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Signatures for fourth-generation quarks and a heavy top quark at the Superconducting Super Collider

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We examine methods for detection of new heavy quarks at the Superconducting Super Collider where the heavy quark could be either one of a fourth generation of quarks (a,v), or a very massive (~ 150 GeV) top quark. The signals can be classified according to number of leptons in the final state. Requiring the presence of a single fast isolated lepton along with ≥ 4 jets and $\not{p}_T$ allows one to separate the a, v, or t signal from backgrounds. Heavy-quark pairs are produced with sufficient hemispheric separation to allow the direction of one of the quarks to be tagged by the transverse momentum of the isolated high-p_T lepton. A distinct enhancement is then observed at the heavy-quark mass in the cluster mass spectrum of all jets moving opposite to the lepton. A fourth-generation quark should also be visible in the two isolated lepton channel, and its mass resolvable. Additional signals from multilepton events would then also be present, though these channels may not yield a heavy-quark mass determination.

I. INTRODUCTION

A minimal extension of the standard model consists of the addition of a fourth generation of quarks and leptons. Although the existence of a fourth generation is not generally regarded as a signal of dramatic new physics, there is at least one major question (that of the existence of a grand unified desert) which could receive illumination by the discovery of very heavy (≥ 300 GeV) new quarks. This will be briefly discussed in Sec. II.

On the experimental side, it is arguable that the ability to detect a fourth generation of quarks, or a heavy (~ 150 GeV) top quark, provides an important test of the feasibility to do complex physics at the Superconducting Super Collider (SSC). All of the problems associated with standard-model backgrounds will come into play here, and the extraction of a signal for the presence of these heavy quarks, as well as a measurement of their masses, will require some rather extensive analysis. This is the subject of this paper. We will describe in some detail the production and decay of heavy quarks in pp collisions at $\sqrt{s}=40$ TeV, appropriate to the SSC.

In an earlier preliminary study of this topic,[1] we concentrated on multimuon signals, in the hope that such final states with large numbers of muons (≥ 5) might unequivocally tag the presence of a fourth generation. In the course of the present study, we have found additional backgrounds for such final states from multiple heavy flavors (e.g., $b\bar{b}b\bar{b}$, $t\bar{t}b\bar{b}$ final states) such that additional criteria involving hadron calorimetry (e.g., lepton isolation) are necessary in order to extract a fourth-generation signal. However, the multimuon signals will still be interesting as corroborative evidence for the presence of a fourth generation.

The paper is organized as follows. In Sec. II we present some theoretical points of interest concerning a heavy top quark and a fourth generation: a discussion of the expected mass range, and the implications of discovery of these additional quarks. Section III contains an outline of the calculation of the production and decay of the new quarks. An analysis of the single-isolated-lepton trigger is presented in Sec. IV. We propose a set of cuts which suppress the relevant backgrounds and allow a heavy-quark mass measurement. In Sec. V we present a study of final states characterized by two isolated fast leptons. This will allow discrimination between a heavy top and heavy fourth-generation quarks. Multimuon final states can serve as an additional trigger for fourth-generation quarks, and are discussed in Sec. VI. Section VII contains a summary of our results.

II. MASSES AND MOTIVATION

A. Heavy top quark

The t quark remains a major missing link in the standard model, where its existence is required to cancel triangle anomalies.[2] The latest direct limits on m_t come from negative searches at the KEK e^+e^- TRISTAN collider ($m_t > 26$ GeV) (Ref. 3) and CERN [$m_t > 44-56$ GeV (Ref. 4)]. Overall consistency of the three-generation standard model including radiative corrections implies $m_t < 168$ GeV (Ref. 5). If $m_t > 100$ GeV, it will be too heavy to be produced by the CERN e^+e^- collider LEP II. Operation of the Fermilab Tevatron $p\bar{p}$ collider or a 2-TeV pp collider at a luminosity $\gtrsim 10^{31}$ cm^{-2}s^{-1} could eventually probe t-quark masses in the range $m_t = 120-150$ GeV (Ref. 6). If such an upgrade in luminosity at the Fermilab Tevatron collider is not achieved we will have to rely on SSC to discover it, should it be this heavy. Hence, we include calculations here for a t-quark of mass $m_t = 150$ GeV produced at the SSC.

B. Fourth-generation quarks

There is no necessity for a fourth generation of quarks and leptons. However, the presence of a fourth generation could alter predictions for flavor-violating processes in electroweak physics and would be a further background for any other new physics that may be discovered at high-energy accelerators.

In order to bracket the quark masses which one would attempt to measure, we turn to some theoretical considerations. If we denote the new $SU(2)_L$ doublet as (a,v), consideration of the electroweak ρ parameter limits $|m_a - m_v| < 168$ GeV (Ref. 7). Perturbative calculations involving heavy quarks are valid only when partial-wave unitarity of scattering amplitudes is satisfied, which is the case when m_a or $m_v \lesssim 500$ GeV (Ref. 8). Hence, we limit our calculations to quark masses less than 500 GeV.

If there is a "desert" between Planck-scale energies and electroweak energies, and quarks obtain their masses through the Higgs mechanism, then there are considerably more rigid constraints upon the masses. We consider three popular scenarios.

(a) In nonsupersymmetric SU(3)×SU(2)×U(1) with *one* Higgs doublet, the renormalization-group (RG) evolution of the Yukawa couplings from M_{Planck} to the electroweak scale predicts[9] an upper bound of $\simeq 240$ GeV on quark masses and small isospin splitting[10] ($m_a - m_v \sim 5$ GeV if both quark masses are near the upper bound).

(b) In nonsupersymmetric SU(3)×SU(2)×U(1) with *two* Higgs doublets (one coupled to a, the other to v), the upper bound on m_a, m_v is similar, and the isospin splitting of the low-energy Yukawa couplings is small.[11] However, since the ratio of the vacuum expectation values (VEV's) is *a priori* arbitrary, there is not much of a constraint on $|m_a - m_v|$.

(c) In softly broken supersymmetric SU(3)×SU(2)×U(1), the ratio of the two Higgs VEV's is constrained by the full array of RG equations. Several analyses[12] have indicated that for large Yukawa couplings at M_{Planck}, and a low supersymmetry-breaking scale ($\lesssim 200$ GeV), the VEV's tend to be driven to the "flat" direction ($\langle H \rangle \simeq \langle H' \rangle$); this causes the upper limit on the quark masses to be decreased to about 140 GeV, and the isospin mass splitting turns out again to be small (~ 5 GeV).

The lesson to be drawn is twofold. (1) The upper bound from perturbative unitarity is within a factor of 2 of the "reach" of SSC for new physics; therefore, we will not explore quark masses much beyond 500 GeV. (2) The upper bound of 240 GeV is of particular interest: the discovery of a quark with a mass well above 240 GeV (say $\gtrsim 300$ GeV) would constitute strong evidence against the coexistence of the standard Higgs-boson origin for quark masses and a desert between 250 GeV and grand unification energies. Using this discussion as a guide, we will in what follows give results for fourth-generation quark masses of 140, 240, and 500 GeV.

III. PRODUCTION AND DECAY OF HEAVY QUARKS

A. Production

The lowest-order QCD subprocesses for Q production ($Q = t$, v, or a) are

$$q\bar{q} \to Q\bar{Q}, \quad gg \to Q\bar{Q} \; .$$

Recently, Nason, Dawson, and Ellis[13] have calculated $Q\bar{Q}$ production including next-to-leading-order contributions, yielding results which are stable in choice of renormalization scheme to $O(\alpha_s^3)$. We convolute their cross-sectional formulas with the structure functions of Eichten, Hinchliffe, Lane, and Quigg[14] for $\Lambda_4 = 0.2$, evaluated in Q^2 up to $\hat{s}$. The total $pp \to Q\bar{Q}X$ cross sections as a function of m_Q at $\sqrt{s} = 40$ TeV are given in Fig. 1. These results represent enhancements of $\sim$(10, 3, 1.6) for m_Q = (1.87, 5.2, 100 GeV) over the lowest-order leading-log calculation.

It has long been recognized that QCD radiation has important effects on the dynamical distributions of produced heavy quarks, affecting the fraction of events that will survive any given acceptance cuts. We include the bulk of these effects by calculating the dynamical Q and $\bar{Q}$ distributions from the tree-level $2 \to 3$ QCD subprocesses:

$$q\bar{q} \to Q\bar{Q}g, \quad gg \to Q\bar{Q}g, \quad gq \to Q\bar{Q}q, \quad g\bar{q} \to Q\bar{Q}q \; .$$

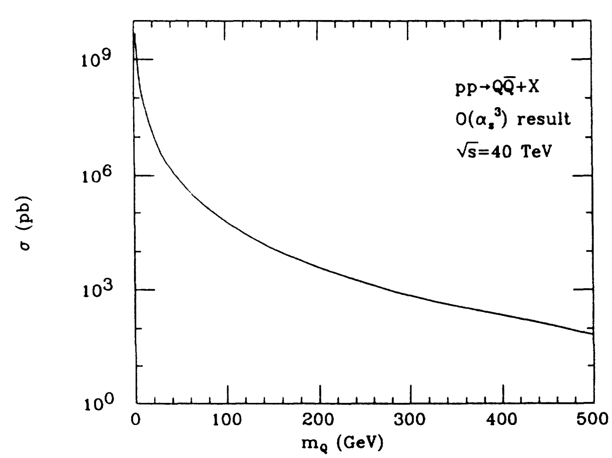

FIG. 1. Total production cross sections for $pp \to Q\bar{Q}$ at $\sqrt{s} = 40$ TeV, including next-to-leading-order contributions from Ref. 13, at $Q^2 = \hat{s}$, $\Lambda = 0.2$ GeV, and using structure functions of Ref. 14. The enhancements over lowest-order calculations are (10,3,1.6) for $m_Q = 1.87$, 5.2, 100 GeV, respectively.

These subprocesses correctly give the p_T dependence of $Q\bar{Q}$ pair production at large $p_T(Q\bar{Q})$. Convenient differential cross-section formulas have been given by Ellis and Sexton.[15] These cross sections have soft and collinear divergences at small $p_T(Q\bar{Q})$. These divergences should be removed in a complete calculation using well-defined regularization and normalization procedures implemented with respect to structure functions and jet formation.

As a phenomenological expedient we remove these divergences by a procedure that is argued to approximate the exact calculation. In particular we remove them empirically by a multiplicative Gaussian cutoff factor

$$F(p_T)=1-\exp(-p_T^2/A^2)$$

with the parameter A adjusted to reproduce the correct total $Q\bar{Q}$ production cross section as calculated in Fig. 1. We find that this cutoff also preserves approximately the correct dependence on the invariant mass $m(Q\bar{Q})$.

This use of a cutoff $2\rightarrow 3$ calculation is essentially the truncated shower approximation described in Ref. 16. It correctly gives the total $Q\bar{Q}$ production rate, the dependence on $m(Q\bar{Q})$, and the dependence on $p_T(Q\bar{Q})$ at large p_T. The details of the small $p_T(Q\bar{Q})$ dependence are not necessarily correct, but these details are in any case smeared by the subsequent fragmentation and decay so that final results are not sensitive to them. This calculation also gives the leading features of associated jet production through the final g, q, or $\bar{q}$ produced along with $Q\bar{Q}$. We remark finally that the $2\rightarrow 3$ parton scatterings already include both flavor excitation ($gQ\rightarrow gQ$, $qQ\rightarrow qQ$, etc.) and gluon fragmentation ($g\rightarrow Q\bar{Q}$) subprocesses within them.

Backgrounds from the lighter flavors $b\bar{b}$ and $c\bar{c}$ are evaluated in the same manner as described above. In addition, substantial backgrounds to multilepton signals can come from simultaneous production of four quarks, e.g., $pp\rightarrow b\bar{b}b\bar{b}, t\bar{t}b\bar{b}$, or production of a vector boson in association with a quark pair, e.g., $pp\rightarrow Wb\bar{b}$. In the latter case, we use the exact matrix element[17] in our calculations; in the former case, precise matrix elements are not known for

$$q\bar{q}, gg\rightarrow Q\bar{Q}Q'\bar{Q}' ,$$

so we approximate them by using

$$\sum|\mathcal{M}(ab\rightarrow Q\bar{Q}Q'\bar{Q}')|^2 = 4\pi\alpha_s\sum|\mathcal{M}(ab\rightarrow Q\bar{Q}g')|^2\frac{2P_{Q'g'}(z)}{s'} ,$$

where $\sum$ denotes spin summation, $s'=(Q'+\bar{Q}')^2$ is the $Q'\bar{Q}'$ invariant mass squared, and

$$z=(Q'\cdot g)/[(Q'\cdot g)+(\bar{Q}'\cdot g)] ,$$

$$P_{Q'g'}(z)=\tfrac{1}{2}[z^2+(1-z)^2+2m_{Q'}^2/s'] ,$$

with $g=Q+\bar{Q}$, $g'=Q'+\bar{Q}'$ the four-momentum of the virtual gluon producing $Q\bar{Q}$, $Q'\bar{Q}'$, respectively. This is essentially the leading-pole approximation discussed in Ref. 15 (applied there to relate $2\rightarrow 2$ with $2\rightarrow 3$ matrix elements). To use this approximation we have to evaluate the $ab\rightarrow Q\bar{Q}g$ subprocess at an off-shell value of the final gluon momentum.

Another source of four-quark events is multiple scattering of partons in the same proton. An estimate of this type of process can be made by computing

$$\sigma_{\rm MS}(Q\bar{Q}Q'\bar{Q}')=\frac{1}{N}\frac{\sigma(Q\bar{Q})\sigma(Q'\bar{Q}')}{\pi R^2} ,$$

where $N=1$ if $Q\neq Q'$ and $N=2$ if $Q=Q'$. Estimates of this type have been used[18] to describe the production of double lepton pairs at low x in pp and πp collisions.

We list in Table I various total cross sections of background processes, along with the $pp\rightarrow v\bar{v}$ ($m_v=240$ GeV) signal for comparison. The first column is the QCD leading-log estimate, i.e., $2\rightarrow 2$ or $2\rightarrow 4$ subprocesses convoluted with the parton distributions of Eichten *et al.*, while the second column gives the multiple-scattering estimate where applicable. Other backgrounds such as $t\bar{t}+2$ QCD jets may also be significant. However, since these depend strongly on the $g\rightarrow gg$ angular distribution, we neglect them until an exact calculation of the $2\rightarrow 4$ subprocesses is made.

Finally, the W and Z cross sections have been evaluated in leading log with $Q^2=M_{W,Z}^2$ and normalized to the $O(\alpha_s)$ cross section by a factor $K=1.4$.

TABLE I. Total cross section for various signals and background processes at the SSC. The first column is an estimate of the tree-level contributions, while the second column is an estimate of the contribution from multiple scattering from partons in the same two protons. Here we take $m_t=60$ GeV for illustration.

Process	$\sigma_{\rm QCD}$ (pb)	$\sigma_{\rm MS}$ (pb)
$pp\rightarrow c\bar{c}$	4.7×10^9	
$pp\rightarrow b\bar{b}$	4.6×10^8	
$pp\rightarrow t\bar{t}(60)$	3.9×10^5	
$pp\rightarrow v\bar{v}(240)$	1.8×10^3	
$pp\rightarrow W^{\pm}$	3.3×10^5	
$pp\rightarrow Z$	1.1×10^5	
$pp\rightarrow Wt\bar{t}$	14	8.6
$pp\rightarrow Wb\bar{b}$	490	1×10^4
$pp\rightarrow b\bar{b}b\bar{b}$	7.1×10^5	7.1×10^6
$pp\rightarrow t\bar{t}b\bar{b}$	2.6×10^3	1.2×10^4
$pp\rightarrow t\bar{t}t\bar{t}$	50	5.1

B. Cascade decays

Once a t, v, or q quark is produced, it is assumed to decay through a cascade which, for example, for a v quark, begins with $v\rightarrow tW^-$, if $m_v>m_t+m_W$; otherwise, $v\rightarrow txy$ with x and y representing the fermion-antifermion decay channels. (We assume that $m_v>m_t$.) Subsequently, we allow all of the cascades of the t and W to develop, with final states consisting of light quarks (u,d,s), leptons $(e,\mu,\nu_e,\nu_\mu,\nu_\tau)$, and their antiparticles. Hence, one has the possibility of finding very many muons in the final state. For instance, whereas a $b(t)$ quark could yield up to 2(3) muons, a v quark could yield up to 8 muons, and an a quark up to 7 or 13 muons depending on whether it decays directly to b or v. In Table II we list the average number of muons per $Q\bar{Q}$ event, and find a substantial fraction of events from heavy quarks containing up to 7 or 8 muons. Of course, many of these muons may be soft. In Sec. VI, however, we see that even after cuts, a substantial multimuon signal remains.

The model of Peterson, Schlatter, Schmitt, and Zerwas[19] is used to calculate the fragmentation of t quarks into top hadrons T. The large top mass implies a δ-function fragmentation for $t \to T$, and the decay of T is approximated by free quark decay

$$t \to bxy \ ,$$

where xy denotes $u\bar{d}$, $c\bar{s}$, $e^+\nu$, $\mu^+\nu$, $\tau^+\nu$. The b and c produced in this cascade are fragmented into B and D hadrons, respectively, according to the Peterson model (calculated in the T rest frame with parameter $\epsilon = 0.5/m_{B,D}^2$, $m_b = m_B = 5.2$ GeV, $m_C = m_D = 1.87$ GeV).

The subsequent cascade decays of B and D hadrons are also approximated by free quark decays

$$b \to cxy, \quad c \to sxy \ .$$

Experiments[20] indicate close to a δ-function behavior for the $c \to D$ fragmentation of the c quark produced in B decay, and we use this empirical behavior.

If $m_t > m_W + m_b$, then top decay proceeds essentially via real W bosons. We have introduced both cases $m_t \gtrless m_W + m_b$ by using a resonance form factor in the three-body $t \to bxy$ matrix element, with $\Gamma_W = 2.1$ GeV.

C. Parton jet algorithm

The formation of hadron jets is simulated by using the original light partons to represent the hadron energy and momentum deposition in the calorimeters of an experiment. Specifically, we order the partons according to p_T. We then coalesce partons lying within a cone

$$\Delta R = [(\Delta\phi)^2 + (\Delta\eta)^2]^{1/2} < 0.5$$

(where ϕ is the azimuthal angle and $\eta = \ln[\cot(\theta/2)]$ is pseudorapidity) and repeat the process with the remaining partons until we are left with a number of distinct, well-separated clusters. These clusters we call jets if they have $p_T > 20$ GeV and $|\eta| < 2.5$. We include the effect of hadronic-energy mismeasurement by generating a Gaussian smearing of the partons, with $\sigma = 0.8(E_{\text{jet}})^{1/2}$.

D. Lepton isolation

A salient characteristic of events which include the production of heavy particles is the presence of leptons unaccompanied by much hadronic activity. Such isolated leptons are an important ingredient in distinguishing a signal from standard-model background.[21] In the parton Monte Carlo model are employing, the isolation criterion is defined by generating a cone ΔR_c (in $\Delta\phi$ and $\Delta\eta$) about the lepton. If the transverse parton energy ($\sum E_T^c$) in this cone is less than some preassigned value, then the lepton is identified as being isolated. We eliminate much of the background from b and c quarks with the choice $\Delta R_c = 0.2$, $\sum E_T^c < 2$ GeV, following Ref. 22.

E. Soft E_T

A note is due here. For each event there will be some underlying soft hadronic activity. Since the isolation criterion involves small E_T, it is important to include the contribution of this soft E_T to the isolation cone. This has been done by representing E_T as the modulus of a Gaussian random variable with mean 0, standard deviation 3.6 GeV. The latter is obtained from UA1 results[23] for leptons produced in W decays using a cone $\Delta R = 1$ and scaled with the expected ratio of mean central multiplicities at SSC and the CERN $Sp\bar{p}S$. From Derrick,[24] this ratio is $\langle n \rangle_{\text{SSC}} / \langle n \rangle_{Sp\bar{p}S} \simeq 2.4$. We then rescale the E_T in accord with our choice of cone size.

IV. SINGLE ISOLATED LEPTON TRIGGER (REF. 25)

A. Signal versus background

A major source of an isolated lepton is the leptonic decay of a W boson which is produced along with any number of jets. We calculate this inclusive process using a QCD shower model.[26] Alternate methods are available,[27] and yield similar results.

Figure 2 shows the differential cross section $d\sigma/dp_T$ for production of the fast lepton for various sources. It is seen that a cut $p_T(l_{\text{fast}}) \geq 100$ GeV is very useful to reduce the background from W+jets, and other light

TABLE II. The number of muons per event (in percent) from various multimuon sources. These are from the production and cascade decay of heavy quarks. No cuts have been applied.

No. of μ's	$b\bar{b}$	$t\bar{t}$	$v\bar{v}$(240)	$a\bar{a}$(241)	$a\bar{a}$(500)
0	41.3	26.9	15.9	24.5	9.6
1	40.8	39.2	32.8	38.3	24.6
2	15.2	24.3	28.2	24.4	28.5
3	2.5	8	15.7	9.6	20.9
4	0.2	1.4	5.5	2.6	10.3
5		0.2	1.3	0.5	4.3
6			0.3	0.1	1.3
7			0.1		0.3
8					0.1

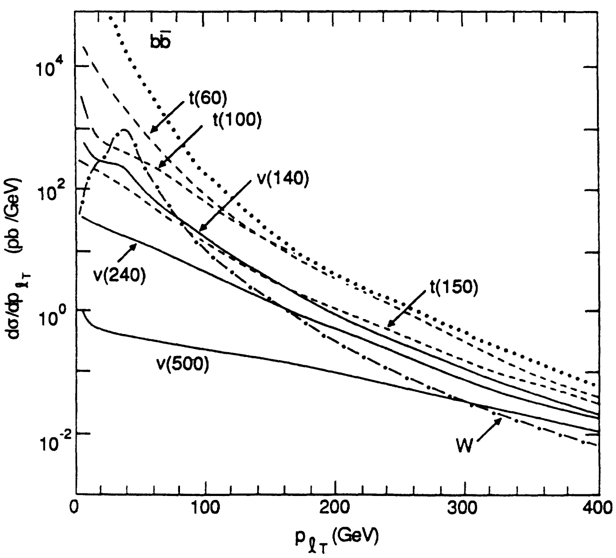

FIG. 2. Distribution in p_T of the fastest lepton in $Q\bar{Q}$ events. Illustrated are the results for $t\bar{t}$ ($m_t=60$, 100 GeV or 150 GeV, dashed curves), $v\bar{v}$ ($m_v=140$, 240, or 500 GeV, solid curves), $b\bar{b}$ (dotted curves) and W+jets (dashed-dotted curves).

flavors. Also, this cut collimates the decay products from light flavors, allowing one to place an isolation cut to reduce the surviving lighter-flavor backgrounds. We require $\sum E_T^c < 2$ GeV in a cone $\Delta R_c = 0.2$ about the direction of the fast lepton.

After imposing the isolation cut (and a pseudorapidity cut $|\eta_{\rm lept}| < 2.5$), we show in Fig. 3 the missing p_T profile of various backgrounds. It is clear that a cut of $\not{p}_T > 50$ GeV is desirable in order to reduce the background.

Finally we show in Fig. 4 the average number of jets expected for various channels of interest. It is apparent that selection of events with 4 or more jets is important in order to enhance the $v\bar{v}$ signal; retention of only events with 5 or more jets would serve to eliminate virtually all background. The combination of all the above cuts serves to eliminate all lighter-flavor backgrounds to $v\bar{v}$ but leaves a surviving background contribution from $t\bar{t}$ events and W+jets events.

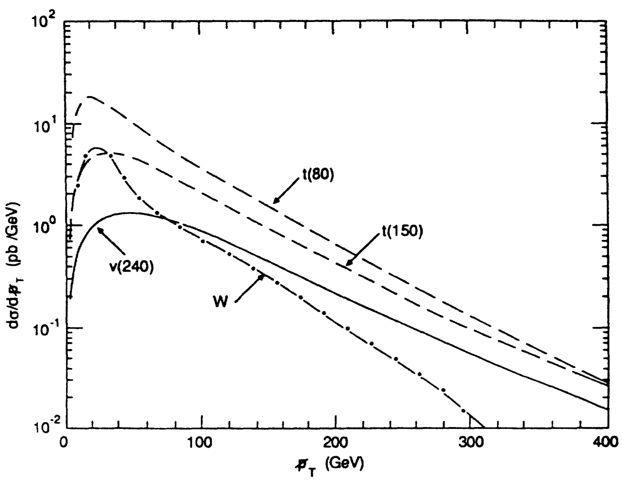

FIG. 3. Distribution in missing transverse momentum from t-quark events (dashed) for $m_t=80$ and 150 GeV, from v-quark events (solid) with $v(240) \to t(60)$, and from W events. These results are after a $p_{lT} > 100$ GeV cut, and an isolation cut on the fast lepton.

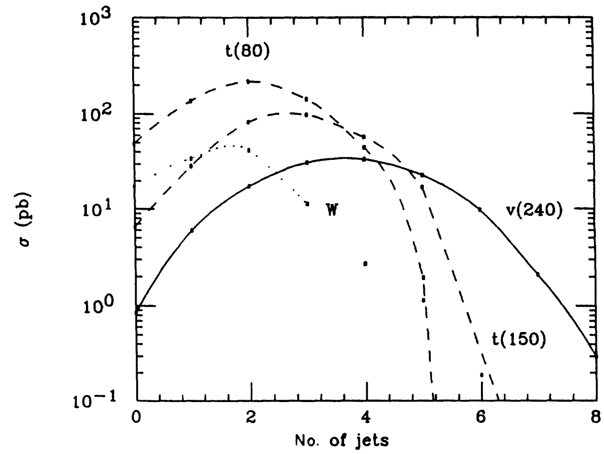

FIG. 4. Variation in cross section with respect to the number of jets expected from various sources of isolated lepton-plus-jet events. We require $p_{lT} > 100$ GeV and $\not{p}_T > 50$ GeV.

B. Mass measurement

In Figs. 5(a) and 5(b) we give the inclusive cross sections for producing $n \geq 4$ (≥ 5) jets, as a function of the heavy-quark mass m_v. Shown are curves for decays $v \to t$ (100 GeV), and $v \to t$ (60 GeV). The combined backgrounds from $t\bar{t}$ (for the same values of m_t) and from W+jets are shown as horizontal curves. It is interesting to note that an absolute cross-section measurement for events with ≥ 5 jets could provide a mass measurement for the v quark, for $m_v \leq 500$ GeV. If $m_t = 150$ GeV, then we would expect after cuts $\sigma_{t\bar{t}}$ ($n_j \geq 3$)=172 pb and $\sigma_{t\bar{t}}$ ($n_j \geq 4$)=74 pb.

A more direct indication of the heavy-quark mass is obtained when it is light enough that there is hemispheric separation of the $Q\bar{Q}$ pair. In that case, we may expect

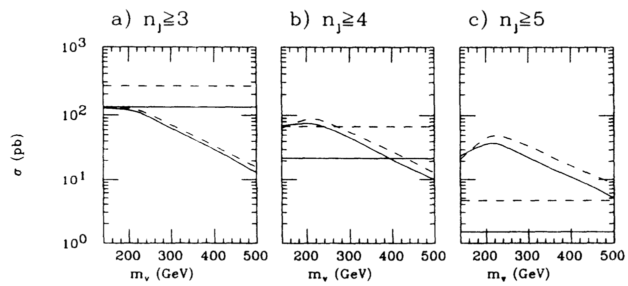

FIG. 5. Cross sections after cuts from $v \to t(60)$ (solid) and $v \to t(100)$ (dashed) vs m_v. The horizontal lines represent the sum of the W and $t\bar{t}$ backgrounds. We illustrate results when the number of jets required is (a) greater than 3, (b) greater than 4, and (c) greater than 5.

that much of the time the fast isolated lepton will define a direction for the Q (or $\bar{Q}$) "jet." Then the invariant mass in the hemisphere opposite to the transverse momentum of the lepton, M_{opp}, should show enhancement at $M_{\text{opp}}=m_Q$. In Fig. 6 we see just such an enhancement, in events with ≥ 4 jets. [The peaks at $M_{\text{opp}}=0$ are due to events where a very high $p_T(Q\bar{Q})$ pair recoils against a single parton.] The histograms display Monte Carlo data for $m_t=150$ GeV and $m_v=140$, 240, and 500 GeV. As expected, the effect becomes less pronounced at $m_v=500$ GeV. Thus, it seems clearly feasible to carry out a mass measurement for $m_v \leq 500$ GeV by selecting events with a single fast lepton and ≥ 4 jets. The same mass peak is obtained with the criterion of ≥ 5 jets.

V. TWO ISOLATED LEPTONS

A possible decay sequence of the v quark is $v \to t + l^- \nu$ with $t \to b + l^+ \nu$. Glover and Morris[28] have proposed making use of this sequence to look for fourth-generation quarks by tagging on two same-side isolated leptons. Dawson, Haggerty, Protopopescu, and Sheldon[22] have examined some aspects of this scenario, and have described some cuts which would eliminate $t\bar{t}$ background from the fourth-generation signal.

Using the same cuts and isolation criteria as in Ref. 22, namely,

$$p_{Tl_1}, p_{Tl_2} > 40 \text{ GeV} ,$$

$$\sum E_T^c < 2 \text{ GeV in } \Delta R^c = 0.2 ,$$

$$p_T^{\text{missing}} > 100 \text{ GeV} ,$$

$$\phi(\mathbf{p}_{Tl_1}, \mathbf{p}_{Tl_2}) < 90^\circ ,$$

$$\phi(\mathbf{p}_T^{\text{missing}}, \mathbf{p}_{Tl_1} + \mathbf{p}_{Tl_2}) < 90^\circ ,$$

$$N_{\text{jets}} \geq 4 ,$$

$$p_{T\text{jet}} > 20 \text{ GeV} ,$$

we find the cross-section signals listed in Table III, with no surviving background. It can be seen that, unlike the case of the single isolated lepton signal (Fig. 5), there is not a large variation of cross section with m_v. We show in Fig. 7 histograms generated for the invariant jet mass M_{opp} opposite the fast leptons. Here the "opposite hemisphere" is defined with respect to the vector $\mathbf{p}_{Tl_1}+\mathbf{p}_{Tl_2}$. Clear enhancements at $M_{\text{opp}}=m_v$ are evident for the cases $m_v=140$ and 240 GeV, and a measurable signal exists for $m_v=500$ GeV. There is no significant background from $t\bar{t}$ production with $m_t \leq 150$ GeV.

TABLE III. Cross section in picobarns of the two isolated lepton signals after cuts discussed in the text. Dash indicates rates below 0.1 pb.

Process	σ (pb) (after cuts)
$v\bar{v}(140)$ ($m_t=60$ GeV)	4.0
$v\bar{v}(240)$ ($m_t=60$ GeV)	3.8
$v\bar{v}(500)$ ($m_t=100$ GeV)	0.9
$t\bar{t}$($m_t \geq 60$ GeV)	0
$t\bar{t}b\bar{b}$($m_t \geq 60$ GeV)	—
WW	0

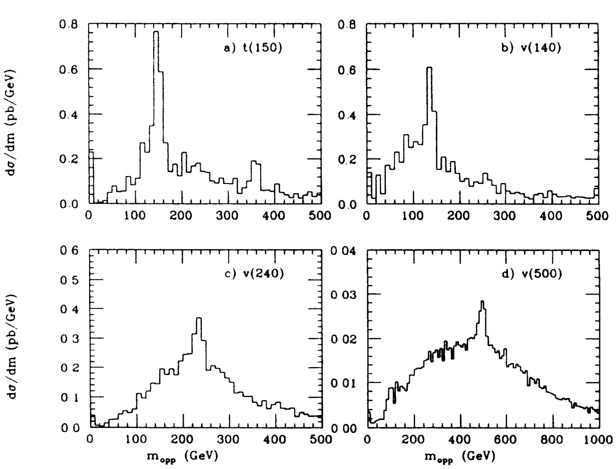

FIG. 6. Histograms of invariant mass of all activity in the hemisphere opposite $\mathbf{p}_{lT}$ vector of the first trigger lepton in (a) $t\bar{t}(150)$, (b) $v(140) \to t(60)$, (c) $v(240) \to t(60)$, and (d) $v(500) \to t(100)$ events containing a fast isolated lepton, $\not{p}_T$ and ≥ 4 jets.

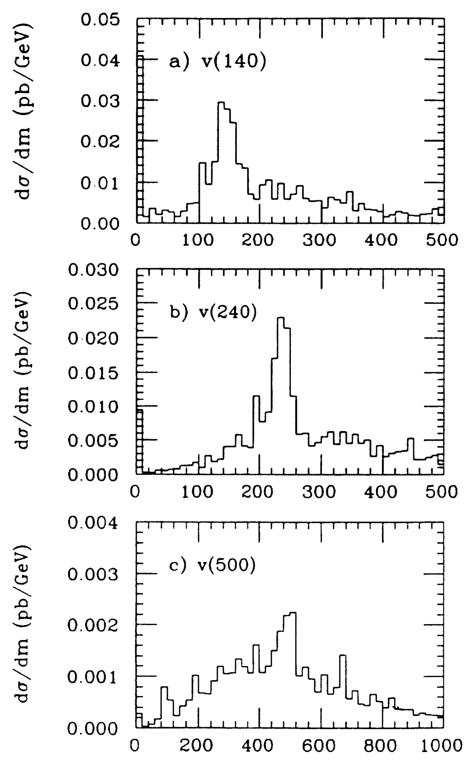

FIG. 7. Histograms of invariant mass of all activity in the hemisphere opposite $\mathbf{p}_{l_1T}+\mathbf{p}_{l_2T}$ from (a) $v(140) \to t(60)$, (b) $v(240) \to t(60)$, and (c) $v(500) \to t(100)$ events containing two isolated leptons, and other cuts as described in the text.

VI. MULTIMUONS

As discussed in our previous work,[1] it is expected that the v quark, through its cascade decays, could potentially generate events with large muon multiplicity per event. (The branching fractions for different $Q\bar{Q}$ pairs into channels with given muon multiplicities are given in Table II.) However, we have found that unless at least one of the muons is required to be isolated, background from double-gluon jet fragmentation ($pp \to gg \to t\bar{t}b\bar{b}$, $b\bar{b}b\bar{b}, \ldots$) and multiple scattering would make extraction of a signal difficult if not impossible. By requiring at least one of the muons to be isolated, we do find appreciable rates for some striking multimuon signals with very little background; these could be used to signal the presence of the fourth generation.

Table IV gives the cross sections for various event topologies, labeled by the minimum number of jets and by the muon multiplicity per event. The jet selection criteria are as before. The cuts on muon momenta are as follows: the fastest muon is required to be isolated and have $p_{T,\text{fast}} > 40$ GeV; all other muons are required to have $p_T > 10$ GeV, but need not be isolated.

We have estimated the background from all sources listed in Table I. All give negligible multimuon backgrounds except for $t\bar{t}$ and $t\bar{t}b\bar{b}$ sources, whose contributions are listed in Table IV.

As an example from Table IV, we see that we may expect in a year of running at SSC 12 000 events with ≥ 4 muons and ≥ 4 jets, from the combined production of $a\bar{a} + v\bar{v}$, $m_a = m_v = 240$ GeV, with background that is typically smaller than the signal.

It may be illustrative to pause here to do a Glover-Bengtsson calculation of another possible background, not given in Table IV. We may imagine the production of a $t\bar{t}$ pair, yielding 3 muons and ≥ 4 jets, with a cross section (given in Table IV) of 2.7 pb for $m_t = 60$ Gev. We may then ask for the probability that an additional muon from the decay of a pion from one of the jets before it reaches the calorimeter. This would then simulate a 4 muon plus ≥ 4 jet event. The following heuristic estimate may be made of this probability.

The requirement $p_{T_\mu} > 10$ GeV gives an approximate cut $p_{\pi^\pm} > 20$ GeV on charged pion momenta contributing to this decay. Then the pion will decay in less than 1 m with probability

$$P_{\pi \to \mu} \sim \left(\frac{m_\pi}{20\ \text{GeV}} \right) \left(\frac{1\ \text{m}}{c\tau} \right) \simeq 10^{-3} .$$

Assuming an average of about two 20-GeV charged pions per jet in the 4 jet events, we find a probability for $\pi^\pm \to \mu^\pm$ decay before the calorimeter of $8P_{\pi\to\mu} \simeq 8 \times 10^{-3}$. Thus, we may estimate background from this source as

$$\sigma_{t\bar{t} \to 4\mu + 4j} \simeq 8 P_{\pi \to \mu} \sigma_{t\bar{t} \to 3\mu + 4j} = (8 \times 10^{-3})(2.7\ \text{pb}) = 0.02\ \text{pb} .$$

This is negligible compared to the fourth-generation signals.

VII. SUMMARY

From this analysis we draw the following conclusions.

(i) In a year of running of the SSC at design luminosity it should be possible to detect the production and measure the masses of new heavy quarks with masses up to 500 GeV, the strong-coupling limit.

(ii) The important triggers for mass measurements will be one or two high-p_T isolated leptons, accompanied by 4 or more jets and substantial missing momentum. In the case of two isolated leptons, they should be "same side" (i.e., separated by $< 90°$).

(iii) The mass of the new quark(s) will be measurable as enhancement(s) in the quantity M_{opp}, which is defined as the invariant mass in a hemisphere opposite to the p_T of the fast isolated lepton, or, in the case of two isolated leptons, opposite to $\mathbf{p}_{T1} + \mathbf{p}_{T2}$. A heavy top quark will appear as an enhancement in only the single-lepton case, whereas a heavy fourth-generation quark will show up in both distributions.

(iv) The inclusive cross section for production of 5 or more jets varies rapidly with the mass of the v quark, and is well above top-quark background (for $m_t < 100$ GeV). Hence, an absolute measurement of the inclusive cross

TABLE IV. Cross sections in picobarns for multimuon events after cuts described in the text, for signals and dominant backgrounds. We list results for events containing greater than or equal to 3 jets or 4 jets. The fourth-generation v and a quarks are assumed to be approximately degenerate in mass. Dash indicates rates below 0.1 pb.

	$v\bar{v} + a\bar{a}$ $m_{a,v}$ (GeV)			$t\bar{t}$ m_t (GeV)			$t\bar{t}b\bar{b}$ m_t (GeV)	
No. of μ's	140	240	500	60	100	150	60	100
				$n_j \geq 3$				
3	37	21	2	9.7	6.1	14.6	3.6	1.3
4	2.3	2.4	0.3	0.6	0.2	1.1	0.3	0.2
5	0.2	0.2	0.03	—	—	0.02	0.02	0.01
				$n_j \geq 4$				
3	20	12.4	1.3	2.7	1.6	5.5	0.6	0.5
4	1.2	1.2	0.2	—	—	0.5	0.07	0.1
5	0.1	0.1	0.02	—	—	—	—	—

section for production of 5 or more jets (predicted to be $\sim 10-20$ pb) will yield a measurement of m_v. (See Fig. 5.)

(v) The production and subsequent decay of fourth-generation quarks will generate events with large numbers of high-p_T muons/events. The detection of the order of 10 events per day with 5 muons and ≥ 4 jets/event is a signal for fourth generation with small background.

(vi) If a signal for fourth-generation quarks is observed in any one of the above channels, then one must also have a signal in the other channels.

Note added. After submission of this paper we received a paper by S. Dawson and S. Godfrey[29] on this subject.

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