m_{ij} is the invariant mass of the ij system.

** in the Sterman-Weinberg[16] definition of a jet, 2 partons are counted as 2 separate jets if their energies are both larger than $\varepsilon \frac{\sqrt{s}}{2}$ and their opening angle is larger then δ.

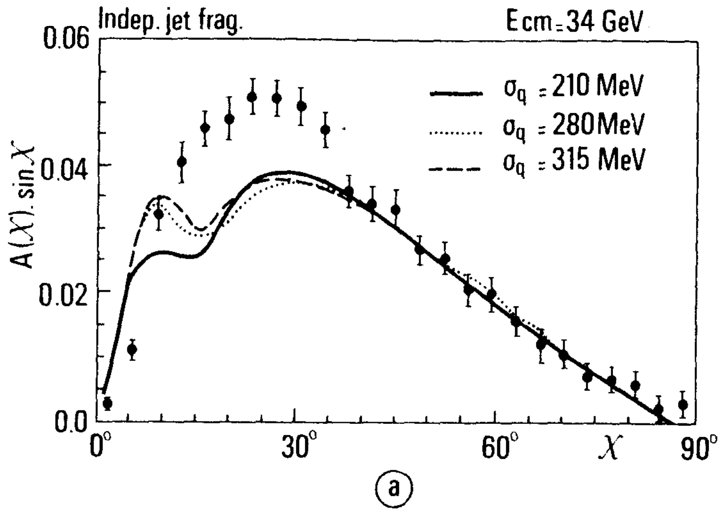

Fig. 5.a - $A(\chi)\ \sin\chi$ for the JADE data[9] compared to the IF model ; σ_q is the width of the transverse momentum distribution relative to the SF model.

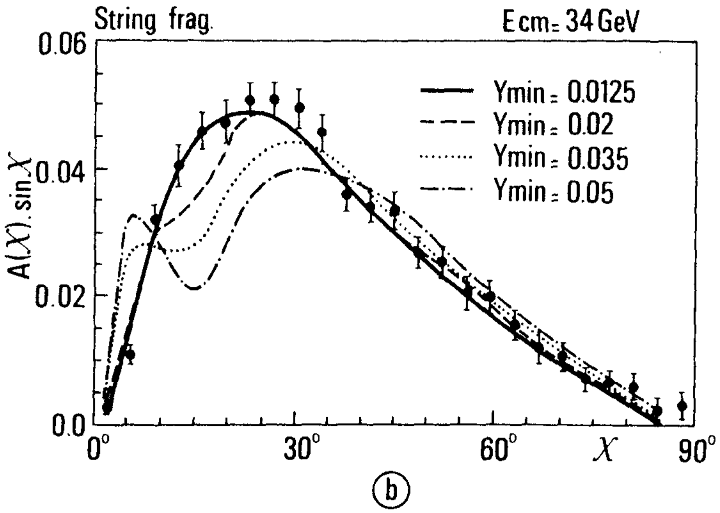

Fig. 5.b - $A(\chi)\ \sin\chi$ for the JADE data[9] compared to the SF model.

All data see a large variation with the p_T of the produced particles, the low-p_T abundance being related to VDM-type contributions where the photon behaves as a hadron. As p_T increases, a tail develops which is interpreted as hard scattering of "elementary" photons into quarks. When this contribution is compared to the expected rate for $\gamma\gamma \rightarrow q\bar{q}$, some large excess is found in TASSO[17] up to $p_T \sim 3$ GeV where p_T is the transverse momentum of the individual charged particles relative to the beams (Fig. 6). CELLO[18] sees a similar effect for individual particles, but also for jets : Fig. 7 shows the p_T spectrum of jets with a rate about 2.5 times larger than the expected QPM yield in a p_T^{jet} range from 2 to 6 GeV. The results from PLUTO,[19] given in Fig. 8, do not indicate such a large excess when one of the photons is virtual: in fact their data agree with the QPM estimate for $p_T^{jet} > 4$ GeV. Some excess in a range of p_T^{jet} between 2 and 4 GeV is noticed, especially at the lowest Q^2 value of 0.3 GeV^2. Either the effect seen by TASSO and CELLO has an unexpectedly fast Q^2 dependence (between 0 and 0.3 GeV^2 ?) or the background is unsatisfactorily handled in the difficult untagged experiments (the 1γ subtraction becomes larger as p_T increases as seen in Fig. 7). Of course some other hard processes are expected to occur[20] in QCD, such as

$$\gamma q \rightarrow gq,$$
$$\gamma g \rightarrow q\bar{q}, \text{ and}$$
$$q\bar{q} \rightarrow gg \ldots$$

where the target $q(\bar{q},g)$ is described by the γ structure function. Preliminary estimates indicate a possibly large contribution but the Q^2 dependence has to be understood, before conclusions are reached.

2.4. Photon structure function

Results on the hadronic photonic structure measured by deep inelastic electron scattering

$$e\gamma \rightarrow e + \text{hadrons}$$

are available from CELLO,[21] JADE[22] and PLUTO.[23] The x dependence

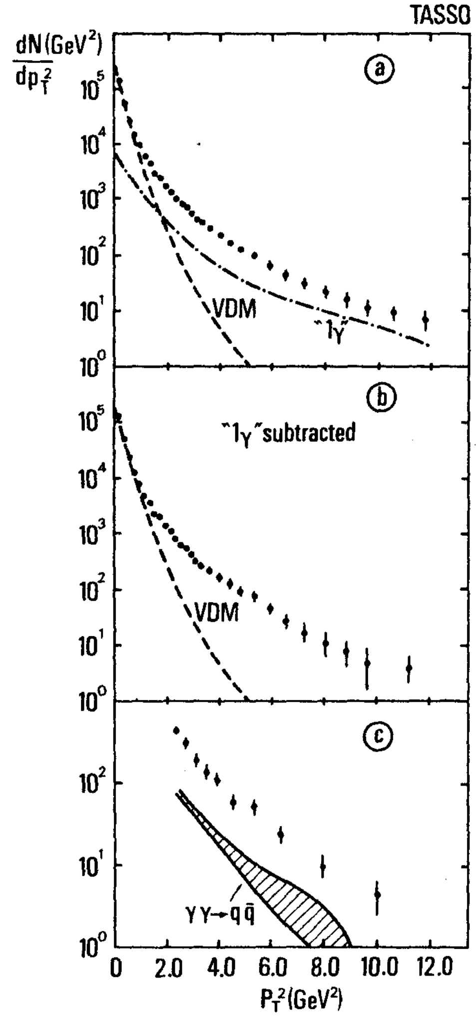

Fig. 6 - The inclusive hadron production cross section in γγ collisions as a function of the transverse momentum squared relative to the beam axis, as measured by TASSO.[17] There is a large subtraction from annihilation processes; however the tail at large p_T is not explained by $\gamma\gamma \to q\bar{q}$.

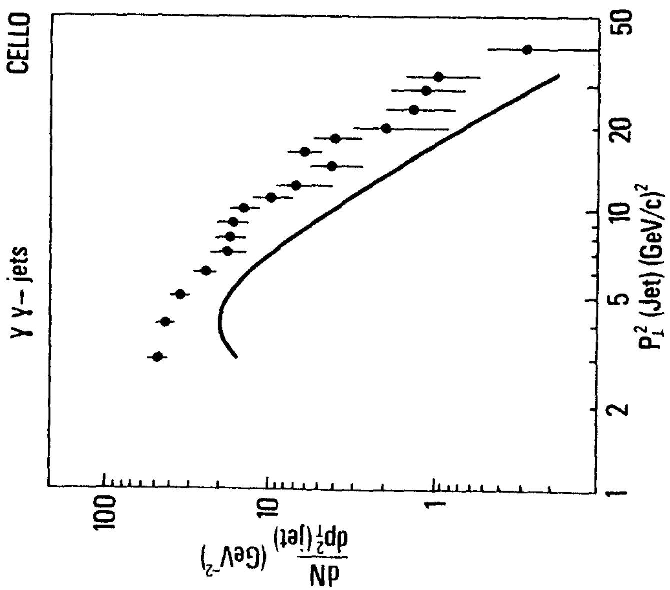

Fig. 7 - The inclusive jet cross section from CELLO[18] in the process $\gamma\gamma \to 2$ jets showing an excess at large p_T^{jet} over the $\gamma\gamma \to q\bar{q}$ yield (curve).

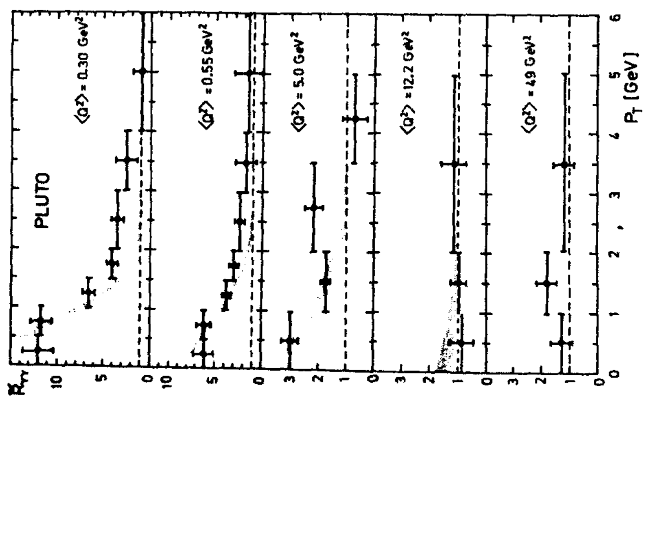

Fig. 8 - The inclusive jet cross section from PLUTO[19] in the process $\gamma\gamma \to 2$ jets for tagged photons ($Q^2 \neq 0$) expressed as the ratio to the $\gamma\gamma \to q\bar{q}$ cross section.

(Fig. 9) shows a clear point-like behaviour contrasting with the expected VDM contribution. The evolution of the structure function with Q^2 should be predictable by QCD although the treatment of heavy quarks (mostly c) and of higher orders is not yet completely understood. Experimentally, a definite rise with Q^2 is seen (Fig. 10) consistent with a value $\Lambda_{\overline{MS}} \sim 200$ MeV, however with a large uncertainty from the complications mentioned above. Also some disagreement exists between the experiments and therefore more detailed work will be necessary.

In summary, although e^+e^- experiments see jets in every event and a good agreement with QCD is observed, one feels somewhat frustrated that a really quantitative understanding has not yet been achieved.

3. TESTING THE STANDARD MODEL : THE ELECTROWEAK SECTOR

3.1. Neutral current lepton couplings

The measurements of the reactions

$$e^+e^- \rightarrow e^+e^-$$
$$\rightarrow \mu^+\mu^-$$
$$\rightarrow \tau^+\tau^-$$

have been extended to $\sqrt{s}$ = 46.8 GeV, but the statistics is still low. Even at these energies the electroweak interference is small in the total cross section (since $\sin^2\theta_W$ is close to 1/4) as seen in Fig. 11 for the MARK J experiment : up to $s \sim 2000$ GeV^2 the measured rate for $ee \rightarrow \mu\mu$ agrees with the QED point-like cross section within 10 %.

The present results[24] on the μ-pair and τ-pair forward-backward asymmetries are given in Tables II and III, and Fig. 12. To extract the relevant couplings, electroweak radiative corrections have to be applied. Recently several calculations[25] have been performed up to one loop giving corrections < 1 %. The results for the axial couplings are

$$\rho\, a_e a_\mu = 1.10 \pm .05, \text{ and}$$

$$\rho\, a_e a_\tau = .92 \pm .19$$

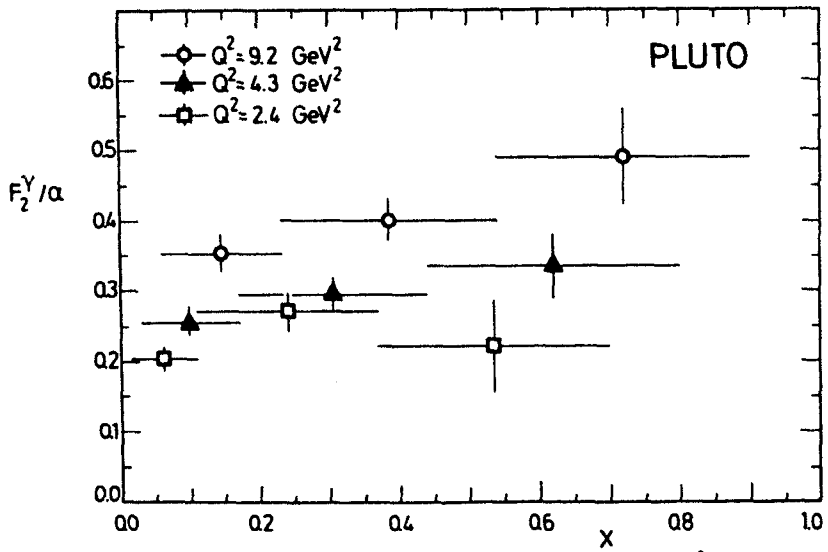

Fig. 9 - The photon hadronic structure function $F_2(Q^2,x)$ as measured by PLUTO[23] showing a distinct point-like behaviour over the VDM component.

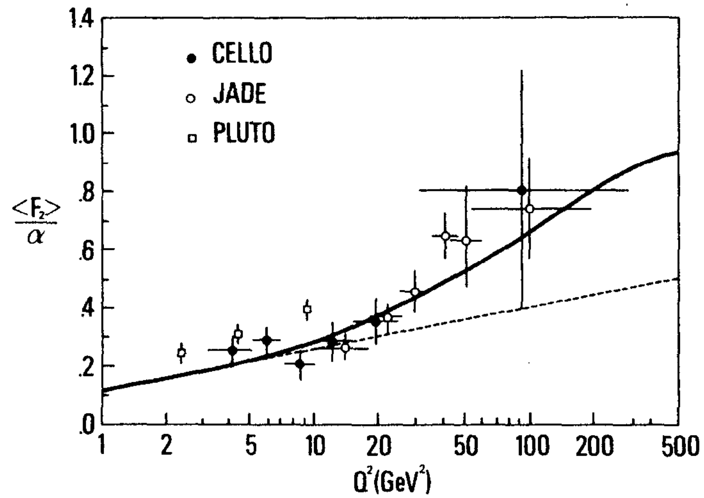

Fig. 10 - The photon hadronic structure function averaged over x (x > 0.1) $\langle F_2(Q^2)\rangle$ as a function of Q^2, pointing to an increase as predicted by QPM and QCD but showing also some disagreement between different experiments (CELLO,[21] JADE,[22] PLUTO[23]). The solid curve corresponds to QCD lowest order (u,d,s,c) with Λ = 0.3 GeV ; the dashed curve is the same without the C quark contribution.

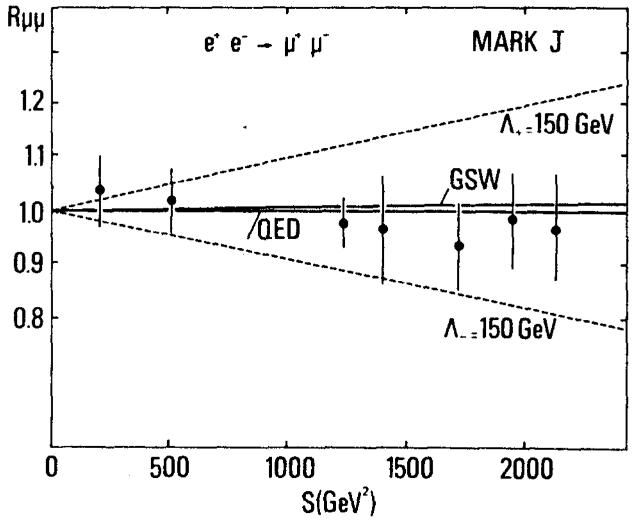

Fig. 11 - The quantity $R_\mu = \sigma(ee \to \mu\mu)/\sigma_{pt}$ as a function of s (MARK J).

Table II

PETRA results on the μ-pair asymmetry

Experiment	$\sqrt{s}$ (GeV)	$A_{\mu\mu}$ (%)
CELLO	34.2	- 6.4 ± 6.4
JADE	34.4	- 11.0 ± 1.8 ± < 1.0
MARK J	34.6	- 11.7 ± 1.7 ± < 1.0
PLUTO	34.7	- 12.4 ± 3.1 ± < 1.0
TASSO	34.5	- 9.1 ± 2.3 ± .5
Combined	34.5	- 10.8 ± 1.1
CELLO	42.5	- 13.4 ± 9.4
JADE	42.4	- 20.1 ± 4.3 ± 1.7
MARK J	41.1	- 15.8 ± 5.3
TASSO	42.4	- 13.1 ± 8.8
Combined	41.6	- 17.6 ± 2.7

Table III

PETRA results on the τ-pair asymmetry

Experiment	$\sqrt{s}$ (GeV)	$A_{\tau\tau}$ (%)
CELLO	34.2	- 10.3 ± 5.2
JADE	34.6	- 7.6 ± 2.7
MARK J	34.6	- 7.8 ± 4.0
TASSO	34.4	- 4.9 ± 5.3 ± 1.3
Combined	34.5	- 7.7 ± 1.9
CELLO	42.5	- 16.7 ± 9.0

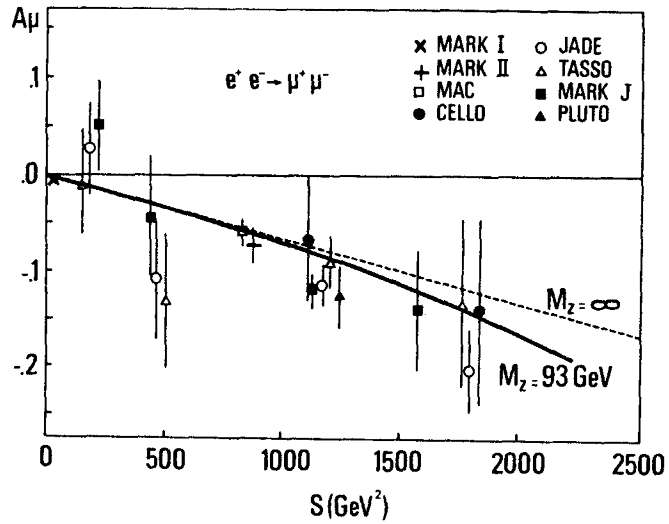

Fig. 12 - The average forward-backward asymmetry A_μ in the angular distribution of the process $ee \to \mu\mu$ as a function of s.

where the standard model predicts a value of 1 for these quantities. If one-loop corrections are included in the W and Z propagators, ρ can differ from unity by 1-2 % depending on the mass of the t quark.[26]

In the standard parametrization,

$$R_\mu = 1 + 2\rho v_e v_\mu \chi + \rho^2 (a_e^2 + v_e^2)(a_\mu^2 + v_\mu^2)\chi^2 ,$$

$$A_\mu \simeq \frac{3}{2}\rho a_e a_\mu \chi , \text{ and}$$

$$\chi = \frac{G_F}{8\pi\alpha\sqrt{2}} \frac{1}{\frac{s}{M_z^2} - 1}$$

the sensitivity to $\sin^2\theta_w$ through R_μ or to M_z through A_μ is limited.[26] It is, however, possible to determine the range allowed by e^+e^- data only involving leptons, for the ρ and $\sin^2\theta_w$ parameters : Fig. 13 shows a reasonable agreement (within 2σ) between this determination and the others from ν and $p\bar{p}$ collider data.

It is possible to parametrize A_μ in a different way[27] to eliminate the ρ parameter,[27]

$$A_\mu = \frac{3 a_e a_\mu}{32 \sin^2\theta_w \cos^2\theta_w} \cdot \frac{s}{s - M_z^2}$$

and determine $\sin^2\theta_w$ from neutral-current measurements alone : M_z and A_μ. Using the value for M_z obtained by UA1[28] and UA2,[29] one can derive

$$\sin^2\theta_w = .185 \pm .022 .$$

It should be pointed out that it is not an independent measurement of $\sin^2\theta_w$ from e^+e^- data alone since the actual value of M_z does not merely enter as a correction as in the previous parametrization, but assumes a crucial role. However it is a nice consistency check of the theory since only the neutral sector is involved here. All ρ-independent determinations of $\sin^2\theta_w$ are given in Fig. 14.

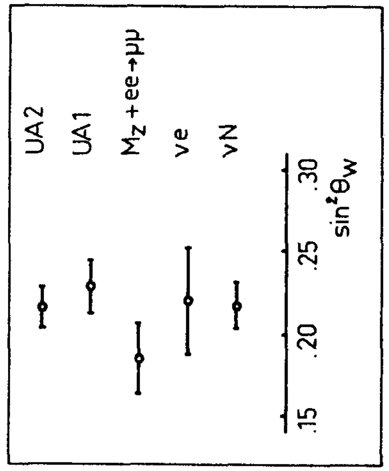

Fig. 14 - The ρ-independent determinations of $\sin^2\theta_w$.

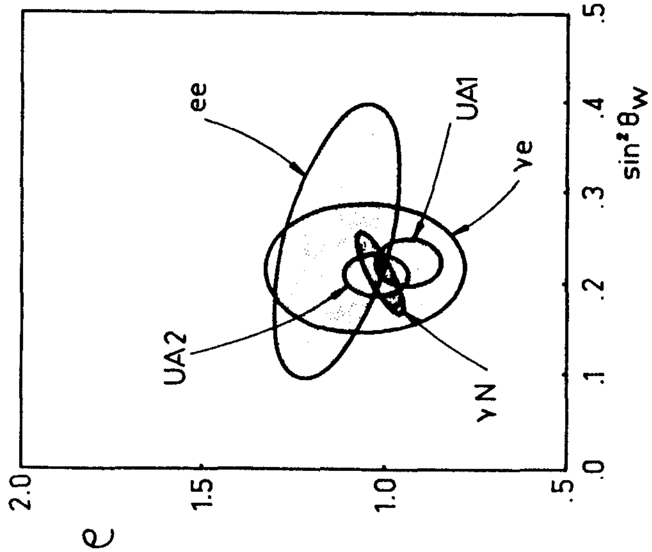

Fig. 13 - The parameters of the standard SU(2) × U(1) model, ρ and $\sin^2\theta$, extracted from ee → μμ data alone. Other determinations are also given.

3.2. τ decays

A new lifetime measurement has been reported by the TASSO collaboration[30] using a precise vertex detector: the accuracy on the decay length of the τ is of the order of 1 mm (Fig. 15(a)) which is comparable to the average decay length. Consequently the distribution of the τ decay path ℓ_τ shows a marked departure from a beam-centered gaussian (Fig. 15(b)) and yields a measurement

$$\ell_\tau = \left(1082 \begin{smallmatrix} + 205 \\ - 260 \end{smallmatrix}\right) \mu ,$$

which can be converted into a lifetime determination:

$$\text{(TASSO)} \quad \tau_\tau = \left(3.18 \begin{smallmatrix} + .59 \\ - .75 \end{smallmatrix} \pm .56\right) 10^{-13} \text{s} .$$

This value is in good agreement with the latest Mark II result, obtained with a sample 25 times larger[31]:

$$\text{(MARK II)} \quad \tau_\tau = (2.86 \pm .16 \pm .25)\ 10^{-13} \text{s} ;$$

and also agrees with the theoretical expectation based on lepton universality in the weak charged current

$$\text{(theory)} \quad \tau_\tau = (2.82 \pm .18)\ 10^{-13} \text{s} .$$

An essentially complete measurement of the τ decay channels has been performed by CELLO.[32,33] Owing to its good calorimetric granularity, multi-π° final states can be reconstructed and identified. The results are given in Table IV. Most of these decay rates are well understood by the standard charged weak current: the comparison is easy for the vector part of the hadronic system as it is related to the corresponding e^+e^- annihilation reactions[34]; however, many theoretical uncertainties remain for the description of the axial-vector component.

3.3. Quark flavour tagging and heavy quark neutral couplings

To have access to the neutral current coupling of heavy quarks (b,c) which are, in practice, not accessible to ν scattering, the problem of quark tagging of jets must be solved. Two methods have

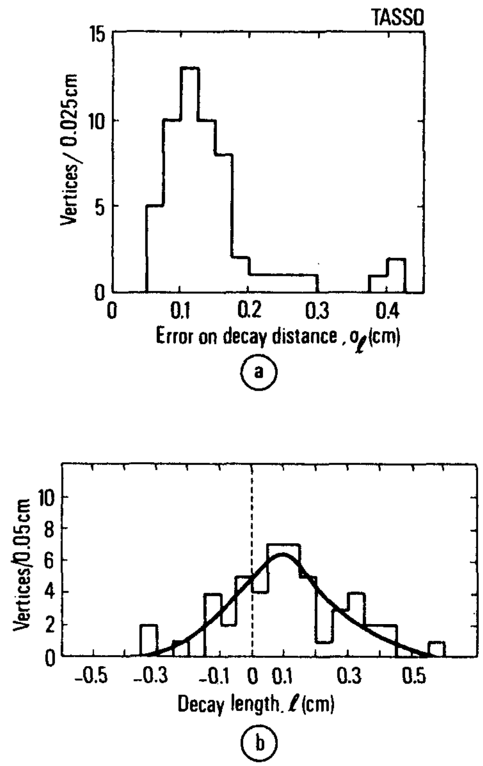

Fig. 15 - Determination of the τ lifetime by TASSO,[30] using $\tau \to 3$ charged tracks:

(a) The distribution of the error on the decay distance, σ_{ℓ_τ}.

(b) The distribution of the decay distance ℓ_τ with the best fit yielding a value for the τ lifetime.

Table IV

Measured τ branching ratios and predictions (CELLO)

decay channel	ref	measured branching fraction (%)	prediction[34] (%)
$e\nu\nu$	(32)	18.3 ± 2.4 ± 1.9	18.3
$\mu\nu\nu$	(32)	17.6 ± 2.6 ± 2.1	17.9
$\pi\nu$	(32)	9.9 ± 1.7 ± 1.3	10.8
$\rho\nu$	(32)(33)	22.1 ± 1.9 ± 1.6	22.3
$\pi\pi^\circ\nu$ (non-resonant)	(33)	0.3 ± 0.1 ± 0.3	very small
$\pi\pi\pi\ \nu$	(33)	9.7 ± 2.0 ± 1.3	upper limit 18.7
$\pi\pi^\circ\pi^\circ\nu$	(33)	6.0 ± 3.0 ± 1.8	
$\pi\pi\pi\pi^\circ\nu$	(33)	6.2 ± 2.3 ± 1.7	6.6
$\pi\pi^\circ\pi^\circ\pi^\circ\nu$	(33)	3.0 ± 2.2 ± 1.5	1.1
$\pi\pi\pi\pi\pi\ \nu$	(33)	< 0.9	0.9
$K\nu$	(35)	1.3 ± 0.5	0.5
$K^*\nu$	(35)	1.7 ± 0.7	1.3
$K\pi\pi\ \nu$			1.5

been used so far : the identification of leading heavy hadrons (only D^* tagging for the moment) and the semi-leptonic transitions of b and c quarks.[35]

The distinctive feature of D^* decay is well-known : the low Q value of the decays

$D^{*+} \rightarrow D^\circ \pi^+$, and

$D^{*-} \rightarrow \bar{D}^\circ \pi^-$

with $\Delta M = 145$ MeV, leads to a combinatorial-free determination of the D^* mass with good resolution. The method has been used at PETRA by TASSO and JADE[36] : it is almost free of background (see Fig. 16), therefore very clean, but it suffers from low efficiency yielding results with low statistics. The D^* angular distribution (Fig. 17) with respect to the e^- beam can be used to measure the forward-backward asymmetry of the reaction $e^+e^- \rightarrow c\bar{c}$ and hence determine the axial neutral coupling of the c quark.

The semi-leptonic transitions of b and c quarks offer a convenient tagging of these quarks : however, there are significant backgrounds in the e and μ identification and the separation of b and c contributions are not easy[37] (see for example Fig. 18). No new result has been given on the c component of inclusive lepton production, but improved results are now available on the b contribution since other variables can be used to enhance it over all the other sources. Essentially b jets are expected to be somewhat fatter due to the large mass of the b quark. The most complete analysis along these lines has been presented by JADE[38] : the $b\bar{b}$ component of the total μ inclusive production is measured in a statistical way by considering 3 quantities which discriminate between different components : the jet transverse invariant mass, the transverse momentum of the μ with respect to the jet axis, and the missing transverse momentum relative to the same axis.[39] The last quantity measures, in fact, the transverse momentum of the neutrino. Each component of the μ yield is assumed to contribute to these distributions in a known way, determined by Monte-Carlo simulation (Fig. 19). It is possible at the end to fit for

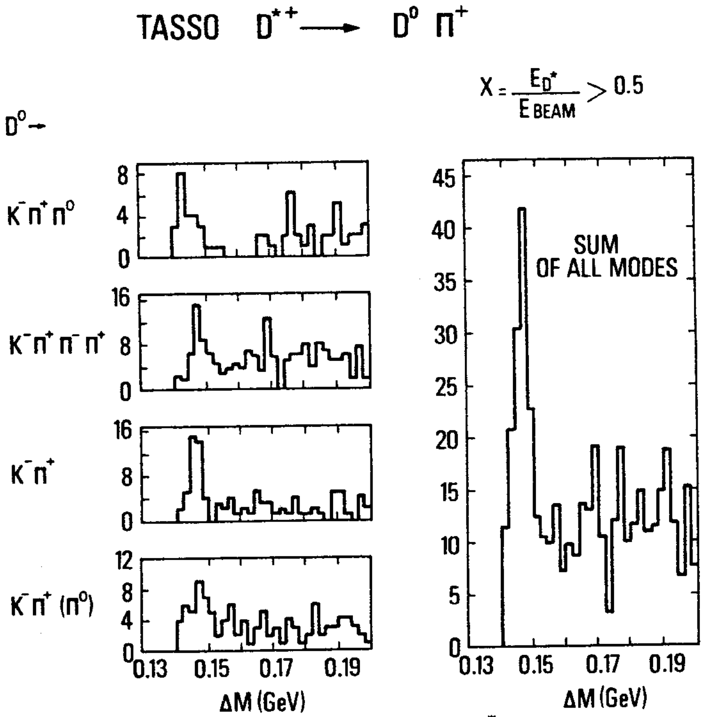

Fig. 16 - Reconstruction of the D^* mass from $D^* \to D\pi$, using various D decay modes (TASSO[36]).

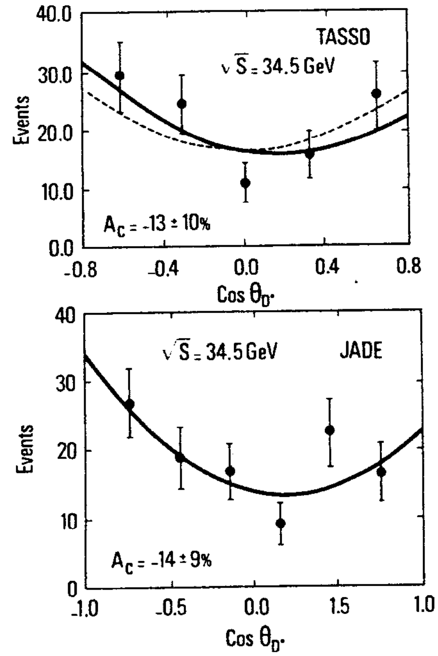

Fig. 17 - The angular distribution for $e^+e^- \to D^*$ from TASSO and JADE[36] allowing a measurement of the asymmetry for the process $e^+e^- \to c\bar{c}$.

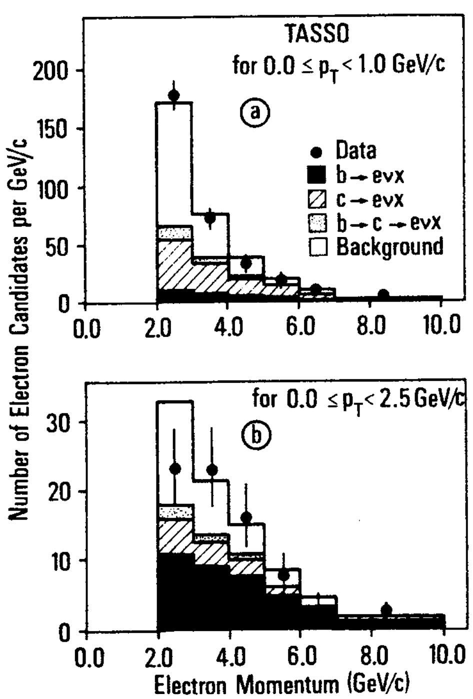

Fig. 18 - The different components of the inclusive electron yield in hadronic events (TASSO[37]).

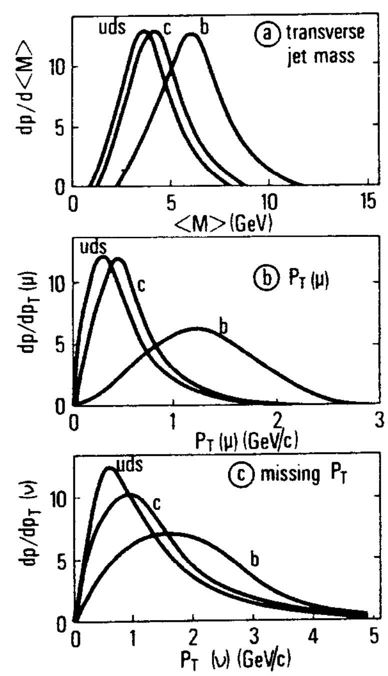

Fig. 19 - Expected distributions for a) the transverse jet mass, b) the transverse momentum of the muon, and c) the missing transverse momentum where all quantities are relative to the event main axis[39]

the $b\bar{b}$ fraction, even in different $\cos\theta$ bins, thereby mapping the $b\bar{b}$ angular distribution. The result, shown in Fig. 20, is a good description of the 3 distributions yielding a b rate of (306 ± 20.5) events from a sample of 1780 hadronic events with a muon tag. At the statistical level, such a result is remarkable since the overall procedure is almost equivalent to the analysis of a pure $b\bar{b}$ sample ! The angular distribution is given in Fig. 21, rendering an asymmetry

$$A_b = (-\ 22.8 \pm 6.0 \pm 2.5)\ \%.$$

The method clearly uses a maximum of information and is obviously powerful, however one may worry somewhat about the correct estimate of systematic effects since the final result is the product of an elaborate fitting procedure of quantities involving many contributions.

The PETRA results on the neutral weak couplings of b and c quarks are given in Fig. 22 and 23, with the combined results :

$$\rho\, a_e\, a_c \;=\; 1.0\ \pm 0.4\,, \text{ and}$$

$$\rho\, a_e\, a_b \;=\; 0.94 \pm 0.22\,.$$

Again the standard model predicts a value of 1 for these quantities.

3.4. Determinations of the b lifetime

Preliminary results on the b lifetime have been presented by JADE[40] through the standard analysis of the lepton impact parameter in the semi-leptonic decays. Two methods are used : standard cuts to isolate a $b\bar{b}$ sample or weighted distributions using p_T and aplanarity to determine the weights. Both methods yield consistent results and the preliminary value is

$$\text{(JADE)}\quad \tau_b = (1.8 \pm {}^{.5}_{.3} \pm .35)\ 10^{-12}\text{s}\,.$$

An even more preliminary result was communicated by TASSO[41]

$$\text{(TASSO)}\ \tau_b = (1.9 \pm .4 \pm .6)\ 10^{-12}\text{s}\,.$$

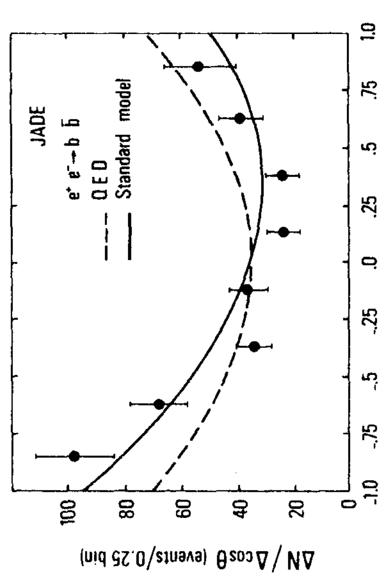

Fig. 21 - The results of the fits given in Fig. 20 used to determine the angular distribution of the process $e^+e^- \to b\bar{b}$.[38]

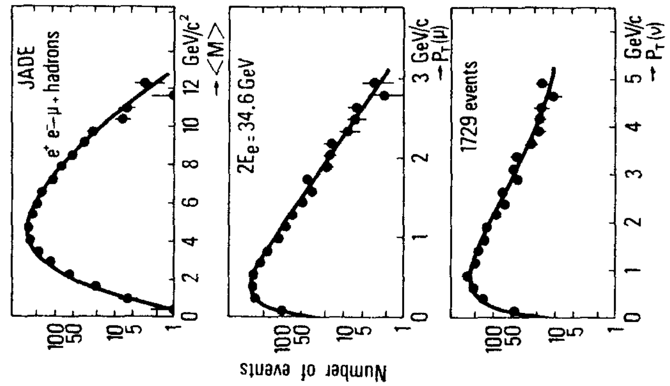

Fig. 20 - The fits to the JADE data[38] using the distribution functions of Fig. 19.

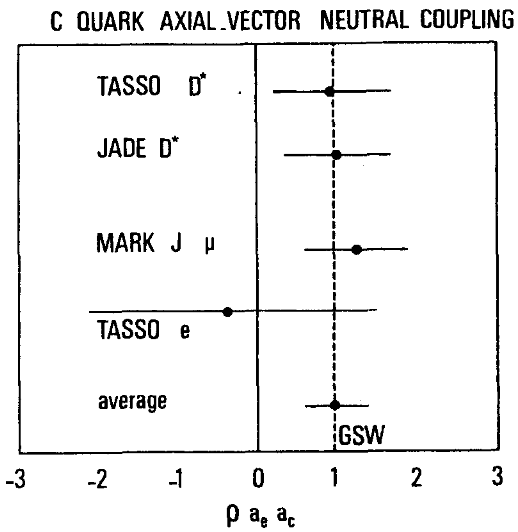

Fig. 22 - The axial-vector neutral coupling of the c quark.

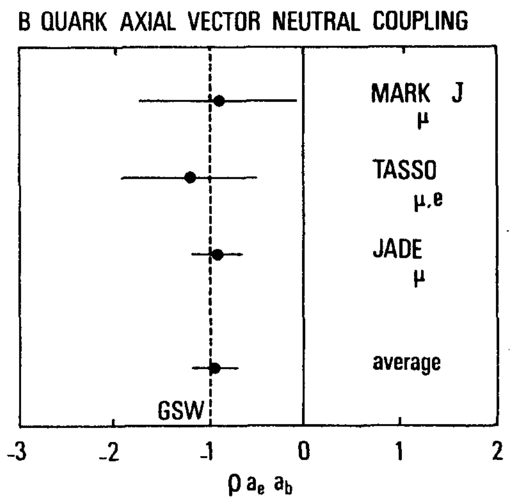

Fig. 23 - The axial-vector neutral coupling of the b quark.

These numbers are in agreement with the previously published results from MAC and MARK II collaborations at PEP.[42] They are somewhat higher than the most recent preliminary values from MARK II and DELCO[31]

(MARK II) $\tau_b = (0.85 \pm 0.17 \pm 0.21)\ 10^{-12}$s, and

(DELCO) $\tau_b = (1.16 \begin{smallmatrix} + .37 \\ - .34 \end{smallmatrix} \pm .23)\ 10^{-12}$s.

The present situation is summarized in Fig. 24.

4. COMPLETING THE STANDARD PICTURE : THE SEARCH FOR THE t QUARK

The outstanding pieces of the standard model are the top quark and the Higgs boson (s). A neutral Higgs boson cannot be realistically looked for in the continuum and requires a toponium state to be produced in significant amounts. Charged Higgses have been searched for and they are ruled out up to a mass of 15 GeV.[43] We now focus on the t quark search, a major effort carried out at PETRA over the last year(s).

4.1. Toponium scan

An energy scan was carried out for centre-of-mass energies from 38.7 to 46.78 GeV in steps of 30 MeV, matched with the energy resolution of 35 to 40 MeV. Each data point required a luminosity of 50 to 60 nb^{-1} per experiment. The corresponding R values are given in Fig. 25 for the sum of all four experiments.

A toponium peak would yield a cross-section

$$\int \sigma\, d\sqrt{s} = \frac{6\pi^2}{M^2} \frac{\Gamma_{ee}\Gamma_h}{\Gamma} .$$

A charge $\frac{2}{3}$ t quark is expected to give

$$\Gamma_{ee}(t) \sim 3.6 \text{ keV},$$

whereas a value of .9 keV is expected for a b' quark. The four experiments combined can rule out a toponium in the studied mass range since the maximum allowed contribution is : $\Gamma_{ee} B_h < 1.0$ keV (95 % CL).

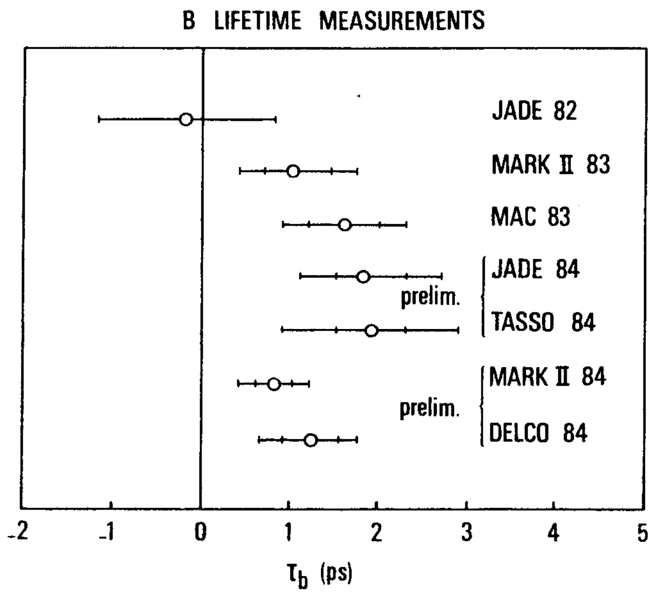

Fig. 24 - Results on the b lifetime.

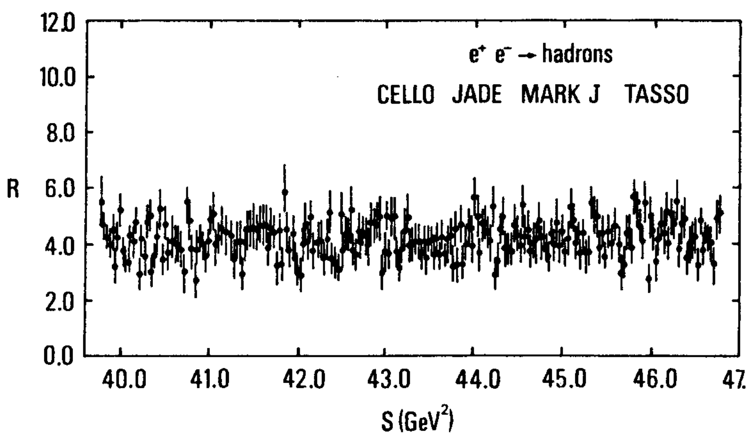

Fig. 25 - The R values for $e^+e^- \to$ hadrons in the scan of the highest energy range of PETRA.

4.2. Open top threshold

The production of u,d,s,c and b quarks is expected in the upper PETRA range to contribute to a R value of 4.07 (including weak effects). A $t\bar{t}$ threshold would correspond to a step going up to 5.5. The measured R values in Fig. 25 do not indicate such a step and the whole energy range is consistent with a single value

$$\langle R \rangle = 4.12 \pm .04$$

which agrees with the expectation without additional quarks.

The occurence of a $t\bar{t}$ threshold can also be sensed through an event shape analysis : aplanarity and thrust are good variables to perform such a test. For example, the aplanarity, A, of events observed by CELLO[44] in the upper 1 GeV mass range of PETRA does not show (Fig. 26) any conspicuous excess which could be due to the production of heavy quarks : from the event yield for A > 0.1, a mass limit of 23.3 GeV can be set for a t quark. A corresponding limit of 22.7 GeV can be given for the mass of a b' quark. Similar results are obtained by the other experiments.

The third method used to look for heavy quark production is the measurement of the yield of inclusive leptons at large transverse momentum to the event main axis. The expected yield is given in Fig. 27 together with the results from MARK J on inclusive muons : the absence of an increase at large energy gives a mass limit of 22.3 GeV for a t quark. Using both electrons and muons, CELLO achieves a mass limit of 22.9 GeV.

In conclusion, the production of t quarks has been ruled out by the PETRA experiments up to a mass of 23.3 GeV.

5. SEARCHING FOR NEW PHYSICS

It is usually advocated that the standard SU(3) × SU(2) × U(1) model cannot be the ultimate theory of matter since many problems are left unresolved, some not even addressed. Many alternatives exist to go beyond the standard model : we shall consider below 2 of these possibilities which are among the most attractive.

5.1. Supersymmetry

Extensive searches for new particles predicted by supersymmetry (SUSY) have been carried out at PETRA. The strategy for these searches of course depends on the possible mass spectrum of the SUSY particles. Of importance is the mass of the photino $\tilde{\gamma}$, spin $\frac{1}{2}$ partner of the photon. Usually the photino is thought to be the lightest of the new particles and a searching scenario then follows. No positive results have yet been obtained in this way and the corresponding mass limits for the searched for particles are indicated in Table V.

For example, the scalar electron $\tilde{e}$ search proceeds through

$$e^+e^- \rightarrow \tilde{e}\,\tilde{e},$$

followed by the fast decay

$$\tilde{e} \rightarrow e\tilde{\gamma} .$$

If the photino $\tilde{\gamma}$ is light and stable, the final state is characterized by an acoplanar pair of electrons with missing energy-momentum. Under this scenario, the mass limit has been pushed to 22 GeV. If the photino is more massive than the scalar electron, the latter would be stable : a limit of 19 GeV is then set. The situation is shown in Fig. 28.

Another possibility could be an unstable photino

$$\tilde{\gamma} \rightarrow \gamma G,$$

where G stands for a spin $\frac{3}{2}$ gravitino, and a still heavier scalar electron. Such a possibility has been investigated by CELLO[45] and more recently by JADE[46] through the reaction

$$e^+e^- \rightarrow \tilde{\gamma}\,\tilde{\gamma}$$

leading to acoplanar photons with missing energy-momentum. Again no evidence was found up to photino masses of 15 GeV.

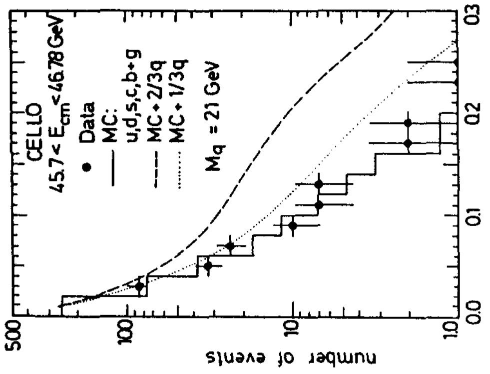

Fig. 26 - The distribution of aplanarity for hadronic events at $\sqrt{s}$ above 45.7 GeV measured by CELLO.[44] Curves are Monte-Carlo predictions for different cases of quark production.

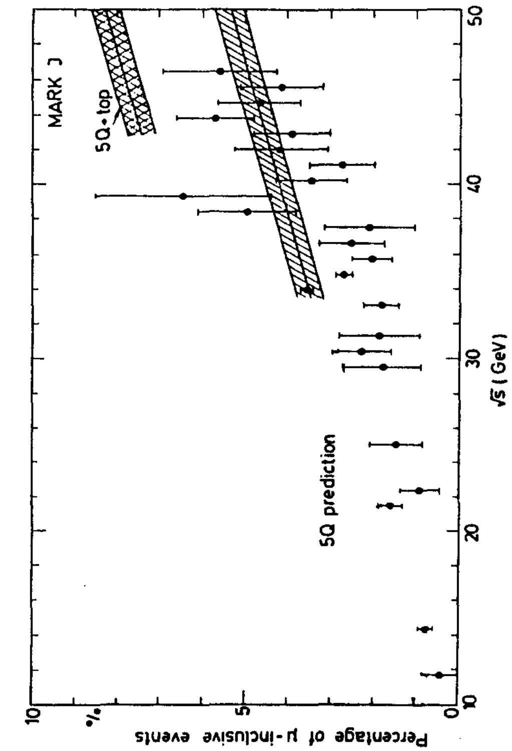

Fig. 27 - The yield for inclusive muons in hadronic events as a function of $\sqrt{s}$ (MARK J) with the expected increase in the event of a $t\bar{t}$ threshold.

Table V

Mass limits for SUSY particles
(light photino case)

process	mass limit (GeV)	experiment
$ee \to \tilde{e}\tilde{e}$	22	CELLO, JADE, MARK J
$ee \to \tilde{\mu}\tilde{\mu}$	20	JADE, MARK J
$ee \to \tilde{\tau}\tilde{\tau}$	16.5	MARK J
$ee \to \tilde{q}\tilde{q}$	19	JADE
$ee \to e\tilde{e}\tilde{\gamma}$	25	JADE
$ee \to \tilde{\gamma}\tilde{Z}$	30 (if $m_{\tilde{e}} < 50$)	CELLO, JADE, MARK J

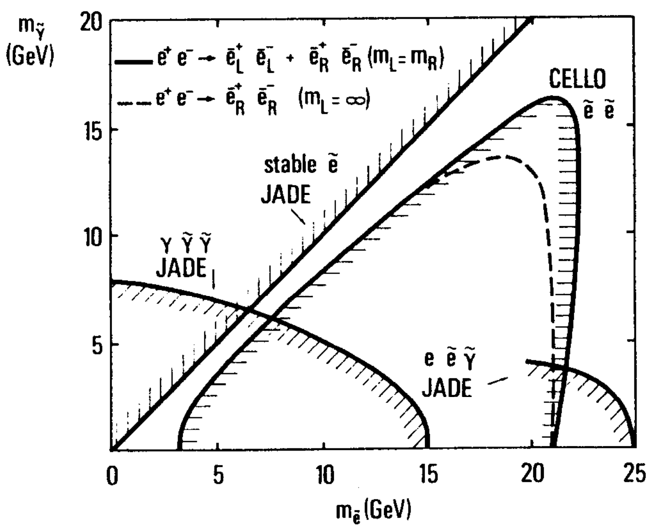

Fig. 28 – Mass limits for the scalar electron $\tilde{e}$ and the photino $\tilde{\gamma}$ from different processes.

Finally, partners for the weak gauge bosons have also been searched for. For example, the process

$$e^+e^- \to \tilde{\gamma}\,\tilde{Z}$$

has been investigated by CELLO, JADE and MARK J with no positive signal. However in this case, to rule out a given mass range requires some amount of assumptions : a typical case is given in Fig. 29.

5.2. Compositeness

The possible structures of quarks and leptons are investigated through the corresponding R values. The fact that the measured values agree with the expected ones under the assumption of point-like fermions, gives limits for possible form factors which can be parametrized by an energy scale Λ. Experimentally, Λ > 200 GeV for μ and e, 160 GeV for τ and 300 GeV for quarks. Therefore no deviation is observed.

Some investigations have been triggered by the proposal of a point-like contact interaction[47] parametrized in a general way with a lagrangian

$$\mathcal{L} = \mathcal{L}_{EW} \pm \frac{g^2}{2\Lambda_\pm^2} (\eta_{LL}\, j_L \cdot j_L + \eta_{RR}\, j_R \cdot j_R + 2\eta_{RL}\, j_R \cdot j_L),$$

where L, R refer to left- and right-handed currents and g is a strong coupling constant. With η being 0 or 1, the results on Λ are typically in the range 1 to 4 TeV.[48]

Composite leptons would probably entail a whole spectroscopy and "excited" leptons would therefore be expected in this case. Whether or not the mass of these objects can be much smaller than the compositeness scale is an open question. At any rate, no such object has been unveiled in the PETRA energy range through the possible processes

$$e^+e^- \to e^* e^*$$
$$e^* e$$
$$\mu^* \mu^*$$
$$\mu^* \mu$$

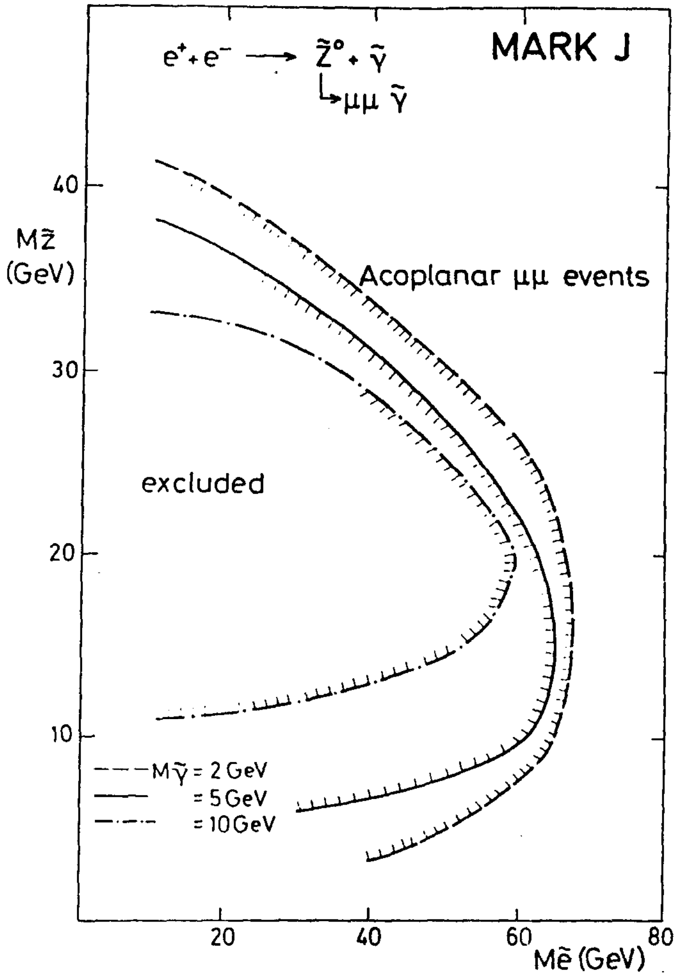

Fig. 29 - Looking for the SUSY partner $\tilde{Z}$ of the Z boson in the process $e^+e^- \to \tilde{\gamma}\tilde{Z}$ (MARK J).

followed by the decays

$$e^* \to e\gamma$$

$$\mu^* \to \mu\gamma \ .$$

Mass limits of 22 GeV are obtained (Fig. 30). The single ℓ^* production does not yield an absolute limit since the interaction will in general depend on a scale parameter Λ[49] :

$$\mathcal{L} = \frac{e}{\Lambda}\, \ell\, \sigma_{\mu\nu}\, \overline{\ell^*}\, F^{\mu\nu} + \text{h.c.}\ .$$

If Λ is choosen to be equal to $2M_{\ell^*}$, then the limits are

M_{e^*} > 70 GeV MARK J,[50] and

M_{μ^*} > 30 GeV JADE.[51]

Weak bosons can also have a composite nature. This has been a flourishing subject among theoreticians[52] and they have welcomed the observation of a possibly too large decay rate of the Z° into radiative modes

$$Z^\circ \to ee\gamma,\ \mu\mu\gamma$$

seen by the UA experiments at CERN.[29,53] One of the proposed explanations could be the existence of a scalar boson X, also composite, which could couple to the fermions and to photon pairs :

$$Z^\circ \to X\gamma$$
$$\hookrightarrow \ell^+\ell^-,\ q\bar{q},\ \gamma\gamma\ .$$

From the observation of radiative events, one expects

$$\Gamma_r = \Gamma(Z \to ee\gamma) \sim 20\ \text{MeV}, \ \text{and}$$
$$M_X \sim 40 \text{ to } 50\ \text{GeV}.$$

Possible effects of such a X boson have been looked for at PETRA. For the processes

$$e\,e \to \mu\,\mu,\ \gamma\gamma,\ q\bar{q}$$

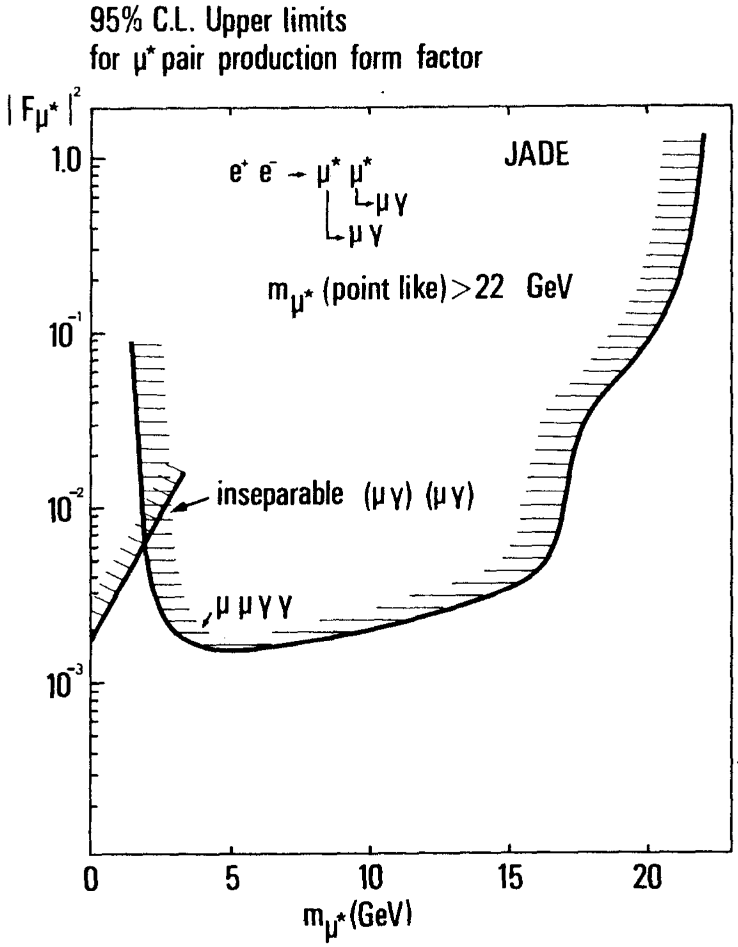

Fig. 30 - Limits on the pair production of an excited state μ^* of the muon (JADE[51]).

no (γ,X) interference is expected, whereas the reaction

$$e\,e \rightarrow ee$$

could be influenced by such an interference (because of the t-channel γ exchange) and therefore is more sensitive for this search. No narrow state has been observed up to a mass of 46.8 GeV in all the possible channels (Fig. 31) with upper limits which are 3 orders of magnitude smaller than the expected ones[54]. Higher masses can still be probed through virtual effects and corresponding limits can be obtained (Fig. 32). In general, the existence of a X boson capable of explaining the Z° radiative events (if taken at face value) is ruled out except for a possible window between 48 and 65 GeV as shown by CELLO (Fig. 33).

5.3. Possibly new physics : the CELLO 2-μ, 2-jet event

A peculiar event has been recorded by the CELLO detector[55] at $\sqrt{s}$ = 43.45 GeV,

$$e^+e^- \rightarrow \mu^+\mu^- + 2 \text{ jets}$$

with the following properties (Fig. 34) :

(i) the event is planar : $\langle p_T \rangle$ = 270 MeV for hadrons relative to the μμ plane,

(ii) each μ is nearly colinear with the opposite jet,

(iii) the topology is rather "symmetric" with each parton sharing about equally the overall energy, and

(iv) all 2 - parton masses are large :

$$M_{\mu\mu} = 20.4 \pm 1.1 \text{ GeV}$$
$$M_{\text{jet jet}} = 17.3 \pm .3 \text{ GeV}$$
$$M_{\mu\ \text{jet}} = \begin{cases} 19.4 \pm 1.3 \text{ GeV} \\ 22.2 \pm 1.6 \text{ GeV}. \end{cases}$$

Possible sources of such events have been simulated by Monte-Carlo :

(a) semi-leptonic b and c decays, hadron punch through and decays are expected to produce $\ll 8\ 10^{-4}$ events in the energy range from 43.2 to

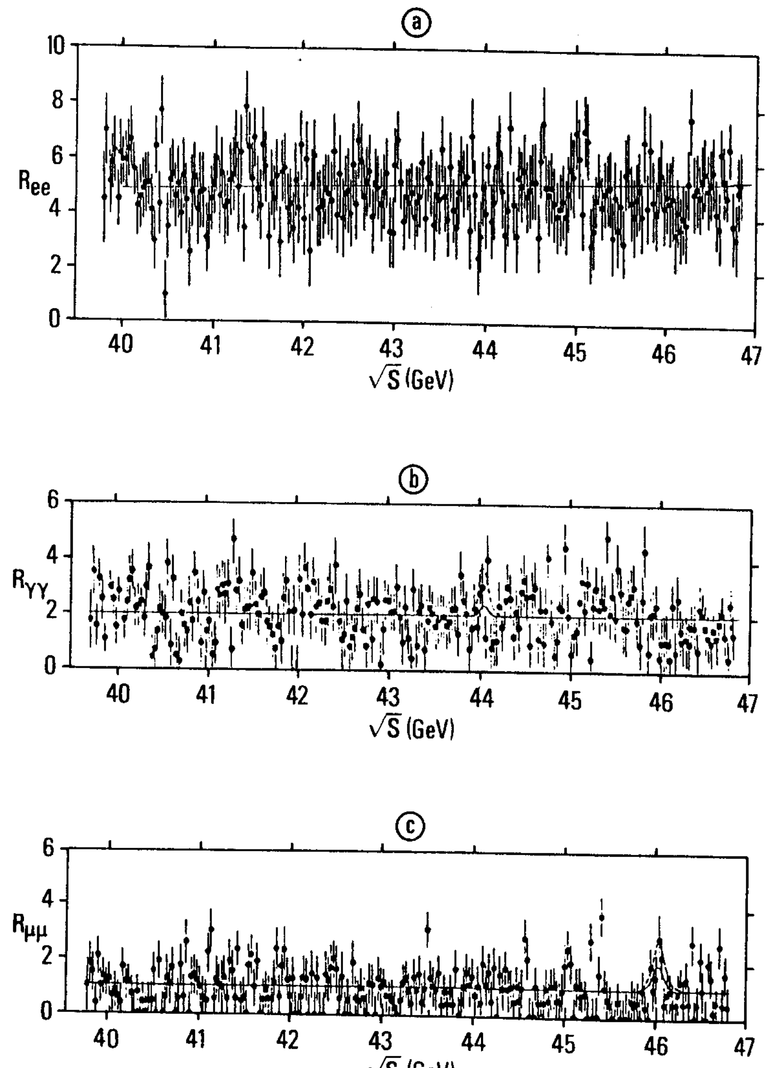

Fig. 31 - The rate for ee, μμ and γγ production as a function of s in order to search for a possible scalar boson (MARK J[54]).

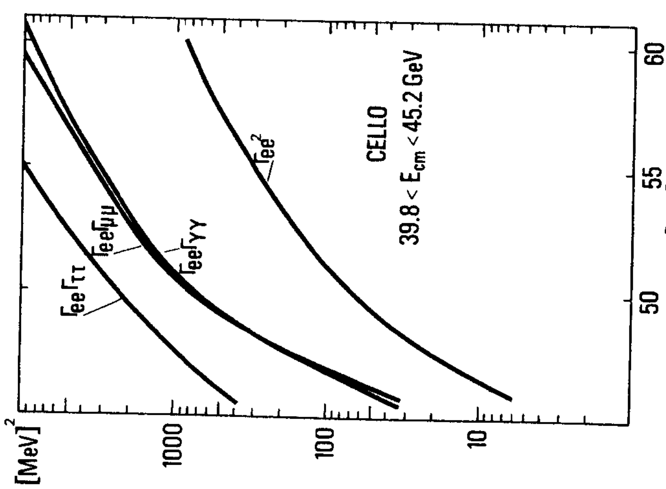

Fig. 32 - Limits on the partial widths of a scalar boson obtained in the CELLO analysis[54].

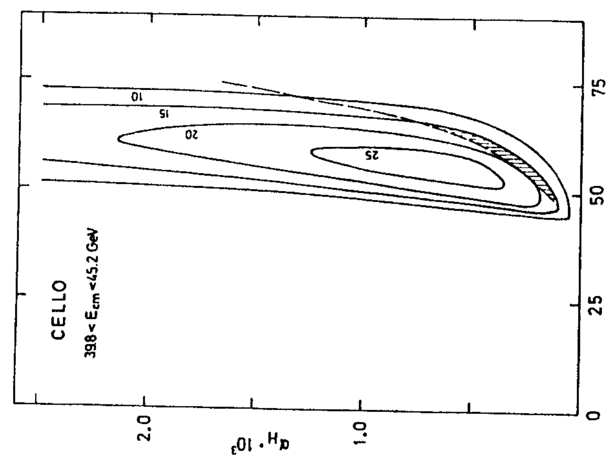

Fig. 33 - Limits at 95 % CL for the assumed universal coupling α_b of a scalar boson X to any fermion pair, as a function of the mass M_X from fits to the differential cross sections for $e^+e^- \to \gamma\gamma$ (solid lines) and $e^+e^- \to e^+e^-$ (dashed lines). The hatched area indicates the region allowed by the data for $\Gamma_r < 15$ MeV (CELLO[54]).

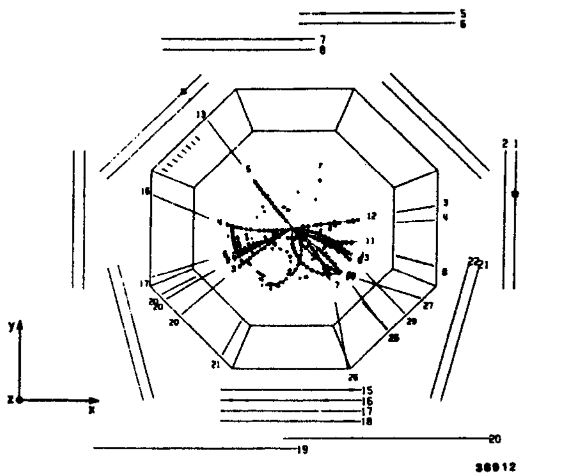

Fig. 34.a - View of the 2-μ 2-jet CELLO event[55] in the plane perpendicular to the beams.

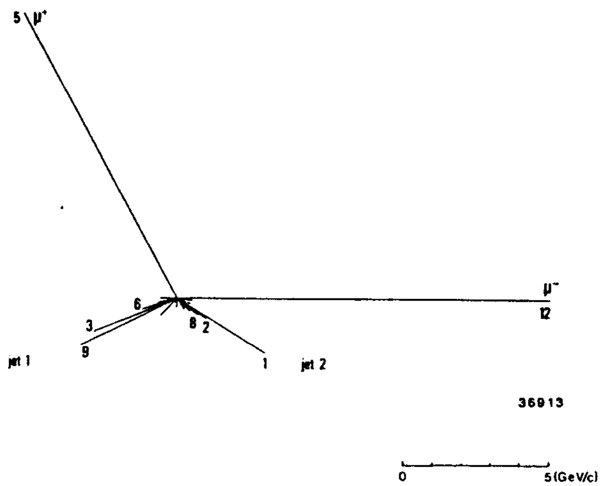

Fig. 34.b - Momentum diagram of the event in the $\mu^+\mu^-$ plane.

45.2 GeV where the event was detected ($\mathcal{L} \simeq 4\ pb^{-1}$).

(b) The α^4 QED production could lead to a similar final state, however the most probable masses are much smaller. The probability that the QED rate produced such an event or one with larger μμ and jet-jet masses is only $(3.2 \pm 1.0)10^{-4}$. However, the expected QED rate to see large masses such as $M_{\mu\mu}/E_B$, $M_{q\bar{q}}/E_B > .85$ is about 0.1 event when all PETRA and PEP experiments are taken together. More probable masses, with ratios to $E_B > .25$, should yield $\sim$ 10 events ; they should be seen, mostly in the PEP data.

If this event is a signature for a new production process, its threshold must be around 43 GeV. Since these data were taken, the integrated luminosity accumulated by CELLO above 43 GeV has doubled and no additional event was found, at least in the on-line scanning of events. The observed event corresponds to $< 3\,10^{-3}$ units of R and no similar event involving ee or μe has been found. Since the event has such a distinct topology, the possibilities for its explanation are limited[55] : among those, the production of a neutral lepton of about 21 GeV mass is a best fit to the data.[55,56] More exotic possibilities could involve lepto-quarks.[57]

The remaining running time at PETRA in 1984 will be mostly taken at 22 GeV beam energy to optimize the (luminosity/energy) chances to discover yet unknown phenomena.

In preparing this report, I had informative discussions with many PETRA colleagues. I thank M. CHEN, R. FELST and G. WOLF for making the data of their collaborations available to me. I am grateful to G. FELDMAN, F. GILMAN and D. LEITH for inviting me to this very special SLAC Summer Institute.

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