Multimuon Signals at the Superconducting Super Collider from Heavy Quarks

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An analysis is presented of the cross section at Superconducting Super Collider energies for events containing a large number of muons, arising from the production and decay of t quarks and of fourth-generation quark-antiquark pairs. We find that for fourth-generation masses in the range $140 \leq m_Q \leq 240$ GeV, events containing six muons (of both signs) or four same-sign muons, with realistic momentum and rapidity cuts, will be detectable in the 0.1–1.0-pb range with essentially zero background from t-quark production or other sources.

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Even if new physics exists in the teraelectronvolt energy region, its discovery at new high-luminosity facilities such as the Superconducting Super Collider (SSC) will challenge all the sophistication of high-energy physicists. The reason is simply that standard-model processes provide enormous backgrounds for many processes of interest, as has already been amply demonstrated at the CERN S$p\bar{p}$S collider. Many methods for detection of new heavy particles are based on a reconstruction of their masses from a detailed kinematic analysis of exclusive decays. Undoubtedly, this is a preferred method of operation for the extraction of maximum information. However, the drawback of this method is that it relies on elaborate Monte Carlo simulations to extract signal from background. It is thus of interest to ask whether there are any signals for the onset of new physics which may not provide details of this physics, but would simply act as a sign for the opening of new thresholds.

One such possibility, explored in a preliminary manner in this work, is the production of a particle or particles which decay copiously into channels containing a large number of muons per event. Examples may include a $t\bar{t}$ pair, a pair of fourth-generation quarks ($a\bar{a}+v\bar{v}$), or any of the various objects which characterize a new strongly interacting or composite sector. In the latter case, the sizeable multiplicity of b or t quarks (per event) will in turn spawn copious multimuon events. It is these multimuon signals that we wish to explore in this work. We will study these multimuon events in the case where the new physics consists of the production of a pair of (third-generation) t quarks,[1] or pairs of fourth-generation a and v quarks, but the method used will be applicable for any new object or objects with the multimuons prevalent in the final state.

It is arguable that the ability to detect a fourth generation of quarks provides a litmus test for the feasibility to do complex physics at accelerators. Several methods have been proposed, involving the decay of the fourth-generation down quark[2] $v \to t + W^-$ followed by $W^- \to l^- + \bar{\nu}$ and either[3] $t \to$ jets or[4] $t \to l^+ + \nu + b$. The $\bar{v}$ decays to jets. There are crucial prerequisites for these specific methods to work: one is the obvious mass constraint $m_v \geq m_t + m_W \geq 125$ GeV; the other is the availability of clear algorithms for isolating the primary heavy quark jet, as well as for finding the secondary hadronic jets resulting from t quark and W decay. Since this method is not free of serious (although probably surmountable) trigger and background problems,[5] it is of interest to see whether multimuon measurements can provide an alternate tag on production of fourth-generation quarks. First, however, we will briefly sketch the presently favored theoretical scenarios for fourth-generation fermion masses.

(a) In nonsupersymmetric SU(3)⊗SU(2)⊗U(1) with *one* Higgs doublet, the usual Yukawa couplings and a desert between electroweak and grand-unification-theory energies, the renormalization-group equations for the Yukawa couplings predict[6] an upper bound of $\simeq 240$ GeV on the quark masses, and about 60–70 GeV for the charged-lepton mass. In addition, the isospin splitting $m_a - m_v$ is predicted[7] to be small ($\simeq 5$ GeV).

(b) In nonsupersymmetric SU(3)⊗SU(2)⊗U(1) with *two* Higgs doublets, the upper bound on quark masses is similar, and the isospin splitting of the Yukawa couplings is small.[8] However, since the masses are given by Yukawa coupling × vacuum expectation value (VEV), and the two VEV's can have widely different values, there is not much of a constraint on the isospin *mass* splitting.

(c) In softly broken supersymmetric SU(3)⊗SU(2)⊗U(1) (with the mandatory Higgs doublets), the full array of renormalization-group equations involves not only gauge and Yukawa couplings, but all the soft-breaking parameters, including the Higgs-boson (mass)^2 terms. The evolution of the latter controls the eventual ratio of the two Higgs-boson VEV's. It was found[9,10] that when the Yukawas at grand-unification-theory energies are large enough so that they reach their approximate fixed points ($\simeq 1$) at low energies, and for moderately small values of the supersymmetry-breaking mass ($m_{3/2} \leq 200$ GeV) *then also the VEV's are forced to be approximately equal.* This has two important consequences: (1) The upper bound on the quark masses becomes $\simeq 140$ GeV and (2) the isospin splitting between masses again becomes small ($\simeq 5$ GeV).

The signal for onset of fourth-generation pair production proposed in this Letter is based on the simple fact that many muons can be produced as a result of the decays of the a and v quarks. If $m_v > 2m_t + m_b$, then a maximum of sixteen muons may be produced during the decay of the $v\bar{v}$ pair. Of course, the probability of this occurring is miniscule. What is possibly surprising is that the probability of more modest but still startling configurations (such as five or six muons) will turn up in a sizeable number of events at proposed SSC luminosities.

Briefly, our work consists of the following: We calculate $pp \to Q\bar{Q} + X$ heavy-quark production via the lowest of order $2 \to 2$ parton subprocesses $q\bar{q}$, $gg \to Q\bar{Q}$, where we convolute the subprocess with the structure functions of Eichten, Hinchliff, Lane, and Quigg[11] using $\Lambda = 0.2$. The heavy quarks are fragmented to heavy hadrons by use of the fragmentation functions of Peterson *et al.*[12] at each stage of the cascade decay, although this is of importance only for the b and c decays.

We assume that the isospin breaking $m_a - m_v$ is small enough so that we have the following cascades:

$$
\begin{aligned}
&a \to b + W^+, \quad W^+ \to (e^+\nu_e, \mu^+\nu_\mu, \tau^+\nu_\tau, u\bar{d}, c\bar{s}, t\bar{b}),\\
&v \to t + W^-, \quad W^- \to (e^-\bar{\nu}_e, \mu^-\bar{\nu}_\mu, \tau^-\bar{\nu}_\tau, \bar{u}d, \bar{c}s, \bar{t}b),\\
&t \to b + (e^+\nu_e, \mu^+\nu_\mu, \tau^+\nu_\tau, u\bar{d}, c\bar{s}),\\
&b \to c + (e^-\bar{\nu}_e, \mu^-\nu_\mu, \tau^-\bar{\nu}_\tau, \bar{u}d, \bar{c}s),\\
&c \to s + (e^+\nu_e, \mu^+\nu_\mu, u\bar{d}),\\
&\tau^- \to \nu_\tau + (e^-\bar{\nu}_e, \mu^-\bar{\nu}_\mu, \bar{u}d).
\end{aligned}
\tag{1}
$$

The widths and branching fractions were calculated according to previously published formulas for heavy-quark decay[2]; the latter include all mass and propagator effects. The masses used (in gigalectronvolts) are $m_t = 60$, $m_b = 4.6$, $m_c = 1.5$, $m_s = 0.5$, $m_\tau = 1.784$. We implement the complete heavy-quark cascade sequence (e.g., $a \to b \to c \to s$; $v \to t \to b \to c \to s$), including cascades of all particles produced. This means, for example, that as many as eight muons can result from the decay of a single v quark. (If $a \to v + W$ were allowed, as many as thirteen muons can result from the decay of a single a quark!) Finally, the complete final state of quarks and leptons is boosted to the laboratory frame where p_T and rapidity cuts are applied to the muons.

Cuts and background: π decay.—A 3-GeV muon-momentum cut and a 1.75 rapidity cut implies $E_\pi > 6$ GeV, $p_{\pi T} > 2.0$ GeV. This will suffice to eliminate mul-

TABLE I. Cross sections at 40 TeV for various multimuon configurations resulting from production and decay of heavy fourth-generation $Q\bar{Q}$ pairs and of $t\bar{t}$ pairs, subject to cuts of $p_{T\,\text{muon}} \geq 3$ GeV, $\eta_{\text{muon}} \leq 1.75$. Entries in parentheses are cross sections resulting from an additional cut placed on the momentum of the fastest muon, $p_{T\,\text{fast}} \geq 50$ GeV. There will also be small multimuon contributions from $W \to t\bar{b}$ decay that are not included here. These results may be compared to the total inclusive $Q\bar{Q}$ cross sections from quark-antiquark and gluon-gluon fusion. These are, for $m_Q = 4.6$, 60, 140, and 240, $\sigma = 1.7 \times 10^7$, 3.1×10^5, 1.5×10^4, and 1.75×10^3 pb, respectively.

	Cross section (pb)			
	$v\bar{v} + a\bar{a}$		$t\bar{t}$	$b\bar{b}$
	$m_a \approx m_v$ (GeV)		m_t (GeV)	m_b (GeV)
Muons/event	140	240	60	4.6
Both signs				
3	473(133)	111(43)	1325(126)	9845(113)
4	57(19)	15(8)	60(10)	44(6)
5	4.3(1.6)	1.6(0.9)	1.3(0.3)	⋯(⋯)
6	0.8(0.4)	0.2(0.1)	⋯(⋯)	⋯(⋯)
Same sign				
2	1525(342)	271(102)	5295(374)	9×10^4(349)
3	81(23)	19(9)	78(8)	⋯(⋯)
4	1.5(0.5)	0.66(0.33)	⋯(⋯)	⋯(⋯)

tiple μ's originating from diffractivity produced pions. In order to accommodate cylindrical detection geometry, we (conservatively) implement cuts of $(p_T)_{\text{muon}} \geq 3$ GeV, $|\eta_{\text{muon}}| \leq 1.75$. We then consider μ's originating in the decay of pions which are part of an ordinary QCD jet. The minimum pion energy implies for them a mean free path of 360 m before decay, and a probability for decay of $\simeq 3\times 10^{-3}$ prior to entering the hadron calorimeter. With[13] $\langle n_{ch}\rangle$/jet$\simeq 10$, and a jet cross section[11] of about 1 μb, the number of multimuon events from pion decay in light parton jets is negligible when compared with our signal.

$c\bar{c}$ and $b\bar{b}$ backgrounds.— The semileptonic decays of t and heavier quarks give isolated high-p_T muons[14]; isolated means that there is little hadronic p_T in a broad cone about the muon direction. In contrast, muons from b and c semileptonic decays occur within or near a jet of the associated hadronic decay products. By requiring that multimuon events contain at least one isolated high-p_T muon, the $b\bar{b}$ and $c\bar{c}$ backgrounds resulting from gluon evolution[15,16] can be suppressed at little cost to the signals from a, v, or t quarks.[14] In the following we assume that such an isolation requirement will be imposed, though we do not specifically implement it in our cross-section calculations.

Results.— Our results are summarized in Table I and Fig. 1. In Table I we give the expected cross sections at SSC (subject to our cuts) for various muon configurations originating from $t\bar{t}$ and from fourth-generation quark production. We also include (in parentheses) the cross section predicted when an additional cut, $p_{T\,\text{fast}} \geq 50$ GeV, is made on the transverse momentum of the highest-p_T muon in the event. In Fig. 1, we give the distribution of events with respect to the transverse momentum of the highest- and second-highest-p_T muon in the events. These results are based on Monte Carlo runs of 10^6 events.

Discussion of results.— (1) The multimuon cross sections given in Table I are large and relatively free of background. (Recall that at design luminosity 1 pb $=10000$ events/yr.) If there is a fourth generation, and if the a,t,v masses are in the approximate range used in this Letter, then *the detection of events with six both-signs or four same-sign muons at the 0.1–1-pb level should provide strong evidence of a fourth generation.* The five *both-signs* muon channel, with the $p_{T\,\text{fast}}$ cut imposed, also provides a large (3:1–5:1) signal/noise with respect to the t quark, and a cross section of $\simeq 1$ pb.

(2) Same-sign trimuons produced at the 100-pb level can provide a convenient signature for t quarks even if there is no fourth generation.

(3) Events with multiple electrons or with a mix of electrons and muons also provide similar signals for a-, v-, and t-quark production.

(4) Future work may include (a) a study of the multimuon profiles in the case where $m_t \geq m_W + m_b$; (b) a more detailed look at event topologies in order to possibly control the backgrounds (such as $b\bar{b}$) for lower muon multiplicities; (c) the evaluation of some supersymmetric contributions to multimuon backgrounds; (d) examination of the effects of $B^0\bar{B}^0$ mixing on our same-sign multimuon results; (e) exploration of optimal detection geometries and cuts for multimuon measurements at SSC; (f) analysis of multimuons originating in other "new physics" processes, such as the production of pairs of technimesons and their subsequent decays into heavy-quark pairs.[17]

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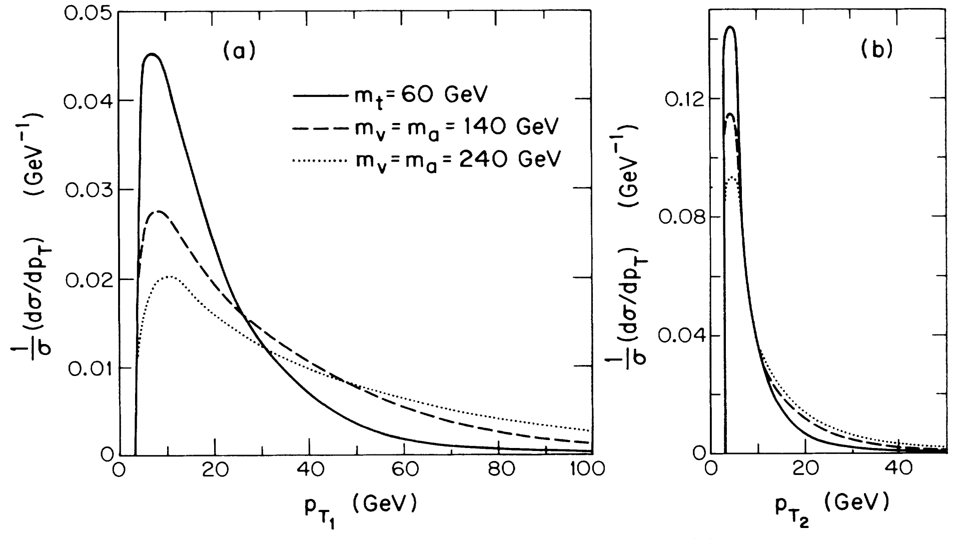

FIG. 1. Distribution of the transverse momentum of (a) the highest-p_T muon and (b) the second highest-p_T muon in multimuon events of heavy-quark origin.

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