ARE THERE HEAVY QUARKS OF MASS 23 GeV?

F CORNET [a,1], E W N GLOVER [b], K HAGIWARA [a], A D MARTIN [c] and D ZEPPENFELD [a]

[a] DESY, Theory Group, D-2000 Hamburg 52, Fed Rep Germany
[b] Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK
[c] Physics Department, University of Durham, Durham DH1 3LE, UK

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An excess of events with an isolated muon and low thrust observed by the MARK-J collaboration at the highest PETRA energy $\sqrt{s} \simeq 46.7$ GeV, is found to be consistent with the near threshold production of heavy quarks of charge $-1/3$. A natural candidate is a fourth-generation "down" quark or, possibly, a member of a 27 representation of E_6. Signatures of such heavy quark pair production at the CERN $p\bar{p}$ collider are investigated and it is concluded that the present data have a chance to confirm the signal.

Recently the MARK-J collaboration have reported [1] events with isolated muons and a broad energy flow at the highest accessible energy (46.30 GeV $< \sqrt{s} < 46.78$ GeV) of e^+e^- collisions at PETRA. They observed eight events with low thrust [2] values ($T < 0.8$) and a muon, whereas at most 1.9 events are expected from an extrapolation of their lower-energy data taken at 36.9 GeV $< \sqrt{s} < 46.3$ GeV. None of the other experiments at PETRA have been able to confirm or to reject these events [‡1], and with the recent modifications PETRA is no longer able to reach 46 GeV. Our main purpose is to examine whether the CERN $\bar{p}p$ collider data can confirm or eliminate possible interpretations of these events.

The main features of the eight MARK-J events are [1]: (1) the muons have low momentum (in the range 2 to 5 GeV) with the exception of one very energetic muon of 16 ± 5 GeV, (2) one event has two muons (of 4.5 and 2.2 GeV), (3) eight of the nine observed muons are well isolated, satisfying $|\cos\delta| < 0.7$, where δ is the opening angle between the muon momentum and the thrust axis (whereas for $T < 0.8$, $|\cos\delta| < 0.7$ only 0.5 muons are predicted from the lower energy data), (4) the missing energy is about 10% to at most 20% of the total energy.

Events with broad energy flow and isolated muons suggest heavy quark pair production. Suppose we assume a top-quark mass of 23 GeV so that the open top threshold lies in the highest-energy bin, then we expect the $n\,{}^3S_1$ toponium states ($n = 1, 2, \ldots$) at lower energies. To calculate the $n\,{}^3S_1 \to e^+e^-$ decay widths, $\Gamma_{ee}(nS)$, we use the QCD-motivated potential of ref. [4], which reproduces the observed $c\bar{c}$ and $b\bar{b}$ data including the leptonic widths. We find

$$M(1S) = 45.1 \pm 0.3\ \text{GeV},$$
$$\Gamma_{ee}(1S) = 3.3 \pm 0.8\ \text{keV},$$
$$M(2S) - M(1S) = 0.59 \pm 0.05\ \text{GeV},$$
$$\Gamma_{ee}(2S) = 1.5 \pm 0.2\ \text{keV},$$
$$M(3S) - M(1S) = 0.92 \pm 0.05\ \text{GeV},$$
$$\Gamma_{ee}(3S) = 0.9 \pm 0.1\ \text{keV}, \qquad (1)$$

where the errors correspond to the uncertainty in the short-distance potential arising from changing the QCD mass scale, $\Lambda_{\overline{MS}}$, from 0.1 to 0.4 GeV. The comparison of (1) with the 95% confidence limit [3,1]

$$\Gamma(\theta \to e^+e^-)\,B(\theta \to \text{hadrons}) < 1.9\ \text{keV}$$
$$\text{for } \sqrt{s} < 46.78\ \text{GeV} \qquad (2)$$

[1] On leave from Departamento de Fisica Teorica, Universidad Autonoma de Barcelona, Barcelona 28, Spain.
[‡1] For a recent review see e.g. ref. [3].

for a new resonance θ produced at PETRA, makes the presence of a top quark of mass 23 GeV rather unlikely

Another possibility is that the MARK-J events could be due to $L\bar{L}$ production, where L is a fourth-generation charged lepton (of mass 23 GeV) with decay branching fractions

$$B(L \to \nu_L \ell \bar{\nu}_\ell) \simeq 0.11 ,$$

$$B(L \to \nu_L s\bar{c}) \simeq B(L \to \nu_L d\bar{u}) \simeq 0.33 \qquad (3)$$

Detailed decay calculations [5] show that $L\bar{L}$ events with primary decay muons ($L \to \mu$) have on average 50% missing energy and muon momentum of about 8 GeV Events with secondary muons ($L \to c \to \mu$ and $L \to \tau \to \mu$) occur at $3B(c \to \mu) + B(\tau \to \mu) \simeq 0.5$ times the primary muon rate and have about 40% missing energy and average muon momentum of about 3 GeV The observed missing energy is much smaller than that for $L\bar{L}$ events, and this alone excludes a sequential heavy lepton as an explanation of the MARK-J events

Now the experimental bound, eq (2), does not rule out bound states of a charge $-1/3$ heavy quark Possible candidates are either a fourth-generation weak-isospin down quark (which we call v quark [6]) or a weak singlet, colour triplet quark (the h quark), which together with $\bar{h}$ and a family of 15 known fermions, belongs to the 27 representation [‡2] of the E_6 gauge group The latter possibility has recently received great attention due to the advent of anomaly-free superstring theories [8] (the first serious candidates for the theory of quantum gravity) which predict E_6 as the most promising grand unification group

Assuming a continuation of the observed trend of smaller mixing between generations as the generation number increases, then the v quark dominantly decays into a charmed quark and a virtual W boson Thus the branching fractions are predicted to be

$$B(v \to c\ell\bar{\nu}_\ell) \simeq 0.11 ,$$

$$B(v \to c\bar{u}d) \simeq B(v \to c\bar{c}s) \simeq 0.33 , \qquad (4)$$

with $\ell = e, \mu, \tau$ On the other hand the h quark, being an $SU(2)_L$ singlet, can only decay through mixing with the d quark To maintain weak universality the mixing must be small, giving [9]

‡2 For a review see e g ref [7]

$$B(h \to \text{hadrons}) \simeq 0.66 , \quad B(h \to u\ell\bar{\nu}_\ell) \simeq 0.08 , \qquad (5)$$

$$B(h \to d\nu_\ell\bar{\nu}) \simeq 0.02 , \quad B(h \to d\ell\bar{\ell}) \simeq 0.01 \qquad (5)$$

Note that the $v\bar{v}$ and $h\bar{h}$ production cross sections are equal for quarks of the same mass up to small Z-boson contributions at PETRA energies, and that $B(v \to c\mu\bar{\nu}_\mu) \simeq B(h \to u\mu\bar{\nu}_\mu)$ If the h quark has a larger mixing to the s or b quark than to the d quark, then $h \to c\mu\bar{\nu}_\mu$ and the muon spectrum (including secondary as well as primary decays) arising from $h\bar{h}$ and $v\bar{v}$ production would be very similar Therefore most of the discussion presented below for the v quark applies equally well to the h quark

For $v\bar{v}$ events the muons arising from secondary decays ($v \to c \to \mu$ and $v \to \tau \to \mu$) occur at $12B(c \to \mu) + B(\tau \to \mu) \simeq 1.6$ times the rate of events with primary decay muons ($v \to \mu$) Moreover the missing energy is small, being on average about 15% for events with a primary muon and much less for those containing a secondary muon The muon-momentum distributions arising from primary and secondary decays of V mesons are shown in fig 1 for $e^+e^- \to v\bar{v}$ at $\sqrt{s} = 46.6$ GeV with $m_v = 23$ GeV The curves are obtained using the $V - A$ matrix elements for v decays, the charm quark fragmentation function of ref [10] with $\epsilon = 0.2$, and the collinear approximation for the secondary decays, which although not strictly valid

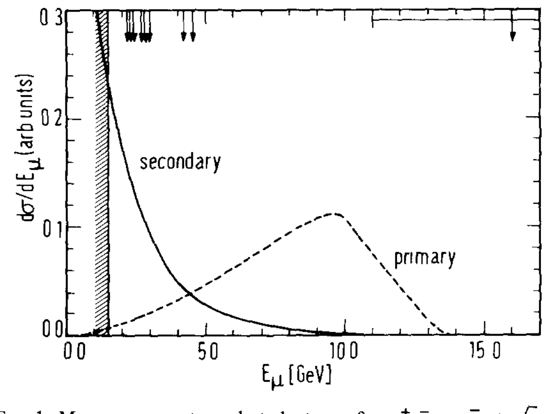

Fig 1 Muon-momentum distributions for $e^+e^- \to v\bar{v}$ at $\sqrt{s} = 46.6$ GeV arising from primary decays ($v \to \mu$) and from secondary decays ($v \to c \to \mu$ and $v \to \tau \to \mu$) with $m_V = 23$ GeV The arrows indicate the momenta of the nine muons observed by the MARK-J collaboration [1], the detection efficiency depends on the muon momentum and, in fact, muons below 1 5 GeV cannot be detected (shaded region) [1]

for low-momentum muons should give a reasonable guide to the distribution No acceptance corrections have been made The momenta of the observed muons are indicated by arrows at the top of fig 1, and have large experimental uncertainties The three highest-momentum muons can be seen in the cos $\theta-\phi$ "Lego" plot [1] to be relatively more isolated from hadronic activity and may be attributed to primary muons Approximately half of the $v\bar{v}$ events are expexted to contain muons and the eight observed events correspond to a $v\bar{v}$ production cross section of about 0 15 in units of $\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)$, which is consistent with the expectations of a charge $-1/3$ quark in the resonance region

Since the isolated muon events observed by the MARK-J collaboration appear consistent with the production and decay of charge $-1/3$ quarks, it is important to study $v\bar{v}$ production at the CERN $p\bar{p}$ collider The production cross section due to QCD fusion subprocesses ($q\bar{q} \to v\bar{v}$ and $gg \to v\bar{v}$) is about 6 6 nb at $\sqrt{s}$ = 630 GeV using the parton distributions of Duke and Owens (set I) [11], and that via an intermediate Z boson ($Z \to v\bar{v}$) is predicted to be 0 16 nb The best signatures of these events are the isolated electrons or muons from the semileptonic decays $v \to c\ell\bar{\nu}_\ell$ Primary-decay leptons from heavy quarks have a much better chance of being well isolated from accompanying hadronic debris than the leptons from b or c decys We calculate the primary-decay lepton and accompanying jet distributions assuming that the v quarks fragment into unpolarized (V) mesons, using a heavy quark (Q) fragmentation function of the form of ref [10] with $\epsilon_Q = 0\ 5/m_Q^2$ in units of GeV, and that the V and $\bar{V}$ mesons then decay with bare $V - A$ matrix elements The momenta of the final decay products contribute to jet formation We impose acceptance cuts in order to approximately simulate the UA1 lepton-isolation and jet-acceptance criteria used in their top-quark search [12 13] Namely, for the electron + jets events we require (i) that the electron transverse momentum $p_T > 15$ GeV, (ii) that the transverse energy deposited in a cone around the electron track given by $\Delta R \equiv [(\Delta\phi)^2 + (\Delta\eta)^2]^{1/2} < 0\ 7$ should be less than 10% of the electron energy, (iii) that the transverse energy in a similar cone with $\Delta R < 0\ 4$ be less than 1 GeV, (iv) that hadronic energies (final decay momenta) be combined if two adjacent momenta satisfy $\Delta R < 1$, and (v) that hadronic energies be accepted as jets if their transverse momenta $p_T(\text{jet}) > 10$ GeV and rapidity $|\eta(\text{jet})| < 2\ 5$ For mass 23 GeV quarks we expect the (electron + n jet) contributions to be sensitive to the efficiency of identifying low-p_T jets, and to examine this effect we repeated the calculations using $p_T(\text{jet}) > 8$ GeV

We show in table 1 the cross sections calculated, using the above criteria, for events containing a single isolated electron plus n jets arising from the decay of v quarks (of mass 23 GeV) and from the decay of t quarks (of mass 40 GeV) produced in $p\bar{p}$ collisions at $\sqrt{s}$ = 630 GeV Contributions to v production via a W boson, and $Z \to t\bar{t}$, are small and are not shown There are several sources of uncertainty in these predictions coming from possible effects of parton-fragmentation and of spectator-jet contributions, from higher-order QCD effects, and from the choice of structure functions and of α_s Nevertheless the results

Table 1
The lepton plus n-jet cross sections (in pbs) for v-quark (23 GeV) and t-quark (40 GeV) production in $p\bar{p}$ collisions at $\sqrt{s}$ = 630 GeV using the lepton-isolation and jet-acceptance criteria described in the text The cross sections correspond to $p_T(\text{jet}) > 10$ GeV, with those for $p_T(\text{jet}) > 8$ GeV in parentheses The cross sections for W and Z initiated events are normalized to $\sigma(W^+ + W^-)$ = 5 3 nb and $\sigma(Z)$ = 1 6 nb [14]

Subprocesses	$\sigma(e + n\text{ jets})$ pbs			
	$n = 0$	$n = 1$	$n = 2$	$n = 3$
$(gg, q\bar{q}) \to v\bar{v}$	1 8 (0 6)	48 5 (33 9)	19 0 (31 6)	2 6 (6 7)
$Z \to v\bar{v}$	– –	1 9 (1 2)	1 6 (2 0)	0 3 (0 7)
$(gg, q\bar{q}) \to t\bar{t}$	0 1 –	2 7 (1 2)	7 8 (6 6)	4 5 (6 6)
$W \to (t\bar{b}, \bar{t}b)$	0 5 (0 3)	11 9 (9 1)	10 1 (13 0)	– –

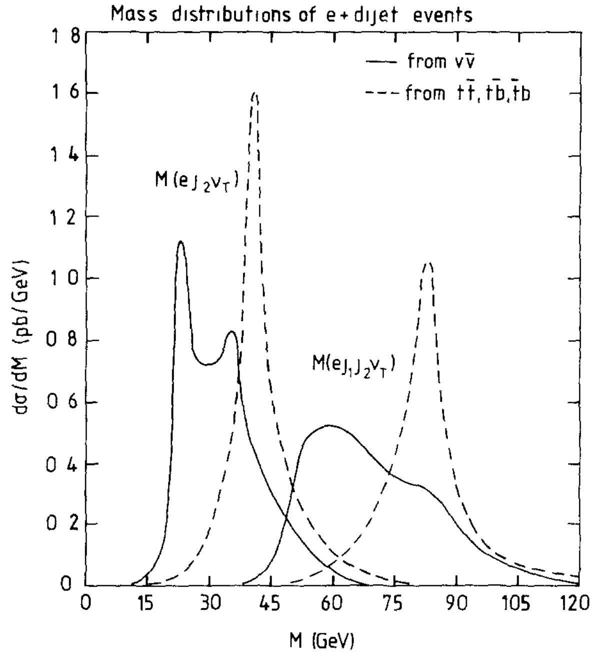

Fig 2 Invariant-mass distributions for electron + dijet events resulting from heavy-quark production in $p\bar{p}$ collisions at $\sqrt{s}$ = 630 GeV The continuous curves are the distributions from the sum over the subprocesses $q\bar{q}$, gg, Z → $v\bar{v}$ with m_v = 23 GeV, whereas the dashed curves result from $q\bar{q}$, gg → $t\bar{t}$ and W → $t\bar{b}$, $\bar{t}b$ with m_t = 40 GeV The electron-isolation and jet-acceptance criteria are applied as described in the text (jet p_T > GeV)

should give a semiquantitative guide to the expected signal

We note from table 1 that the lepton + dijet signal, used to identify the t quark, is populated approximately equally by events coming from $v\bar{v}$, and top-quark production, moreover, we find the background from $b\bar{b}$ and $b\bar{b}X$ events is negligible Fig 2 shows the $M(ej_1j_2\nu_T)$ and $M(ej_2\nu_T)$ invariant-mass distributions for the electron + dijet events Here ν_T indicates the neutrino four momentum with the (unknown) component along the beam direction set to zero, and j_2 corresponds to the jet with the lower p_T, so that for the majority of events we would expect $M(ej_2\nu_T)$ to average to the mass of the heavy quark parent The double peak in $M(ej_2\nu_T)$ shows that this is only partially true for the $v\bar{v}$ events, using the above acceptance cuts, many events have both j_1 and j_2 coming from one v-quark decay and the electron from the other

The v- and t-quark signals look quite different (cf fig 2) in our parton-model calculation, which assumes the momentum of the electron and jets can be perfectly measured In practice the distributions will be much less sharp, and less distinctive, due to various effects which we have ignored, such as jet-fragmentation and spectator-jet contributions, as well as the experimental uncertainties in resolving jets and measuring their momenta

Despite the large cross section of 6 7 nb for $v\bar{v}$ production as compared to 1 1 nb for t production, we see the v-quark signal is weaker The electron and jets from v decays have, on average, lower p_T and are much more often eliminated by (and sensitive to) the acceptance criteria, than those from t decays In view of the sensitivity of the $v\bar{v}$ signal to the detection efficiencies, and to the hadron dynamics, it is not clear if the available electron + dijet data from the $p\bar{p}$ collider can exclude quarks of mass around 23 GeB

Apart from the small difference in the semileptonic branching fractions [cf eqs (4) and (5)] and the Z-initiated contribution (which is negligible anyway), the signature for $h\bar{h}$ production should be comparable to that for $v\bar{v}$ production Events containing two isolated leptons are additional signatures for these quarks Although significant mixing in the neutral-V-meson system is not expected in any of the extrapolations of the KM matrix elements considered in ref [6], large mixing is expected among neutral mesons containing an h quark, that is in both the $(h\bar{d})$–$(\bar{h}d)$ and $(h\bar{s})$–$(\bar{h}s)$ systems, due to its direct neutral-current couplings This may lead to observable signals, such as relatively isolated like-sign dimuons at hadron colliders The h can be clearly distinguished from the v quark by its small coupling to the Z and the resulting lack of forward–backward asymmetry in e^+e^- annihilation experiments at TRISTAN energies

Note that the muon-momentum distribution of the MARK-J events suggests more muons arise from secondary than from primary decays (see fig 1) and so the h quark would have to have larger mixing to the s or b quark such that h → cX dominates over the h → uX decays

In summary, we find that the MARK-J isolated muon events at the top PETRA energy can be interpreted in terms of a charge −1/3, mass 23 GeV quark A natural condidate is a fourth-generation "down" quark (denoted by v) or, possibly, a h quark belonging to the 27 representation of E_6 We noted that $h\bar{h}$ and $v\bar{v}$ phenomenology could be very similar Since PETRA can no longer reach this energy the confirmation of the isolated muon signal must await e^+e^- collisions at TRISTAN or SLC/LEP However dedicated studies at the CERN $p\bar{p}$ collider should be able to identify a v (or h) quark of this mass We presented rates for isolated lepton + n jet events arising from $v\bar{v}$ (or $h\bar{h}$) production and compared these with those coming from $t\bar{t}$ and $t\bar{b}$ production Provided there is good identification of jets with $p_T \simeq 10$ GeV the present $p\bar{p}$ data should be able to decide if such a quark exists

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