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by

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RECENT RESULTS ON e^+e^- ANNIHILATON FROM PETRA*

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Abstract:

Over the past year the energy of PETRA has been steadily increased in order to extend the search for the top quark. Neither topponium bound states nor a threshold for open top production has been found below a c.m. energy of 43 GeV. The implication of the measurement of R, the ratio of the hadronic to the point-like μ-pair cross section, on the determination of the strong coupling constant α_s is discussed. The analysis of jets reveals, that the primary hadron fragments are heavy, that the fragmentation function of heavy quarks c and b is hard, and that gluons tend to have a wider transverse momentum distribution than quarks. The search for exotic particles is reported as negative for new heavy leptons, for scalars - like charged Higgs mesons or technipions - and for supersymmetric particles. Mass limits are given.

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1. Introduction

In this report I shall discuss the search for the top quark, the implication of a measurement of R on the determination of α_s, the analysis of jets, and the search for exotic particles. In order to extend the top search beyond the maximum energy of 37 GeV, already obtained$^{1)}$ with PETRA in 1981, an extensive energy upgrading program was started in the fall of 1982. Doubling the RF power and adding 32 cavities made it possible to cover the energy range up to 43 GeV by August 1983. The physicists from the experiments CELLO, JADE, MARK-J, and TASSO are indebted to the PETRA team for their effort and their efficient operation of the storage ring.

2. Search for the Top Quark

When searching for the missing member of the third quark doublet, one may look for topponium bound states below threshold or for the production of open top above threshold. For the lowest energy and most pronounced topponium state, one expects an increase in the production rate of hadronic final states in terms of the point-like μ-pair production cross section of about

$$\Delta R = \frac{9\sqrt{\pi}}{4\,\alpha^2\sigma_{beam}} \cdot B_{had} \cdot \Gamma_{ee} \simeq 12 \xrightarrow[\text{rad.corr.}]{} 6$$

assuming a Gaussian beam resolution of σ_{beam} = 30 MeV, a hadronic branching ratio of B_{had} = 0.8, and an electronic width of $\Gamma_{ee} \simeq 5$ keV. The radiative corrections$^{2)}$ amount to 50% and reduce the signal from about 12 to 6.

An energy scan has been performed in steps of 30 MeV in the c.m. energy and with an integrated luminosity of 50 nb^{-1} per step per experiment. The measurements from all four PETRA experiments have been combined and the result is shown in Fig. 1. The highest energy point, obtained in this scan, is 43.15 GeV. The R distribution is consistent with being flat and has an average value of <R> = 3.94 ± 0.06 ± system.error, where the systematic error has still to be avaluated for each of the experiments. The strongest deviation from flatness is observed at 43.09 GeV. The integrated cross section at this energy yields an 95% CL upper limit for $B_{had} \cdot \Gamma_{ee}$ of 1 keV, which has to be compared with the expected value of 4 keV for a 2/3 charged quark. Topponium states are therefore excluded up to 43 GeV.

One may argue that one missed the topponium states, because they lie in the energy

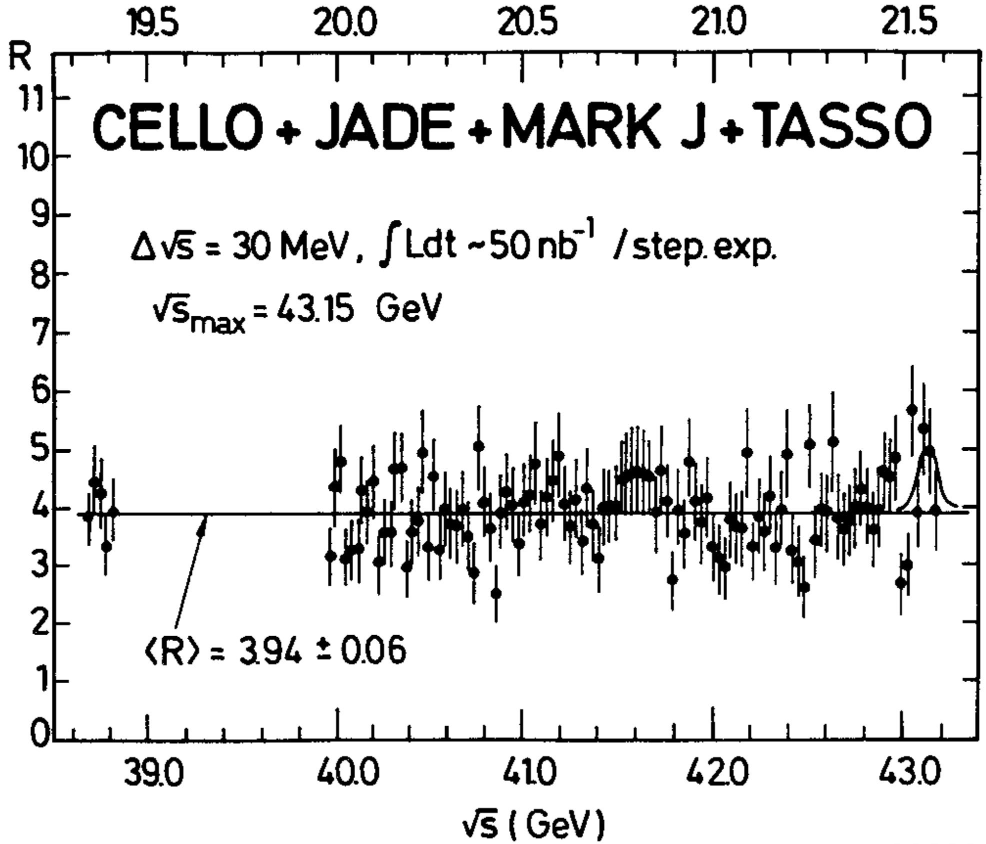


Fig. 1: $R = \sigma_{had} / \sigma_{\mu\mu}^{point}$ for all experiments (CELLO, JADE, MARK-J, and TASSO) combined.

intervals not scanned below 40 GeV, and that a point-like threshold for open top production $\Delta R_{t\bar{t}}^{point} = \frac{2}{3}\,\beta(3-\beta^2)$ in the energy range from 40 to 43 GeV is hard to detect. In fact, the actual threshold behaviour is not known, and a point-like threshold is the most pessimistic assumption. The most sensitive measure in this case is the event topology. Most events from light quarks have two or three jets and consequently are planar. Heavy top quarks would be pair produced nearly at rest, and the decay destribution would therefore be almost isotropic. If one selects events with a high aplanarity$^{3)}$, one can compare the number of observed events with the number of events expected for a specific threshold assumed. From Fig. 2 one can see that the threshold for $\frac{2}{3}$ charged quarks has to be higher than 40 GeV in order to be compatible with the number of observed events in the energy range from 40 to 43 GeV. Even for $\frac{1}{3}$ charged quarks, a threshold below 40 GeV is excluded.

Another indicator of open top production is the copious occurrence of leptons. In Fig. 3 the thrust distribution of the hadrons for inclusive muon events is compared with the prediction for the light quarks and with predictions which include the top quark. From the small number of observed events at low thrust values one can once again exclude a threshold for open top production below 40 GeV.

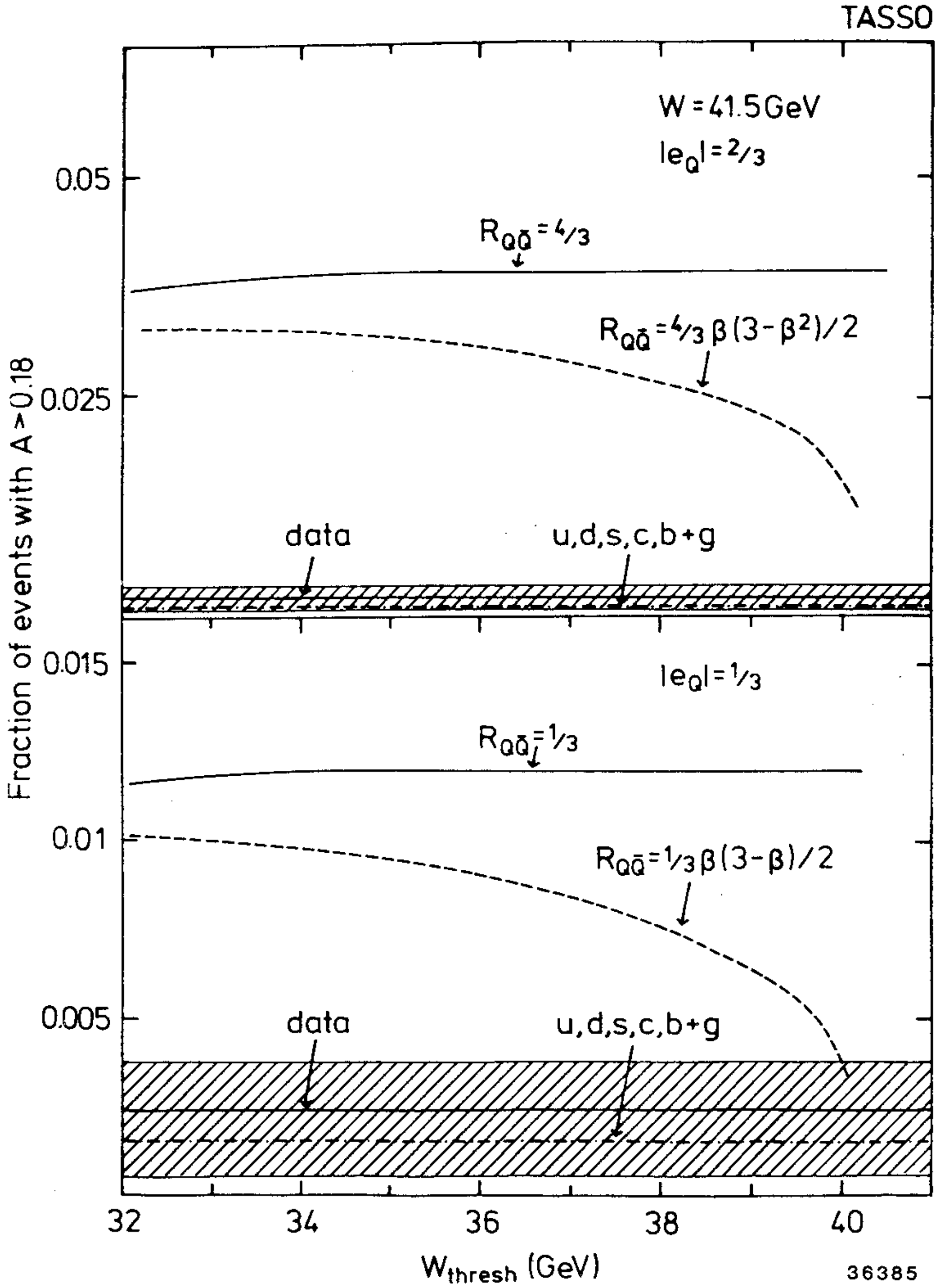


Fig. 2: The fraction of events with aplanarity A > 0.18, observed in the energy range from 40 to 43 GeV, is given by the solid line in the shaded band showing one standard deviation to either side of the data. The expectation for light quarks is given by the dash-dotted line and a possible point-like open top production is shown as function of the threshold energy by the dashed curve.

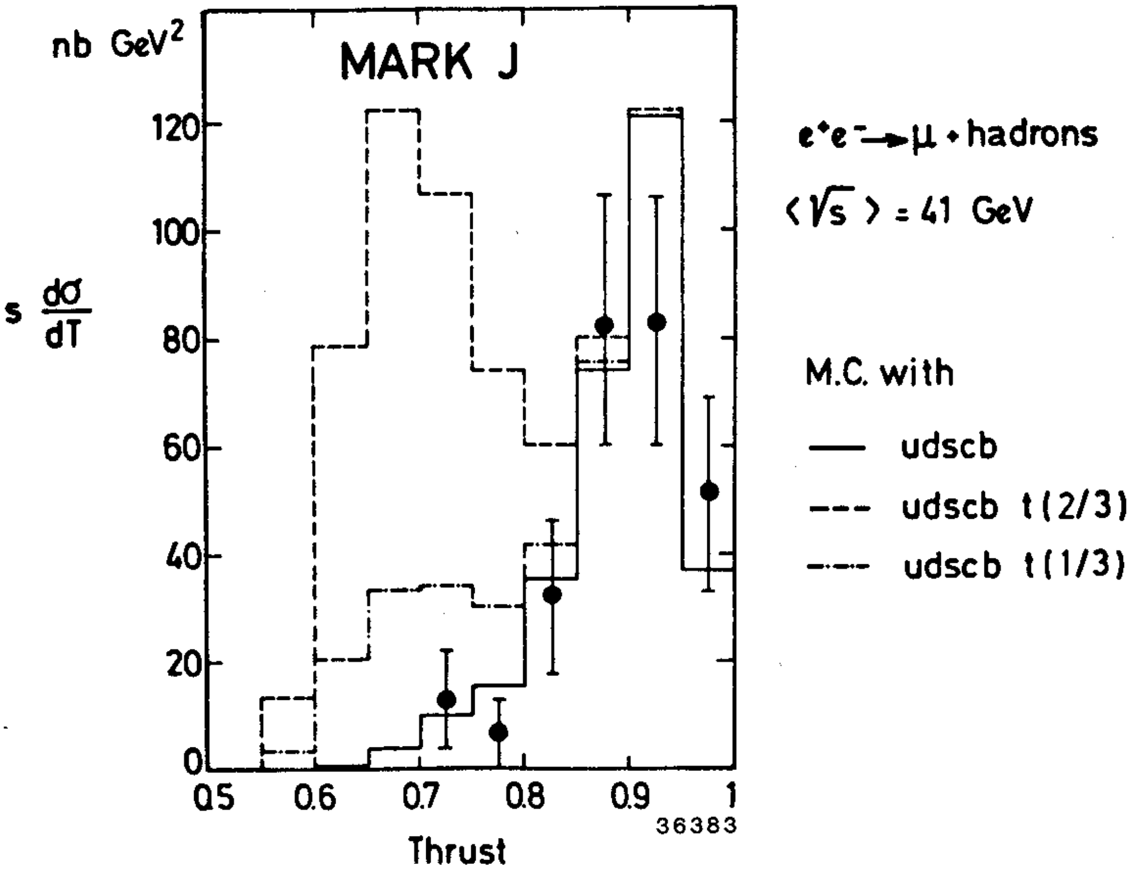


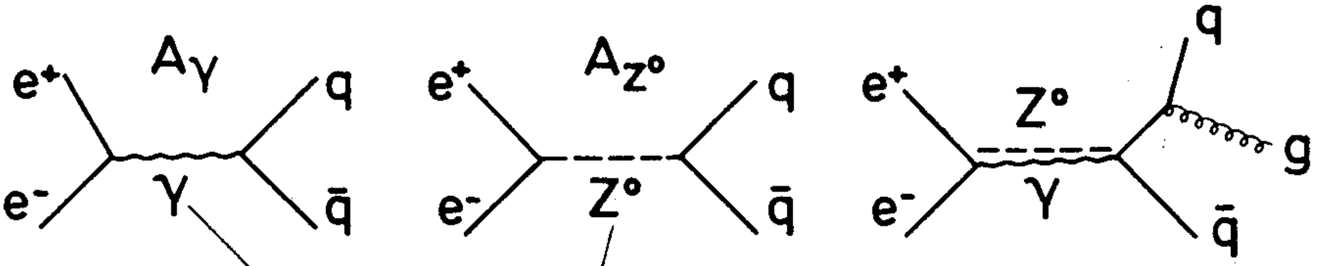
Fig. 3: Differential thrust distribution of the hadrons for inclusive muon events. The full line is the QCD Monte Carlo prediction for the light quarks. For the dashed and dash-dotted histograms a top quark contribution is added for 2/3 and 1/3 charge respectively.

The combined information on the absence of an open top threshold below 40 GeV and on the non-observation of topponium bound states in the energy range from 40 to 43 GeV really pushes the top threshold beyond 43 GeV.

Within the context of present-day theories the quark masses and the quark decay rates have to be determined experimentally. A framework for the transition amplitudes was provided by Kobayashi and Maskawa 4) and later modified by Maiani 5). In addition to the Cabibbo angle θ, relevant for semileptonic and strange particle decays, two more charged current mixing angles β and γ as well as a phase δ are required in the scheme of six quark flavours (u,d,s,c,b, and t). The angle β has to be small in order not to modify the relative rates of semileptonic and purely leptonic decays (Cabibbo universality), and the angle γ can be determined by measuring the b lifetime. A compilation of various bounds on β and γ was presented a year ago, when the JADE experiment determined 6) a 95% CL upper limit of 1.4 x 10^{-12} sec on the b lifetime. According to recent measurements 7) at PEP, this upper limit now seems to correspond to an actual value. An interesting theoretical question is whether a knowledge of the b lifetime can be used to place limits on the top mass. One group of theorists[8)] compares its short distance prediction of the CP violating parameter with the experimental value and concludes that, for a b lifetime of 10^{-12} sec, the top mass should be larger than 30 GeV. Others[9)], who are proponents of some class of composite models, would like to see the top mass in the range from 20 to 25 GeV, even for a long b lifetime. Certainly, a determination of the top mass and a precise measurement of the b lifetime could settle a number of interesting theoretical questions.

3. Measurement of R

The ratio of the hadronic to the point-like μ-pair cross section $R = \sigma_{had}/\sigma_{\mu\mu}^{point}$ has now been measured over a wide range of energies (see Fig. 4) and is seen to be consistent with being constant above 12 GeV. The average R value is slightly higher than $R_o = 3\sum_{u,d,s,c,b} Q_f^2 = \frac{11}{3}$ expected from the parton model. This excess in R can be explained by QCD corrections which, for high energies, have to compete with weak interaction effects. The various contributions to R are illustrated in the following and the expected numerical values are given:



$$R = 3\sum_f \{Q_f^2 + \underbrace{\overbrace{2A_\gamma A_{Z^0} + A_{Z^0}^2}}_{}\} \cdot (1 + \frac{\alpha_s}{\pi} + Q(\alpha_s^2) + \dots)$$

Expected ΔR = 36% if $Q = \frac{2}{3}$		5%	0.3%
9% if $Q = \frac{1}{3}$	1% at W = 35 GeV ($\sin^2\theta_W = 0.23$)		
for new	3% at 40 GeV		
flavours	6% at 45 GeV		

New flavours were the topic of the previous chapter; weak interaction effects - changing R significantly from 40 GeV upwards - are discussed in a separate report[10)] to this conference, and the remaining contributions are the QCD corrections characterised by the strong coupling constant α_s. From the numerical values one can readily see that, in order to determine α_s within 20%, R has to be measured with an accuracy of at least 1%. Therefore, I shall now discuss how well the experiments can do.

Three of the PETRA experiments have accumulated large amounts of data below 37 GeV

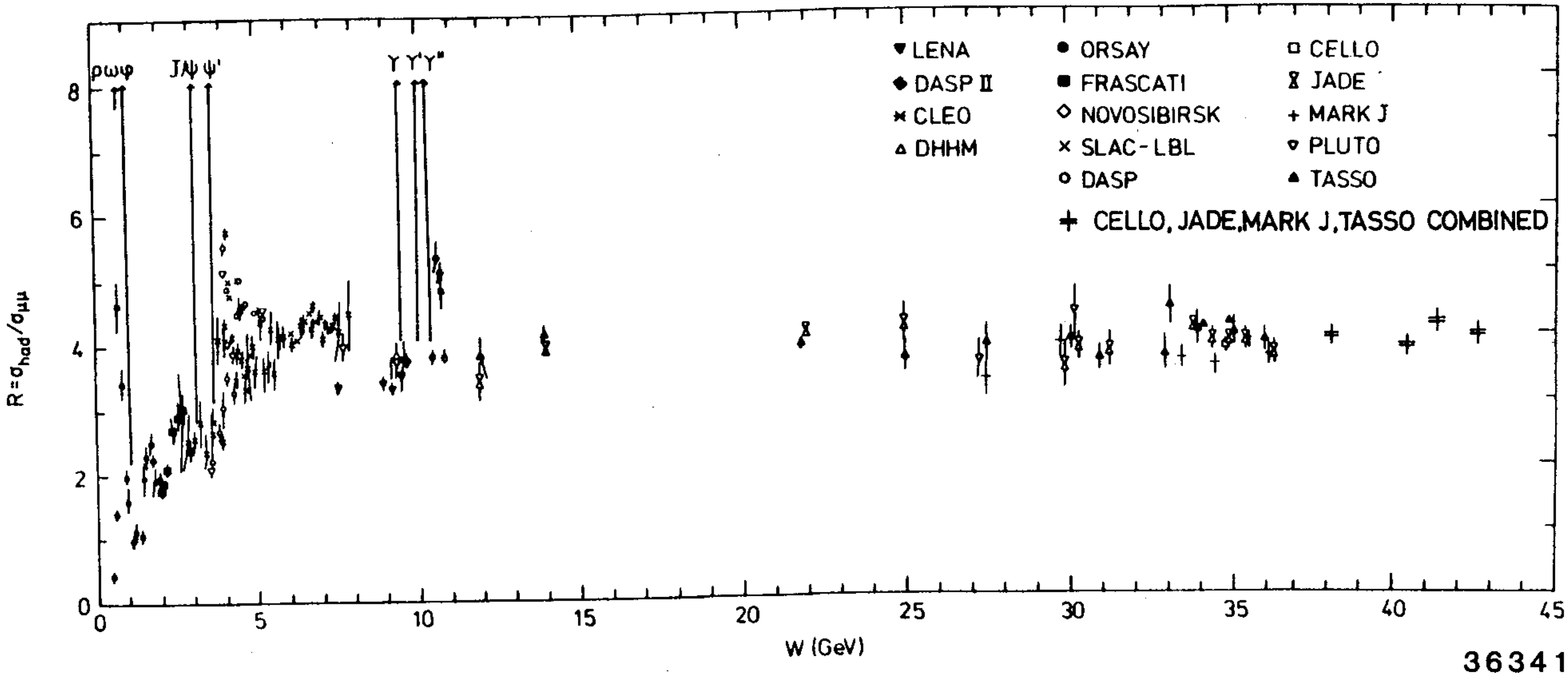


Fig. 4: Measurements of R = $\sigma_{had}/\sigma_{\mu\mu}^{point}$. The cross section is determined from the corrected number of hadronic events $N_{had} - N_{bg}$ via the formula

$$\sigma_{had} = \frac{N_{had}-N_{bg}}{L\cdot\varepsilon\cdot(1+\delta)}$$

where L is the luminosity, ε the acceptance, and δ the radiative correction.

and therefore have small statistical errors on R. In the following, the R values are averaged over a wide range of energies for each experiment. The point-to-point errors are mainly statistical, whereas the normalization errors are from overall systematic effects.

$R \pm \Delta R_{\text{pt.topt.}} \pm \Delta R_{\text{norm.}}$	$\sqrt{s}$ (GeV)	Experiment
$R_i = 3.97 \pm 0.05 \pm 0.10$	12 - 36.7	JADE
$3.84 \pm 0.05 \pm 0.22$	12 - 36.7	MARK-J
$\underline{4.01 \pm 0.03 \pm 0.20}$	14 - 36.7	TASSO
$\overline{R} = 3.94 \pm 0.03 \pm \ldots$		

For the average $\overline{R}$ of the three experimental values one can certainly form the quadratic average of the point-to-point errors but it is not so clear what to do with the normalization errors. However, from the variation of the individual measurements R_i, one can estimate the smallest possible error on $\overline{R}$, given by $\Delta = \sqrt{\Sigma(\overline{R}-R_i)^2/2} = 0.09$. Therefore, in the most optimistic case one can write $\overline{R} = 3.94 \pm 0.03 \pm 0.09$ and get for the strong coupling constant $\alpha_s = 0.19 \pm 0.07$. The JADE experiment by itself has performed a detailed analysis[11] of the various error sources, to minimize the normalization error, and arrives at a similar value of $\alpha_s = 0.20 \pm 0.08$. This shows that the strong coupling constant, when determined from a measurement of R, has a very large error, and the future holds little prospect of reducing this error below 2%.

4. Analysis of Jets

The analysis of jets is of interest, in order to experimentally test QCD and the fragmentation of quarks and gluons. There have been extensive review talks[12,13] on this topic at recent conferences. In this report I can only touch on a few aspects of jet analysis, and I shall start with a number of simple observation.

The PETRA experiments have accumulated data over an energy range from 12 to 34 GeV. Plotting the transverse momenta P_T of the hadrons w.r.t. to an overall jet axis, e.g. the thrust axis, one observes that particles with high transverse momenta are more abundant at high c.m. energies. If one now investigates the event shape in greater detail and defines an event plane, e.g. by taking the plane perpendicular to the aplanarity axis[3], one finds - as shown in Fig. 5 - that the average P_T in the event plane or the event 'width' increases whereas the average P_T out of the event plane or the event 'thickness' stays nearly constant as the energy W increases. Therefore one can conclude that one of the jets splits

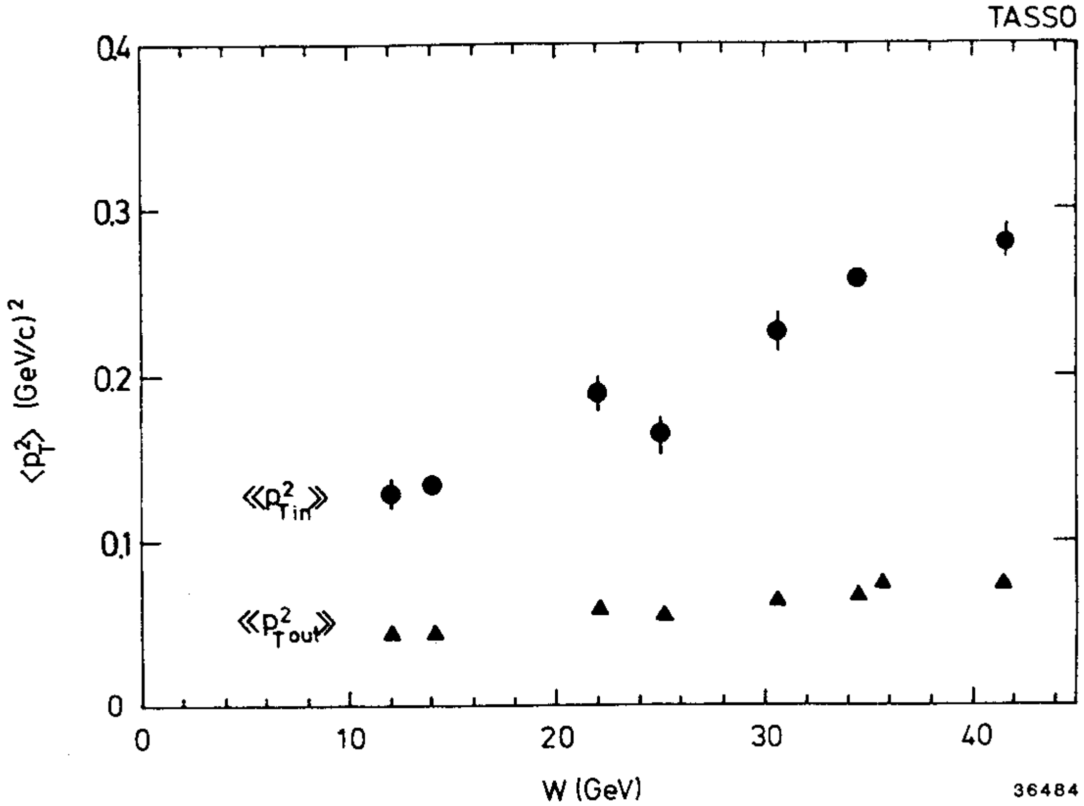


Fig. 5: The transverse momentum components in (●) and out of (▲) the event plane are averaged over all tracks of an event and over all events at a given energy W.

up or in other words that a quark radiates off a gluon. This observation combined with the fact, that the jet cones get narrower as the energy increases, has provided a useful tool for identifying jets and investigating their properties.

A point of interest is the particle contents of jets. From inclusive hadron spectra it has been known[14)] for a while that the relative yield of kaons and protons w.r.t. pions increases with increasing particle momentum. At the highest particle momenta one observes 50% $\pi^\pm$, 30% $k^\pm$, and 20% $p, \bar{p}$. Also a number of resonances have been observed by now, and if one lists their relative fractions one finds that one can attribute close to 90% of the pions to resonance decays[12)]. These results show that the primary hadrons in the fragmentation process are preferentially heavy.

Since quarks are pair-produced in e^+e^- annihilation, they provide a clean laboratory for studying the fragmentation of heavy quarks, like charm and bottom, if one succeeds in identifying these flavours. The flavour tagging for charm quarks has been achieved by selecting $D^{*\pm}$ mesons. These mesons can be identified[15)] by using the fact that, in the decay $D^{*\pm} \rightarrow \pi^+ D^o$, the mass difference between D^* and D^o is just about the pion mass. The fractional energies $X_{D^*} = E_{D^*}/E_{beam}$ are plotted

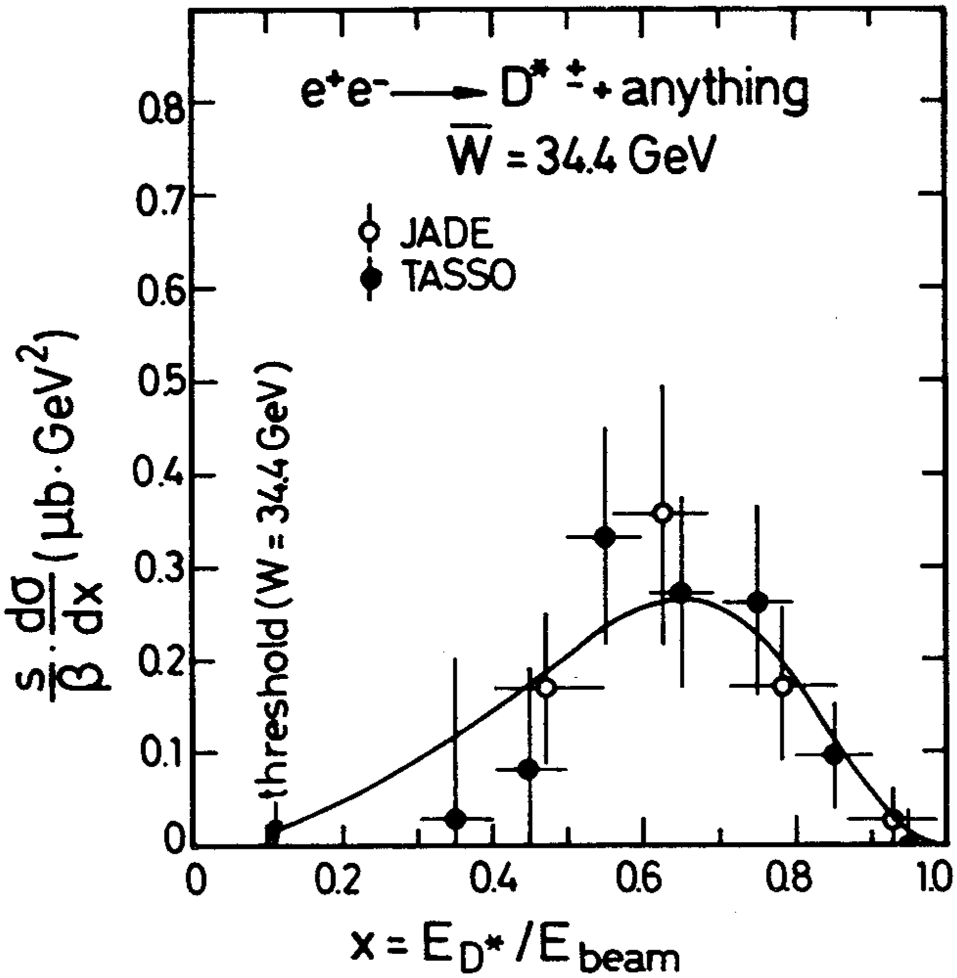


Fig. 6: Invariant differential cross section for inclusive D* production. The curve shows a fit with the fragmentation function given in the text.

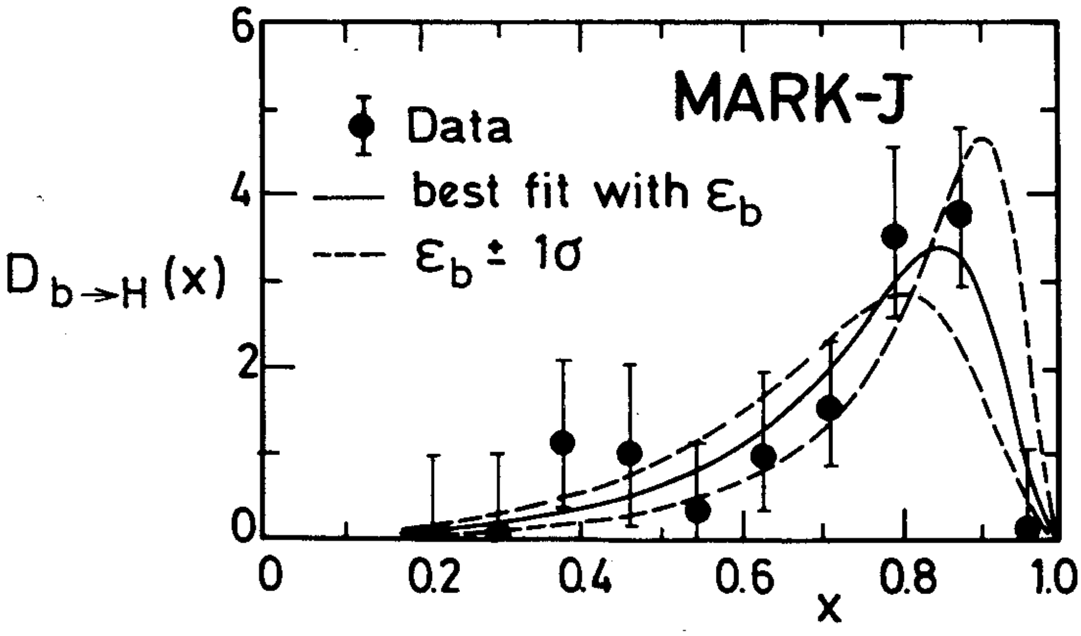


Fig. 7: Fragmentation function of bottom hadron from the reaction $e^+e^- \to \mu$ + hadrons as a function of $x = (e+P_{\parallel})_H/(E+P_{\parallel})_b$.

in Fig. 6 where an average x_{D*} of about 0.6 is observed[16)]. This hard spectrum strongly suggests that the D* mesons fragment from primary c quarks (and not from the decay chain $b \to c \to D^*$ where one expects an average x_{D*} of only 0.3). This behaviour has found a simple kinematical interpretation[17)] which implies that the heavy quark Q is not slowed down much by picking up a light quark q. Therefore the final hadron $(Q\bar{q})$ or (Qqq) should carry nearly the energy of the original Q. Using this interpretation the following fragmentation function has been derived[18)]

$$D_{Q\to H}(x) = \frac{\text{const.}}{x\left[1-1/x-\varepsilon_Q/(1-x)\right]^2}$$

where ε_Q is $\sim M_q^2/M_Q^2$, the ratio of the effective light and heavy quark masses. The curve in Fig. 6 is just this distribution with $\varepsilon_c = 0.18 \pm 0.07$. If this interpretation is correct, one expects an even harder fragmentation for the b quark. The b flavour is tagged via muons which carry a particularly high transverse momentum w.r.t. the hadron jet, because $P_T^\mu \sim M_Q$. The muons are expected to be decay products of the primary hadrons and therefore probe the fragmentation more indirectly than the direct observation of the heavy primary hadrons themselves. Nevertheless, with a suitable fitting procedure the fragmentation function has also been obtained[19)] for the b quark - as shown in Fig. 7 - and indeed the fragmentation is found to be much harder, with an average fractional energy of about 0.75 and $\varepsilon_b = 0.039 \pm 0.008$.

Gluons are less accessible for analysis, since outside the ψ and Υ resonances they appear only as second order effects in e^+e^- annihilation. Because of their larger number of colour degrees of freedom gluons are expected[20)] to fragment with a higher particle multiplicity and a wider P_T distribution than quarks. There are also conjectures that the leading particles are isoscalars or glueballs[21)] and that baryons[22)] might be abundant. In order to investigate the transverse momentum dependence of the particle fragments, 2-jet events at 14 GeV c.m. energy are compared[23)] in Fig. 8 with the lowest energy jet (#3) of 3-jet events at 33 GeV. Whereas all jets at 14 GeV are purely q or $\bar{q}$ and have an energy of 7 GeV, the lowest energy jet at 33 GeV by Monte-Carlo simulation is found to be a gluon in 50% of the cases and experimentally has an energy in the range from 6 to 10 GeV. Therefore one compares quarks and gluons at similar jet energies. From Fig. 8 one concludes that the gluon jets indeed have a wider P_T distribution.

The isoscalar particle content of jets may be probed by looking for η, η', ω, and ϕ mesons[21)]. The JADE collaboration has identified[24)] η mesons by their two

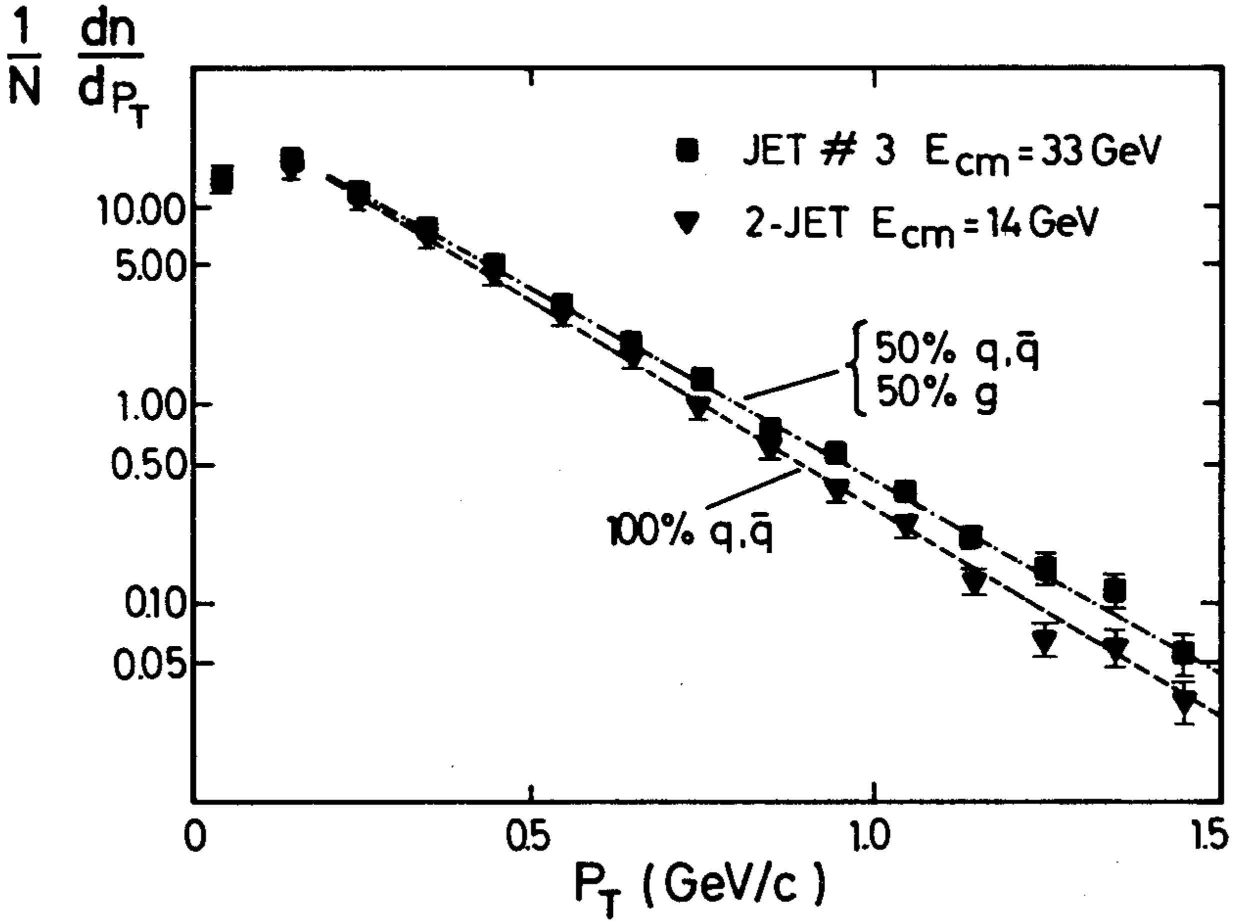


Fig. 8: Differential P_T distributions of lowest energy jet (#3) from 3-jet events at 33 GeV and of 2-jet events at 14 GeV. Particles within a cone of 50° around the jet axis have been selected. From JADE experiment.

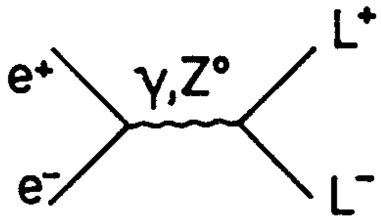
photon decays and divided the data into a sample of sphericity < 0.15 (mostly 2-jet events) and a sample of sphericity > 0.15 (enriched with 3-jet events). Whereas the η/π^0 ratio is 0.13 ± 0.04 for the 2-jet events, it is 0.23 ± 0.07 for the more spherical events. The experimental errors are still large, but one may have here a first hint that gluons are accompanied by more η fragments than are quarks.

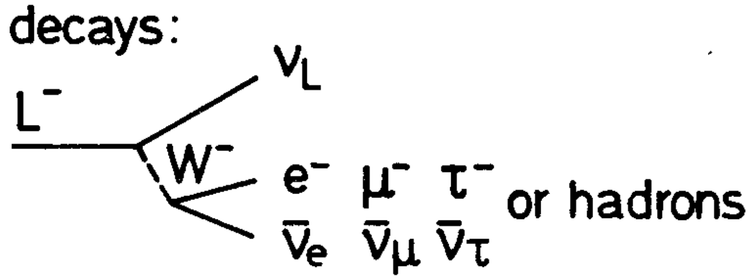
A suitable way of testing QCD and determining the strong coupling constant, α_s, is to study higher order corrections to jet formation in e^+e^- annihilation. However, this approach requires an extensive Monte-Carlo simulation of the data. For this simulation, two widely different models are used; one assumes that quarks and gluons fragment independently[25)], while, in the other, fragmentation takes place along colour strings[26)] between quarks and gluons. In this short review one cannot do justice to the experimental effort which went into determining α_s, and only the basic results are summarized. It is important to include not only the 1st but also the 2nd order corrections in the analysis, and these 2nd order effects lower the resulting value of α_s by about 20%. All PETRA experiments[12] have determined α_s to 2nd order, and the values obtained range from 0.12 to 0.21, thereby indicating that the error (about 0.04) is roughly half as big, as when α_s is determined from a precise measurement of R.

5. Search for Exotic Particles

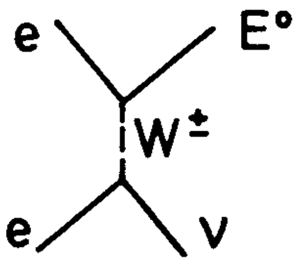
The search for exotic particles absorbs substantial effort on the part of the PETRA experiments. Not only has the detector acceptance for rare or unseen processes to be understood, but one also has to make sure that one does not miss these processes from the outset due to the trigger. In the searches described in the following, three classes of exotic particles will be considered: new leptons, scalars, and supersymmetric particles.

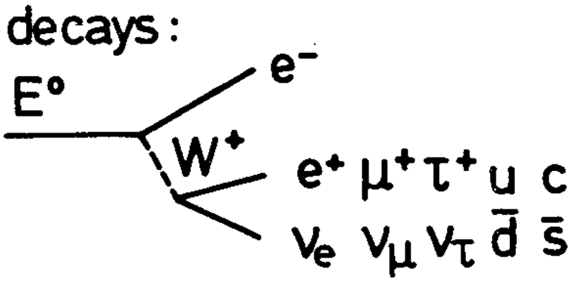
When looking for new heavy leptons[27], the first candidate, that comes to mind, is a sequential heavy lepton, identical to the already known leptons except for its higher mass. Its production and decay characteristics are:





Due to the neutrinos involved in the decay, the experimental signature is missing transverse energy. The lepton mass is found to be $M_L > 20.6$ GeV.
An interesting type of lepton is encountered when the neutral partner is heavier than the charged one. In this case the charged lepton has to be stable and would look like a heavy muon. Because this is not seen, one concludes that $M_{L^0} > M_{L^-} > 16.6$ GeV.
A neutral heavy lepton can only be produced via weak interactions:





In this case there are also neutrinos involved and the process is characterized by missing transverse energy. The mass limits depend on the assumed weak coupling, and one obtains $M_{E^0} > 22.5$ GeV for (V-A) and > 24.5 GeV for (V+A).
A virtual excited electron e* would modify the cross section of the standard QED process $e^+e^- \to \gamma\gamma$. From the agreement with QED it follows that $M_{e^*}/\sqrt{\lambda} > 61$ GeV, where λ is the relative coupling strength of the new type of current involved.

An excited muon μ^* could be produced in pairs, or singly in conjunction with a normal muon, and would decay into a μ by emitting a photon. No such signature has been observed and therefore $M_{\mu^*} > 17.9$ GeV.

Scalar particles, like charged Higgs mesons or technipions, have been addressed[28] as the key to our understanding of symmetry breaking. If the Higgs is heavy, it decays preferentially into heavy quarks and leptons:

$$\begin{array}{l} e^+e^- \to H^+H^- \\ \qquad\quad |\ \hookrightarrow \bar{c}s,\ \bar{c}b,\ \bar{\tau}\,\bar{\nu} \\ \qquad\quad \hookrightarrow c\bar{s},\ c\bar{b},\ \tau^+\nu \end{array}$$

However, the relative branching fractions are not known. The experimental situation is illustrated in Fig. 9. A detailed discussion of the signatures has been given at a recent conference[27]. Essentially, low masses are excluded by CLEO's analysis of b decays, and higher masses are excluded by PEP and PETRA experiments. Except for small $\tau\nu$ branching ratios and masses between 13 and 16 GeV, the Higgs mass has to be $M_{H^\pm} > 16$ GeV.

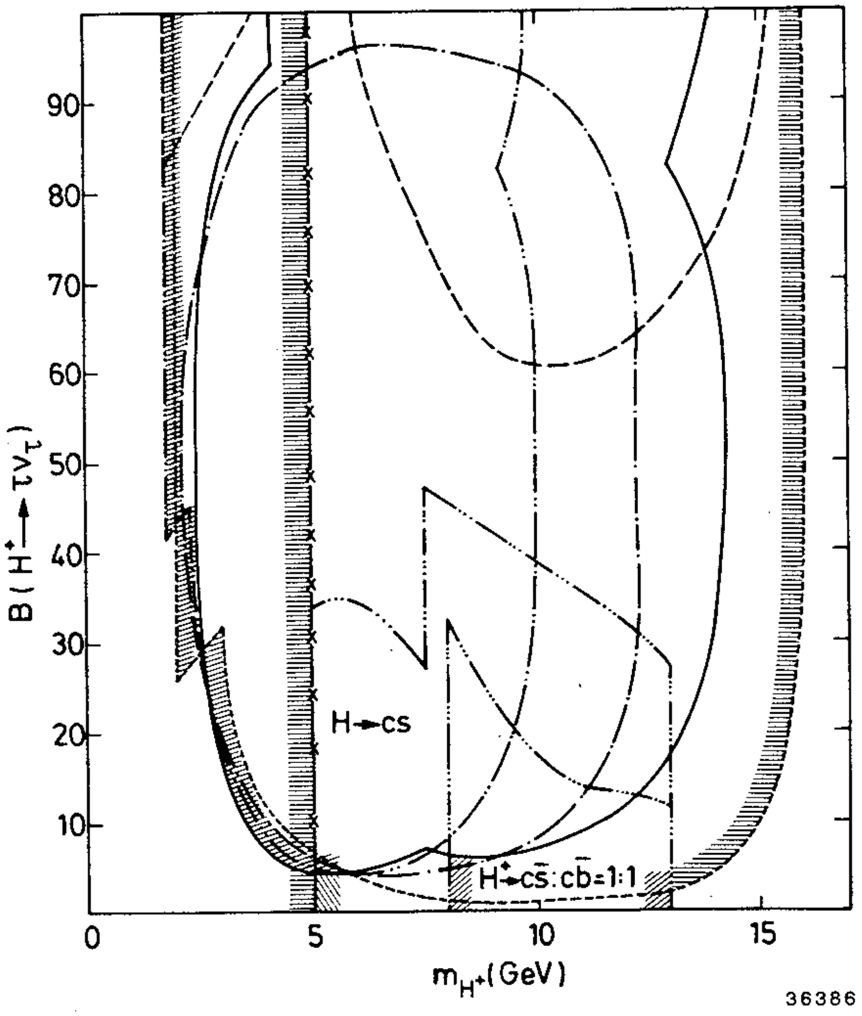


Fig.9: Limits on mass and branching ratio into $\tau\nu_\tau$ for technipion or $H^\pm$ (95 % C.L.)
CELLO---,CLEO—x—,JADE——,MAC—-—-,
MARK J-------,MARK II (90%C.L.)—·—·—,TASSO—··—

Supersymmetry is of theoretical beauty and elegance[29], but it does not enjoy any experimental support so far. Each particle is postulated to have a supersymmetric partner with a spin different by half a unit. For leptons and quarks there are scalar leptons $\tilde{\ell}$ (sleptons) and scalar quarks $\tilde{q}$ (squarks), and for the photon there is the photino $\tilde{\gamma}$. Since no partners are observed at the same masses as normal particles, supersymmetry must be broken, but one does not know whether the mass breaking scale is $M_S \simeq 100$ GeV or $\gtrsim 10$ TeV. Supersymmetric particles are pair-produced and decay by conserving the supercurrent, i.e. the lightest supersymmetric particle is stable. However, it is not clear whether the photino, goldstino, or gravitino is lightest. Since the theory does not fix any masses, there is a wide choice of particle lifetimes and decay characteristics. Consequently the experimental search$^{27)}$ for such objects is bound to be very model dependent. If the photino is not the lightest supersymmetry particle, one may look for its decay into a photon, accompanied by an invisible gravitino. Since the photino lifetime depends on the mass breaking scale: $\tau_{\tilde{\gamma}} = 8\pi M_S^4/M_{\tilde{\gamma}}^5$, experiments at PETRA can exclude the mass range between 90 MeV and 17 GeV if $M_S = 100$ GeV. However, photino masses are only excluded from 2 to 17 GeV if $M_S = 10$ TeV. Without going into any further details$^{27)}$, the following limits on sleptons are quoted: $M_{\tilde{e}} > 17.8$ GeV, $M_{\tilde{\mu}} > 18$ GeV, and $M_{\tilde{\tau}} > 16.5$ GeV. Squarks have to be searched for in hadron fragments, and, under special assumptions$^{27)}$ a mass range between 2.5 and 14 GeV can be excluded. At present, the most sensitive test$^{30)}$ for or against supersymmetry seems to be whether or not a stable or decaying photino is found in the mass range up to 10 or 20 GeV.

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