Possible v-Quark Signatures at e^+e^- Colliders

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We describe distinctive signatures of a possible fourth-generation charge $-\frac{1}{3}$ quark v (assumed lighter than the t quark) arising from $e^+e^- \rightarrow v\bar{v}$ production, especially at the Z^0 resonance. We emphasize the special charm and topological characteristics expected from v-quark cascade decays and the possibility of $v \rightarrow b+\text{gluon}$ decays by an effective flavor-changing neutral current.

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Two of the outstanding open questions in particle physics are the systematics of quark and lepton masses and the possible existence of a fourth generation of fundamental fermions. If a fourth generation exists, it is entirely possible that the charge $-\frac{1}{3}$ quark v is not only less massive than its charge $\frac{2}{3}$ partner a but is also lighter than the t quark of the previous generation.[1-3] Interest in such a light v quark has received fresh stimulus recently from the suggestion[4] that an excess of low-thrust events containing muons, seen with low statistics at the topmost energy at the DESY e^+e^- storage ring PETRA in the Mark J and JADE experiments,[5] may be due to $e^+e^- \rightarrow v\bar{v}$ production. If this is the case, confirmation will soon be available from the Tristan e^+e^- collider and especially from the Stanford Linear Collider and the CERN e^+e^- collider LEP operating at the Z^0 resonance. In the present paper we discuss— in more detail than hitherto—the signautres of $e^+e^- \rightarrow v\bar{v}$ production, especially at the Z^0 resonance where the maximum cross section will be.

The hypothesis $m_v \leq m_t$ leads to very interesting phenomena in the weak decays of v particles. Charged-current (CC) $v \rightarrow a$ and $v \rightarrow t$ decays are kinematically forbidden; the empirical systematics of the quark mixing matrix U_{ij} then suggests[2,6] that $v \rightarrow c$ transitions dominate but are strongly suppressed with $|U_{cv}| \sim \theta_C^4$ or θ_C^5 where $\theta_C = 0.23$ is the Cabibbo angle. Flavor-changing neutral-current (FCNC) decays $v \rightarrow bX$ that proceed via virtual loops[7] are enhanced, since the relevant mixing matrix elements $U_{tv}U_{tb}^*$ and $U_{av}U_{ab}^*$ are less suppressed than U_{cv}, and also because the loop amplitudes grow with the mass of the virtual quark (t or a) in the loop. These arguments indicate the following distinctive properties: (i) The v lifetime is exceptionally long, possibly of order 10^{-13}–10^{-12} s. (ii) Almost all $v\bar{v}$ events contain at least two charm particles; about 44% (11%) of events contain 3 (4) charm particles, due to $v \rightarrow cs\bar{c}$ decays, unlike $b\bar{b}$ events where the corresponding fractions are 12% ($\frac{1}{2}$%) as a result of phase-space suppression. (iii) FCNC decays such as $v \rightarrow bg$, $v \rightarrow bq\bar{q}$ ($q = u,d,s,c,b$) may occur at observable rates.

These properties lead to new signatures for the v quark, in addition to the standard ones based on its mass ($m_v \geq 23$ GeV experimentally), electric charge, and couplings to the Z^0 boson. The signatures fall broadly into four categories—threshold effects, jet broadening, leptons, and topology; the later three have the advantage that they do not require energy scans and can be used at the Z^0 resonance.

Threshold effects.—The cross-section ratio $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ rises sharply above each new quark threshold. Far below the Z^0 resonance the rise is $\Delta R \simeq 3e_Q^2$, where e_Q is the new quark charge, but for heavy quarks we must take account of Z^0 couplings (which cause R to change with energy even for fixed quark content) and threshold factors. For practical purposes we concentrate attention on the enhancement in R at a finite 5-GeV interval above threshold, relative to R at the same energy but without the extra quark (i.e., relative to the extrapolation of R from below threshold):

$$\Delta R(E = 2m_Q + 5\text{ GeV}) = R(E, \text{with } Q) - R(E, \text{no } Q).$$

For $Q = v$ or t and various mass choices, we find the following values of ΔR [R and σ (hadrons) are shown at the same E also]:

$m(Q)$ (GeV)	$\Delta R(Q=v)$	$\Delta R(Q=t)$	R(no Q)	σ(had, no Q) (nb)
23	0.31	1.17	4.1	0.14
30	0.36	1.04	5.3	0.12
35	0.55	0.90	8.5	0.18
40	1.00	0.68	15.8	0.61

These use the standard model with $m_Z = 95$ GeV, $\sin^2\theta_W = 0.21$, and QCD corrections of order α_s.

These numbers illustrate some of the difficulties in ΔR studies; $\Delta R(v)/R$ is less than 8%; below Z^0 the cross section is very small; near Z^0 the cross section is much bigger but changes rapidly with E; for $m_Q > 35$ GeV the cases $Q = v$ and $Q = t$ are no longer dramatically different [because Z^0 couplings favor v over t, unlike photon couplings; see Fig. 1(c)].

The signal-to-background ratio $\Delta R/R$ greatly increases if one selects rather spherical events, which near threshold include most of the new physics but exclude most of the old-physics events. The degree of enhancement depends on the selection criteria. The production of $Q\bar{Q}$ states just below threshold is another signal of new-quark production.

Jet broadening.—The large energy release in v decay should dominate over fragmentation and QCD radiation in determining v-jet broadness (for $\sqrt{s} \leq m_Z$).

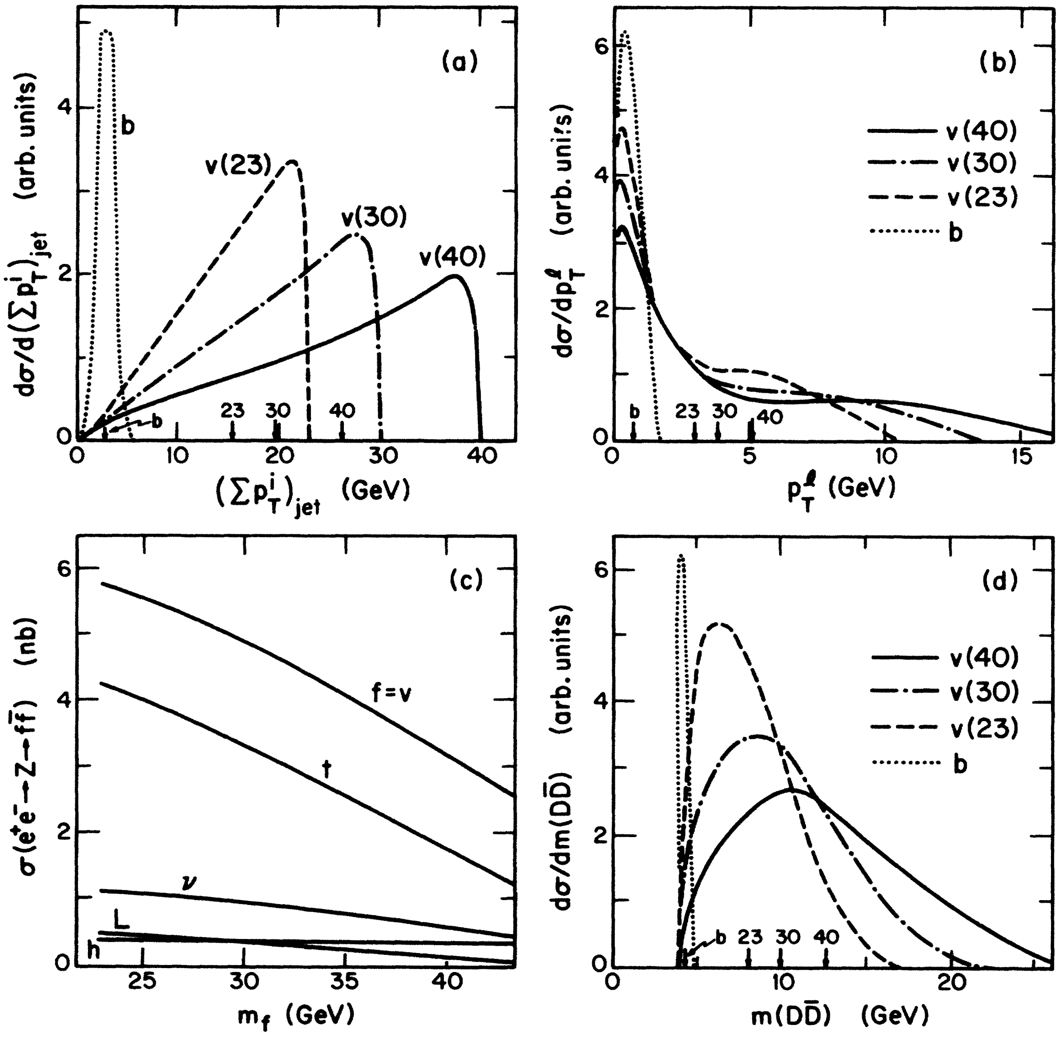

FIG. 1. Properties of $e^+e^- \to v\bar{v}$ events. (a) Distribution vs $\sum p_T^i$ transverse to the jet axis, summed over detectable particles in a v jet for $m_v = 23$, 30, and 40 GeV, compared to b jets; arrows indicate the mean values in each case. (b) Distribution vs p_T of charged leptons; charm hadrons have a different distribution but similar mean value in each case. (c) Z^0-resonance production cross section compared with other heavy fermions $f = t,h,L,\nu$; h is the isosinglet quark in the 27-plet of E_6 symmetry, suggested by superstrings; L,ν denote isodoublet heavy leptons, for which the hadronic part of the cross section ($\approx 45\%$) is shown. (d) Distribution vs invariant mass of $D\bar{D}$ pairs in a v jet.

Thus $Z \to v\bar{v}$ events would typically have low thrust; we estimate that more than 85% have $T < 0.9$ for $m_v > 23$ GeV. They would look quite unlike most $q\bar{q}$ events with lighter quarks, except for $q\bar{q} + ng$ events with additional noncollinear gluons.

Jet broadening then measures the heavy-quark mass; e.g., the sum of the momenta of the light final decay products normal to the v momentum (i.e., normal to the jet axis) is on average[8]

$$\langle \textstyle\sum_i p_T^i \rangle \simeq (\pi/4) m_v$$

from decay kinematics for spinless or unpolarized v hadrons with mass m_v. In practice, missing neutrinos reduce the sum a little. Figure 1(a) shows the distribution versus $\sum p_T^i$ for visible particles, calculated by the Monte Carlo method at the quark-lepton level for $Z \to v\bar{v}$ events including all cascade decays. We emphasize the importance of using the jet axis as a reference direction in heavy-quark tagging; distributions relative to the beam axis owe more to the angular distribution of quark production (broadly similar for all flavors) than to decay kinematics, and are therefore less distinctive.

Similarly, the transverse momenta of electrons or charm particles, produced in v decay, also reflect the energy release; see Fig. 1(b). If we choose instead momenta *transverse to a plane* containing the jet axis (e.g., components along the minor sphericity axis, to reduce the effects of additional gluons) the mean $|p_T|$ values in Fig. 1 are reduced by $2/\pi$.

It may be impossible to identify and separate the v and $\bar{v}$ jets (indeed $v \to cd\bar{u}$, etc. may appear as two or three minijets). One then takes the event thrust or sphericity axis to be the jet axis and sums both jets together.

Isolation is another aspect of jet broadening; leptons from heavy-quark decays should be more isolated from other particles than leptons from b or c decays.[9] At the Z^0 resonance, we calculate that 16%–19% of $v\bar{v}$ events would contain an electron with momentum > 10 GeV and summed energy of other detectable particles < 8 GeV within 15° relative angle. In $Z \to b\bar{b}$ $(c\bar{c})$ production, soft hadronization leads to narrow jets with nonisolated decay leptons, but hard gluon emission can lead to broader jets. We have studied this effect in $b\bar{b}g$ $(c\bar{c}g)$ final states, which are the first step in gluon shower development, and estimate that the fraction of $Z \to b\bar{b}$ $(c\bar{c})$ events with a correspondingly isolated electron is about 1% $(< 0.1\%)$.

Charm particles from v decays are less isolated than leptons, because of accompanying fragmentation products. Nevertheless, here too one can establish quantitative differences. We calculate that 21%–24% of $Z \to v\bar{v}$ events would contain a charm particle with energy > 5 GeV accompanied by less than 10 GeV of other particles within 15°; this compares with 2% (1%) for $b\bar{b}$ $(c\bar{c})$ events.,

If $Z \to v\bar{v}$ events are identified and m_v is measured via jet broadening, the total $e^+e^- \to Z^0 \to v\bar{v}$ cross section gives another signature and cross-check; see Fig. 1(c).

Leptons.—Charged leptons or missing neutrinos from semileptonic decays are popular tags for heavy flavors. At the Z^0 resonance, the addition of $Z \to v\bar{v}$ production would raise the mean number of electrons per hadronic event from 0.14 to 0.20 (0.17) for $m_v = 23$ (40) GeV. The distinctive properties of the $v\bar{v}$ leptons are that they are more isolated and have larger p_T relative to the jet axis (already discussed).

Missing total energy or p_T transverse to the jet axis are hard to measure well. Missing p_T transverse to the beam axis is measurable but less distinctive (as already remarked).

Multilepton modes are also interesting but we do not pursue them here. The special[10] dilepton mode $v \to \psi X \to l\bar{l}X$ should have even smaller branching fraction than the corresponding b decay $(B \sim 10^{-3})$ from phase-space considerations.

Topology.—Microvertex detectors should be able to identify decay vertices in many $Z \to v\bar{v}$ events. The most interesting are the primary v-decay vertices. A lifetime as long as $\tau_v = 10^{-12}$ s is quite conceivable[2]; with this value, the mean decay length for mass 23 (40) GeV would be 540 (190) μm, well within the range of planned detectors; even for a lifetime 10^{-13} s, such vertices should be resolvable. Such a massive decay with such a long lifetime would provide a remarkable and unique signature.

Almost every v decay has a secondary charm particle and about $\frac{1}{3}$ have two (from $v \to c\bar{c}s$ modes), fragmenting mostly to D mesons with observable decay lengths. The $D\bar{D}$ invariant mass usually exceeds that from b decays (where $D\bar{D}$ modes are anyway kinematically suppressed by a factor 0.2), providing a signature and a measure of m_v: see Fig. 1(d). If the v or $\bar{v}$ decay vertex is not resolved (leaving ambiguity between D mesons from different vertices), one can take the minimum $D\bar{D}$ invariant mass with similar results. There are similar signatures from $v \to c\tau\bar{v}$ decays.

Top hadrons can also give $D\bar{D}$ pairs, but with the important addition of a b hadron in the decay chain; this distinguishes them topologically[11] and also makes one of the D mesons less isolated.

Certain FCNC decays have characteristic event topologies on a macroscopic scale. The dominant decay via an effective FCNC would be $v \to b + g$. We follow here the analogous calculation for $b \to s + g$ of Eilam.[7] Thus

$$\Gamma(v \to b + g) = \frac{\alpha_s G_F^2 m_v^5}{32\pi^4} \left| \sum_i U_{ib} U_{iv}^* F_i \right|^2 ,$$

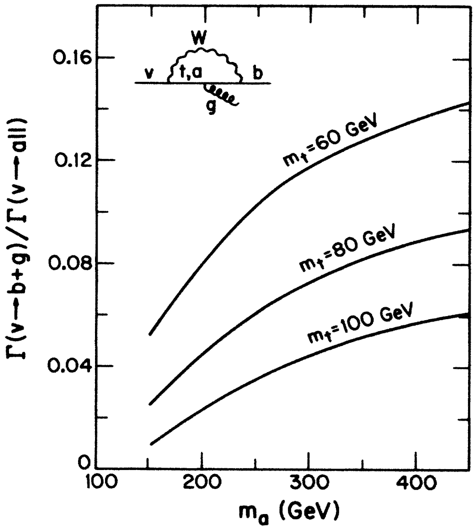

FIG. 2. Branching fraction for the $v\to bg$ decay mode, plotted vs m_a for $m_t = 60$, 80, and 100 GeV, with the parameter choices given in the text. Inset: the relevant Feynman graph.

where the sum runs over $i = u,c,t,a,$ and

$$F_i = (-0.25y_i + 0.75y_i^2 + 1.5y_i^3)x_i - 1.5x_i(\ln x_i)y_i^4,$$

where $x_i = m_i^2/m_W^2$ and $y_i = 1/(x_i - 1)$. The most important contribution to the sum arises from t and a quarks. Using the empirical systematics and unitarity of the mixing matrix we find

$$\Gamma(v\to b+g) \simeq \frac{\alpha_s G_F^2 m_v^5}{32\pi^4} |U_{tb}U_{tv}^*(F_a - F_t)|^2.$$

The corresponding FCNC branching fraction is

$$B(v\to bg) \approx \frac{1}{9}\frac{\Gamma(v\to bg)}{\Gamma(v\to cev)}$$

$$\approx \frac{2\alpha_s}{3\pi}\frac{|U_{tb}U_{tv}^*|^2}{|U_{cv}|^2}(F_a - F_t)^2,$$

where $U_{tb} \simeq 1$ and U_{cv} is expected to be $<< U_{tv}$. For illustration let us take $\alpha_s = 0.1$, $U_{cv} = \theta_C^4$, $U_{tv} = \theta_C^2$ to calculate B. Figure 2 shows the results for a range of masses of a quarks and for t quark of mass 60, 80, and 100 GeV. It is interesting that for a wide range of possible masses for the a and t quarks the FCNC mode $v\to b+g$ may have a branching fraction as large as 5%–10%.

Such FCNC decays would frequently give events with a separated b jet and a gluon jet of a very distinctive kind. The b jet would be identifiable by its low mass and $b\to c\to s$ double-decay topology; the gluon jet would have to satisfy two constraints, namely,

$$E(g\text{ jet}) + E(b\text{ jet}) \simeq E(v) \simeq \tfrac{1}{2}m_Z,$$

$$m(g\text{ jet} + b\text{ jet}) \simeq m(v) \simeq m_v.$$

In summary, if a v quark exists with $m_v \lesssim m_t$, there may be striking signatures in addition to the usual threshold, jet-broadening, and lepton-isolation effects expected for any heavy quark. These possible extra signatures include (i) long lifetime with resolvable decay vertices, (ii) isolated c and $c\bar{c}, c\tau$ production in the primary v decay, recognized by topology, and (iii) FCNC decays with distinctive features.

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