SEARCH FOR A "TOP" THRESHOLD IN HADRONIC e^+e^- ANNIHILATION AT ENERGIES BETWEEN 22 AND 31.6 GeV

PLUTO Collaboration

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Results on e^+e^- annihilation into hadrons at c.m. energies between 22 and 31.6 GeV are presented. The data were accumulated with the PLUTO detector at PETRA. The events are dominantly of the two-jet type. The value of the relative hadronic cross section $R = 3.88 \pm 0.22$ along with the details of the sphericity and thrust distribution rule out an open $(t\bar{t})$ channel ($Q_t = 2/3$) below 30 GeV. The inclusive muon results support the above conclusion.

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The higher energies now available at the e^+e^- storage ring PETRA at DESY allow a search for the heavier quark flavours which have been conjectured for some time. The charm and bottom quarks have been established via the $(c\bar{c})$ and $(b\bar{b})$ bound states as well as the detailed study of charmed mesons [1]. The natural extension would be to search for the top quark ($Q = 2/3$) via a narrow $(t\bar{t})$ bound state. Such a procedure would of course need considerable time due to the large energy range to be covered and the low rates at these energies. Instead, one can adopt a faster procedure and try to find a jump in the relative hadronic cross section $R = (\sigma^{had}/\sigma^{\mu\mu})$ as a first indicator for new open channels containing the top quark [‡1]. Above and near to the threshold, the event topologies characterised by sphericity and thrust should also show significant differences relative to those below the threshold [3]. Another indicator of contributions from a top quark would be an enhanced rate of production of leptons in association with hadrons [4].

We have accumulated data with the PLUTO detector [5] at PETRA at c.m. energies around 22, 27.6, 30 and 31.6 GeV. The main components of the detector are:

(A) A central detector with 13 cylindrical proportional chambers operating in a magnetic field of 1.65 T. The momentum resolution for charged tracks is $\sigma_p/p = 3\% p$ (p in GeV/c) for $p > 3$ GeV/c.

(B) Barrel and endcap shower counters with proportional tubes for position measurement of the showers. The energy resolution for electrons and photons with energy $E > 1$ GeV/c is $\sigma_E/E \sim 35\%/\sqrt{E}$ in the barrel and $\sim 19\%/\sqrt{E}$ in the endcaps. The geometrical acceptance of (A) and (B) is 87% and 94% of 4π sr.

(C) A muon identifier with a 1 m iron absorber for hadrons. The tracks are sampled at two depths within the absorber by a set of proportional and drift chambers.

(D) Small angle ($1.3° < \theta < 4°$) and large angle ($4° < \theta < 15°$) tagging counters (SAT and LAT) for luminosity measurements.

The trigger conditions are similar to those used at 13 and 17 GeV [5]. The allowed event configurations are any one (or more) of the following:

(1) two coplanar tracks with a noncoplanarity angle $< 6°$ in the central detector,

(2) $\geqslant 3$ tracks,

(3) $\geqslant 6$ GeV energy deposition in the barrel and/or endcap shower counters,

(4) $\geqslant 4$ GeV in LAT and SAT,

(5) $\geqslant 1$ track in the central detector and $\geqslant 1.5$ GeV on each side of LAT/SAT or $\geqslant 4$ GeV on one side.

The integrated luminosities at the different energies are given in table 1. The values have been corrected for radiative losses. The luminosities determined from SAT/LAT and the wider angle Bhabha scatters detected in the inner detector agree within the quoted errors. The hadronic events from e^+e^- annihilation via one-photon exchange are selected when all the following criteria are satisfied:

(a) $\geqslant 2$ noncoplanar ($\Delta\phi < 150°$) charged tracks in the inner detector,

(b) $\geqslant 2$ tracks with distances < 20 mm from the beam axis and < 50 mm from the interaction point when measured along the beam,

(c) an observed total energy (charged + neutrals) $> 0.5\, E_{cm}$.

The sample of events so obtained is given in table 1. A visual scan of the events show a dominant two-jet character at all the energies considered here.

The observed events have a non-negligible contribution from two-photon annihilation processes. To estimate this contribution a Monte Carlo program incorporating a Weizsäcker–Williams approximation for the virtual photon energy distribution is used. The hadronic system is generated from a multi-pion phase space with transverse momentum damping. The transverse momentum relative to the direction of motion of the c.m. is assumed to be limited to 300 MeV/c. The mean multiplicity was taken from photoproduction data at the corresponding c.m. energy (W). The $\gamma\gamma$ cross section is assumed constant above the energy cut imposed on the data. Selection criteria for hadronic events as mentioned above are then imposed and the contribution from the two-photon process is estimated. These estimates are listed in table 1.

The relative contribution from $\tau^+\tau^-$ pair production based on the prong number and neutral energy distribution for these events has also been estimated (table 1).

[‡1] Throughout this letter we specifically refer to the top quark in the framework of the six quark model (see ref. [2]).

Table 1
Relative hadronic cross section $R = (\sigma^{\mathrm{had}}/\sigma^{\mu\mu})$ at specified e^+e^- c.m. energies. Background subtraction, correction for initial state radiation and τ subtraction are incorporated.

E_{cm} (GeV)	$\mathcal{L} = \int L\, dt$ [a] (nb^{-1})	N_{had} observed	ϵ	Expected background		Radiative corrections	R [b]
				$N(2\gamma)$	$N'(\tau^+\tau^-)$	δ	
22.0	47± 5	29	0.86	0.8	0.7	0.1	3.41±0.73
27.6 [c]	408±15	169	0.84	7.0	3.9	0.1	3.64±0.31
30.0	561±19	227	0.81	9.4	4.2	0.1	4.38±0.37
31.6	219±13	66	0.80	3.7	1.5	0.1	3.59±0.52
d)	1188±27	462	0.82	20.1	9.6	0.1	3.88±0.22

a) Luminosity values as determined from the central shower counters. The errors shown are statistical. There is an additional systematic error of 5%.
b) $R = (E^2_{\mathrm{cm}}/87\mathcal{L})\,[(N_{\mathrm{had}} - N_{2\gamma})/\epsilon - N'_{\tau^+\tau^-}\,]/(1+\delta)$, ϵ = detection efficiency, $N'_{\tau^+\tau^-} = N_{\tau^+\tau^-}/\epsilon_\tau$.
c) Data from 27.4 and 27.8 GeV.
d) Data from 27.6, 30.0 and 31.6 GeV combined.

In addition there is a small but finite contribution from beam–gas interactions. This background is subtracted on a statistical basis using the observed number of events in regions adjacent to the allowed range in Z, the vertex distance from the beam–beam interaction point as measured along the beams.

A Monte Carlo procedure based on the Field–Feynman [6] jet fragmentation model is used to account for the detector acceptance as well as to compare the observed with the expected distributions of the jet parameters. The program ‡2 incorporates u,d, s,c,b (and t) quarks ‡3. Corrections to the acceptance due to radiation from the initial state have been included. The events so generated are tracked through the detector thereby folding in the acceptances and resolution of our detector as well as the cuts imposed. The systematic uncertainty in the detection efficiency is estimated to be $< 7\%$.

Applying the corrections for the various contributions and the radiative correction we obtain for the relative hadronic cross section R the values listed in table 1. Fig. 1 shows the dependence of R on c.m. energy as observed in the PLUTO detector. The errors shown are statistical. The systematic errors of the full points are estimated to be ≈10%. The value of $R = 3.88 \pm 0.22$ for the combined data from 27.6, 30, and 31.6 GeV agrees well with the expected value of 3.9 obtained from u,d,s,c,b quarks and first-order QCD ‡4 effects, and is clearly below the expectations including a charge 2/3 top quark (dotted line in fig. 1).

‡2 Program from H.G. Sanders and T. Meyer. We thank them for their event generator.

‡3 For u,d,s quarks we use the fragmentation function $f(\eta) = 1 - A + 3A\eta^2$ with $A = 0.77$; for c,b (t) quarks $f(\eta)$ = constant; $\eta = 1 - z$ and $z = p_{\mathrm{H}}/p_{\mathrm{q}}$, where p_{H} and p_{q} are the momentum of the primary meson and the quark, respectively [3,6]. The transverse momentum distribution for the quarks is assumed to be $\sim \exp(-q_\perp^2/2\sigma_q^2)$ with $\sigma_q = 247.5$ MeV/c. The decays of known primary mesons with only u,d,s,c quarks are taken from the particle data tables [7]. The decays of the bottom and top mesons are from refs. [4,8].

‡4 $R_{\mathrm{expec}} = 3\Sigma Q_i^2(1 + \alpha(s)/\pi)$; $\alpha(s) = 12\pi\{(33 - 2N_f)\ln(s/\Lambda^2)\}^{-1}$; $\Lambda = 0.5$ GeV.

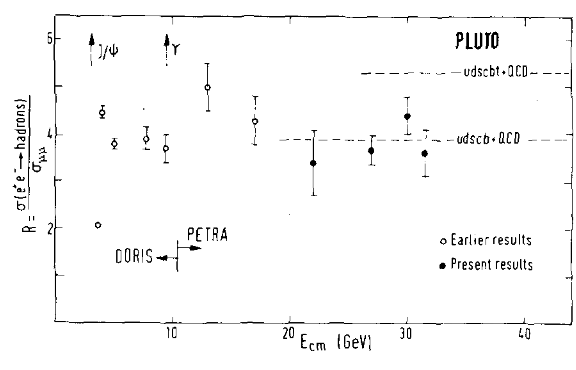

Fig. 1. Corrected values of $R = \sigma^{\mathrm{had}}/\sigma^{\mu\mu}$ from the one-photon process at various e^+e^- c.m. energies. Initial state radiative corrections along with subtraction of the τ and two-photon contributions are included.

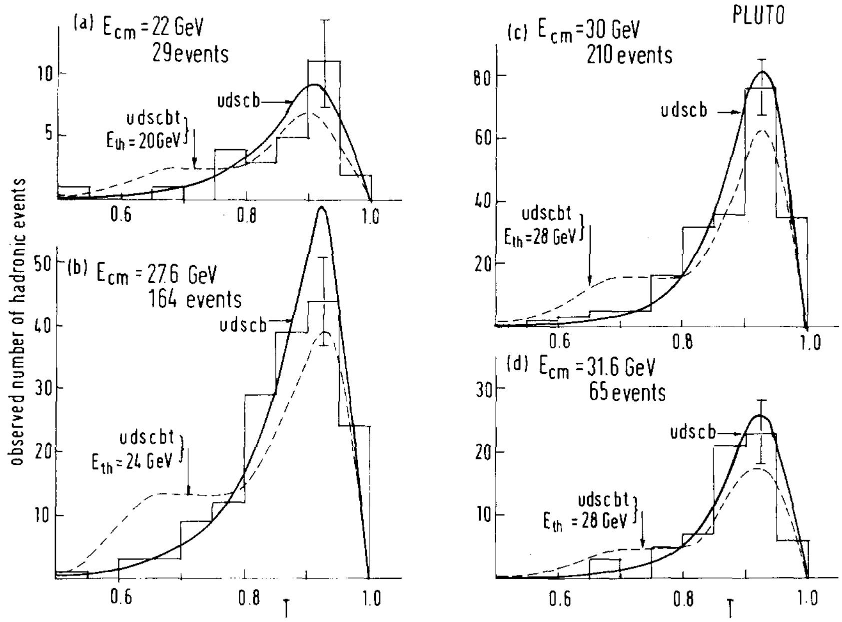

Fig. 2. (a) – (d) Detailed thrust distributions at the specified c.m. energies. Expectations from u,d,s,c,b (——) and u,d,s,c,b,t (– – –) quarks with specified energy thresholds (E_{th}) for the "top" states are shown.

The topological details of the hadronic events provide an independent evidence for the presence of any new flavour threshold. To study the jet characteristics we restrict the sample to events with $\geqslant 4$ prongs. The sphericity or thrust for each event is determined in the usual way by finding an axis which leads to the quantity $S = \frac{3}{2}\min(\Sigma p_{\perp i}^2/\Sigma p_i^2)$ or $T = \max(\Sigma |p_{\parallel i}| / \Sigma |p_i|)$, respectively. Both neutral and charged particles have been used to determine the sphericity or thrust. The observed mean values of $(1-T)$ and S decrease continuously with increasing energy as expected from a dominant two-jet production. Since these mean values are just the first moments of the respective distributions they are not sensitive enough to check for additional contributions from a top quark.

Figs. 2a–d show the observed distributions of the thrust T at the different energies. Since thrust and sphericity are equivalent we show only the detailed thrust distributions. The expectations from the two-jet u,d,s,c,b Monte Carlo computations without (solid) and with (dotted) the top quark are also shown. The computations assume the top threshold to open approximately 2 GeV below the c.m. energy at which the data were taken. A massive top quark would contribute significantly in the region of low thrust. The observed distributions do not show the expected low thrust enhancement at any of our energies. Table 2 gives the observed number of events in the low thrust ($T < 0.8$) region along with the expectations. Also given are the observed and expected ratio of the number of events with T below and above 0.8. The observed values are consistent with the two-jet model with only u,d,s,c,b quarks and rule out a "top" threshold below 30 GeV. The discrimination against a top quark contribution is fairly independent of the details of the jet model. In particular, we have checked that a jet broadening of as much as 40% (increased σ_q) or the inclusion of final state hard gluons expected from QCD do not alter our conclusions.

The same hadronic event sample has also been used to study the inclusive muons as seen in the muon identifier. In order to reduce the background from punch through hadrons we demand a minimum momentum of 2 GeV/c for the associated muons. The number of events with an associated muon and the expectations without and with a top quark are given in table 3. These expectations are calculated [4] under the assumption of a cascade decay for the heavy quarks ($t \to b \to c \to d$) with a 10% branching ratio into muons at each step. The data in the energy range

Table 2.
Comparison of the integral number of hadronic events observed at low and high thrust with expectations from u,d,s,c,b and u,d,s,c,b,t quarks.

E_{cm}	$N_{had}(T < 0.8)$			$N_{had}(T < 0.8)/N_{had}(T > 0.8)$		
(GeV)	observed	expected		observed	expected	
		udscb	udscbt		udscb	udscbt
22.0	6	5.8	10.4	0.29±0.12	0.25	0.56
27.6	28	21.6	57.4	0.21±0.04	0.15	0.54
30.0	31	19.5	61.5	0.17±0.04	0.10	0.41
31.6	8	4.5	18.9	0.14±0.05	0.07	0.41

Table 3
Comparison of inclusive muon signal with expectations from u,d,s,c,b and u,d,s,c,b,t quarks.

E_{cm} (GeV)	No. of events with a muon ($p > 2$ GeV/c)	Computed back-ground	Corrected signal	Expected	
				udscb	udscbt
27.6	7	2.9±0.8	4.1±2.7	4.7	14.6
30.0	8	4.1±1.2	3.9±3.1	5.1	15.9
31.6	2	1.7±0.5	0.3±1.5	1.7	5.3
total	17	8.7±2.6	8.3±4.9	11.5	35.8

27.6 to 31.6 GeV agree well with the expectations for u,d,s,c,b quarks and are significantly ($\sim$ 5.6 stand. dev.) below the values when top quark states are included.

In conclusion, the value of R, the distributions in thrust and sphericity, and the data on inclusive muons exclude an open channel due to a charge 2/3 top quark at c.m. energies below 30 GeV. The statistical limitations of the present data do not allow any conclusions regarding a charge 1/3 quark heavier than the b quark. The relevance of the present data in regard to hard gluon bremsstrahlung will be presented in the following letter.

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