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Trimuon production in $p\bar{p}$ collisions

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Trimuon events in $p\bar{p}$ collisions are a probe of heavy flavors: certain classes of events offer clean signatures for new physics beyond $b\bar{b}$ pair creation. We evaluate the expectations for trimuon production at the CERN $p\bar{p}$ collider, with realistic acceptance cuts, including possible new-physics effects from t quarks, D^0-$\bar{D}^0$ mixing, fourth-generation v quarks, and $b\bar{b}c\bar{c}$ creation.

I. INTRODUCTION

Leptons from semileptonic heavy-quark decays are a very promising tag for heavy-flavor events in $p\bar{p}$ collisions. Single isolated leptons are an essential ingredient in the search for t quarks[1,2] and dimuons are important in the study of b-quark physics and B^0-$\bar{B}^0$ mixing.[3–5] With the integrated experimental luminosity at the CERN $p\bar{p}$ collider now reaching 0.7 pb^{-1}, over 400 dimuon events have been accumulated by the UA1 Collaboration—of which three quarters are believed to be due to open heavy-quark production (mainly $b\bar{b}$ and $c\bar{c}$). With luminosity at this level and typical $p_T > 3$ GeV muon-acceptance cuts,[3] trimuon events are also to be expected[6] which can provide further valuable information on heavy quarks and particularly the t quark.[6,7] The UA1 group has recently recorded[8] the observation of trimuons; details are now awaited.

Although the event rate for trimuons is small, there are distinctive trimuon modes to which the copious production of $b\bar{b}$ or $c\bar{c}$ pairs do not contribute: namely, (i) same-sign trimuons (SST), and (ii) mixed-sign trimuons (MST) with both $\mu^+\mu^-$ pair invariant masses greater than m_b. This is evident in Fig. 1 where the various possible muon charges originating from $t\bar{t}$, $W \to t\bar{b}$, and $b\bar{b}$ decay cascades are shown (a $c\bar{c}$ pair gives at most two muons). The absence of $b\bar{b}$ contributions to these modes persists even if there is B^0-$\bar{B}^0$ mixing. Although $b\bar{b}$ contributions would be allowed if there were D^0-$\bar{D}^0$ mixing, the latter is very small in the standard model short-distance calculations (unless long-distance effects unexpectedly alter this[9]). Thus the modes (i) and (ii) provide clean signatures for new physics, beyond the production of single $b\bar{b}$ or $c\bar{c}$ pairs. Such new-physics sources include the t quark, D^0-$\bar{D}^0$ mixing, a possible[10] fourth-generation charge $-\frac{1}{3}$ quark v, and the simultaneous production of $b\bar{b}$ plus $c\bar{c}$ pairs. In the present paper, we present realistic calculations of trimuon expectations from the standard and new-physics sources above.

The expected trimuon event rates and dynamical distributions depend critically on the experimental acceptance cuts. Our illustrations below are based on two different possibilities.

(a) Tight cuts. Here we impose the same cuts on individual muons as in the UA1 dimuon analysis,[3] namely,

$$p_T(\mu) > 3 \text{ GeV}, \quad |\eta(\mu)| < 2 , \tag{1}$$

where η is the pseudorapidity, $\eta = \ln\cot(\theta/2)$.

(b) Loose cuts. Here we retain a substantial minimum momentum, to assist in the suppression of π and K decay backgrounds, but lower the p_T cut:[11]

$$p(\mu) > 3 \text{ GeV}, \quad p_T(\mu) > 1 \text{ GeV}, \quad |\eta(\mu)| < 2 . \tag{2}$$

Our method of calculation is described in Sec. II. The results and discussion are given in Secs. III and IV.

II. METHOD OF CALCULATION

We calculate $p\bar{p} \to b\bar{b}X$ heavy-quark production by the lowest-order $2 \to 2$ and $2 \to 3$ parton subprocesses

$$\begin{aligned} &q\bar{q}, gg \to b\bar{b} , \\ &q\bar{q}, gq, g\bar{q}, gg \to b\bar{b}x \quad (x = q, \bar{q}, g) , \end{aligned} \tag{3}$$

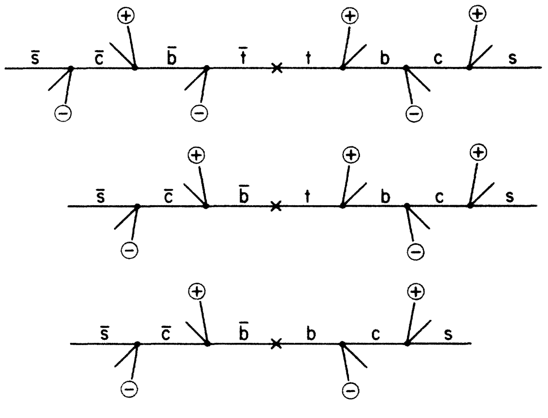

FIG. 1. Diagrams illustrating the signs ± of the charges of muons that can be emitted at each stage of $t\bar{t}$, $t\bar{b}$, and $b\bar{b}$ cascade decays. The decay modes $t \to bc\bar{s}$, $b \to cs\bar{c}$, and modes with τ are not shown but offer the same charge possibilities. B^0-$\bar{B}^0$ mixing would flip all charges downstream of the b quark in question. D^0-$\bar{D}^0$ mixing would similarly flip the lepton charge downstream of the c quark, but is known to be small experimentally.

using Monte Carlo methods with the truncated shower approximation described in the second paper of Ref. 4. The b quarks are fragmented[12] to B hadrons and the complete $b \to c \to s$ cascade is calculated for each quark as in Ref. 4. This calculation, supplemented by $c\bar{c}$ plus Drell-Yan pair plus Υ production, gives a reasonably satisfactory description of the dimuon data from the UA1 Collaboration. Figure 2 shows the agreement between the latest data[3] and the dimuon predictions of Ref. 4 for mean B^0-$\bar{B}^0$ mixing parameter values $\epsilon_b = 0, 0.1, 0.2$; the predictions are absolutely normalized and contain no empirical K-factor enhancement.

The two principal sources of t quarks are $W \to t\bar{b}$ decay and hadroproduction of $t\bar{t}$ pairs. We calculate the former from $q\bar{q} \to W$ and $q\bar{q} \to Wg$ subprocesses with the truncated shower approximation,[4] normalizing to the experimental cross section[13] $\sigma(p\bar{p} \to W^{\pm} \to e\nu) = 0.6$ nb at $\sqrt{s} = 630$ GeV. We calculate $t\bar{t}$ production from the lowest-order QCD subprocesses $q\bar{q}, gg \to t\bar{t}$ with semiempirical momentum-transfer dependence.[14] The full $t \to b \to c \to s$ cascade decay is computed, with semileptonic options at every stage, taking branching fractions 0.10,0.12,0.10 for direct $t \to \mu, b \to \mu, c \to \mu$ decays.

Appreciable B^0-$\bar{B}^0$ mixing is suggested by the UA1 dimuon data.[3,4] Such mixing does not generate any SST from $b\bar{b}$ sources, but it does convert some of the $t\bar{b}$ and $t\bar{t}$ MST into SST and vice versa. We calculate for illustration the extreme case $\epsilon_b = 0.2$, where ϵ_b is the mean probability that $b \to \mu^+$ relative to all $b \to \mu^{\pm}$ decays. As defined here, ϵ_b is directly measurable; its relation to the B_d^0-$\bar{B}_d^0$ and B_s^0-$\bar{B}_s^0$ mixings ϵ_b^d and ϵ_b^s depend on the relative strengths of the various $b \to B$ fragmentation channels and $B \to \mu$ semileptonic branching fractions. With production/semileptonic decay proportions $b\bar{u}:b\bar{d}:b\bar{s} = 1:1:\frac{1}{2}$ we have $\epsilon_b = 0.4\epsilon_b^d + 0.2\epsilon_b^s$. The mixing parameters ϵ_b^q are given by[4] $\epsilon_b^q \simeq \frac{1}{2}(\delta m^q/\Gamma)^2/[1+(\delta m^q/\Gamma)^2]$. In the standard model ϵ_b^s can attain the maximal value $\frac{1}{2}$, but ϵ_b^d is much smaller, and hence $\epsilon_b \lesssim 0.1$.

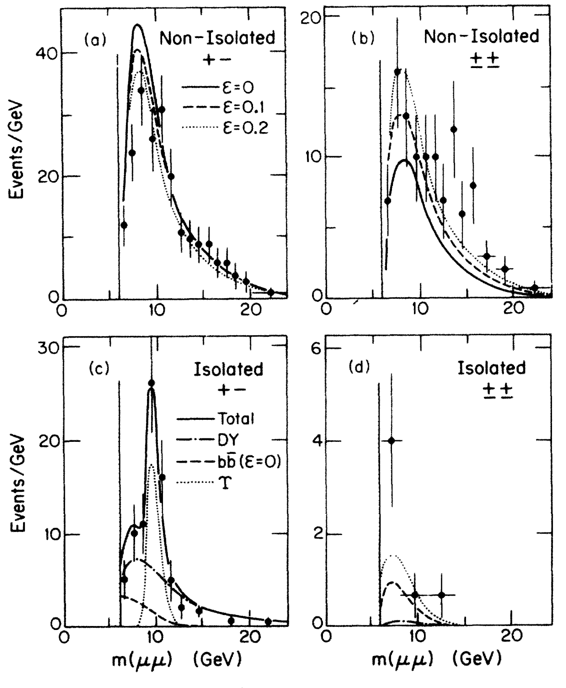

FIG. 2. Comparison of recent UA1 dimuon data (Ref. 3) with the predictions of Ref. 4, for $\epsilon_b = 0, 0.1, 0.2$. The cross section $B_{\mu\mu}\sigma(\Upsilon)$ has been empirically adjusted to 180 pb, within the cuts.

Very little D^0-$\bar{D}^0$ mixing is expected in the standard model, unless long-distance effects are important.[9] The most recent experimental limits,[15] from muoproduction and hadroproduction of same-sign dimuons, indicate that $\epsilon_c < 0.004$ where ϵ_c is the mean probability that $c \to \mu^-$ relative to all $c \to \mu^{\pm}$ decays. Since the fragmentation of c quarks in the $p\bar{p}$ collider environment may differ somewhat from that in muoproduction, we consider here the possibility that $\epsilon_c = 0.01$ (to be regarded as an upper limit) and calculate its consequences for the appearance of trimuons from $b\bar{b}$ in the special classes (i) and (ii) of Sec. I.

It has been suggested that some anomalous muon events found by the Mark J and JADE groups at the topmost DESY PETRA energies may be evidence of a heavy charge $-\frac{1}{3}$ quark of mass about 23 GeV (Refs. 16—18). These events are not inconsistent with expectations[10] for a standard fourth-generation quark v, with $v \to c \to s$ cascade decays; the secondary muons from charm decay would give a soft component in the muon spectrum as observed. If such v quarks exist, they will be hadroproduced in $p\bar{p}$ collisions just like t quarks; however, there will be no $W \to a\bar{v}$ decay contributions, since the associated charge $\frac{2}{3}$ quark a will probably be too heavy. The decays of $v\bar{v}$ pairs will give trimuons just like $b\bar{b}$; there will be no SST (modulo D^0-$\bar{D}^0$ mixing) but there will be MST of the class (ii) in Sec. I. We calculate $v\bar{v}$ production as for $t\bar{t}$ with $m_v = 23$ GeV and take the $v \to \mu$ semileptonic branching fraction to be 0.1 from quark/lepton counting.

A possible way for $b\bar{b}$ production to yield SST is to have additional charm creation in the fragmentation processes. To get a qualitative idea of the effects of such mechanisms, we considered two crude models.

(a) One of the b quarks fragments into a $(b\bar{c})$ meson with subsequent independent b and $\bar{c}$ decays; the spectator c quark has low p_T.

(b) The accompanying parton x (usually a gluon) in $b\bar{b}x$ production converts into a $c\bar{c}$ system carrying all the momentum of x.

These models were calculated via small modifications to the original $b\bar{b}$ Monte Carlo calculation. We have no way to normalize such contributions absolutely (dimuon data place no restriction since these models give like-sign/unlike-sign dimuon ratios similar to those of plain $b\bar{b}$ production); we use the calculations to estimate likely SST/MST ratios and the fraction of class (ii) MST events from such sources.

III. RESULTS

The predicted cross sections from $b\bar{b}$, $t\bar{b}$, $t\bar{t}$, and $v\bar{v}$ sources, with tight and loose muon cuts, are given in Tables I and II. Mean B^0-$\bar{B}^0$ mixing parameter values $\epsilon_b = 0$ and 0.2 are illustrated: this has negligible effect on the MST rates. Mean D^0-$\bar{D}^0$ mixing parameter values

TABLE I. Predicted inclusive trimuon cross sections (in pb) of b-, t-, and v-quark origins in $p\bar{p}$ collisions at $\sqrt{s}=630$ GeV, with the "loose cuts" of Eq. (1), for t-quark mass of 25 or 40 GeV, B^0-$\bar{B}^0$ mixing parameter $\epsilon_b=0$ or 0.2, and D^0-$\bar{D}^0$ mixing parameter $\epsilon_c=0$ or 0.01.

	Source	MST	SST ($\epsilon_b=0$)	SST ($\epsilon_b=0.02$)
$b\bar{b}$	$\epsilon_c=0$	19.0		
	$\epsilon_c=0.01$	19.0	0.04	0.08
$t\bar{b}$	$m_t=25$	1.7	0.14	0.18
	$m_t=40$	1.2	0.11	0.15
$t\bar{t}$	$m_t=25$	5.8	0.29	0.39
	$m_t=40$	1.3	0.07	0.10
$v\bar{v}$	$m_v=23$	1.9		

$\epsilon_c=0$ and 0.01 are illustrated for their effect in generating SST from $b\bar{b}$ decays: the effects on the other table entries are negligible. The cross sections shown are inclusive; i.e., if a tetramuon event were found it would count as four trimuon events, corresponding to the four independent sets of 3μ that it contained (assuming all four muons satisfy the acceptance cuts). MST from $b\bar{b}$ are the dominant modes; SST are less than 3% of all trimuons with tight cuts, less than 1.5% with loose cuts.

Figure 3 shows the predicted trimuon distributions versus the maximum muon transverse momentum. Figure 4 gives the distributions versus the minimum dimuon mass (for SST) or the minimum unlike-sign dimuon mass (for MST); this illustrates our remark in Sec. I, that $b\bar{b}$ trimuons have minimum $m(\mu^+\mu^-)$ below m_B. To be precise, the kinematic limit for dimuons from $B\rightarrow D\mu\bar{v}$, $D\rightarrow K\bar{\mu}v$ cascades is

$$m^2(\mu\bar{\mu})<(m_B{}^2-m_D{}^2)(m_D{}^2-m_K{}^2)/m_D{}^2\ . \tag{4}$$

Figure 5 shows the distributions versus trimuon invariant mass.

TABLE II. Predicted inclusive trimuon cross sections (in pb) of b-, t-, and v-quark origins in $p\bar{p}$ collisions at $\sqrt{s}=630$ GeV, with the "loose cuts" of Eq. (2), for t-quark mass of 25 or 40 GeV, B^0-$\bar{B}^0$ mixing parameter $\epsilon_b=0$ or 0.2, and D^0-$\bar{D}^0$ mixing parameter $\epsilon_c=0$ or 0.01.

	Source	MST	SST ($\epsilon_b=0$)	SST ($\epsilon_b=0.02$)
$b\bar{b}$	$\epsilon_c=0$	125		
	$\epsilon_c=0.01$	125	0.29	0.54
$t\bar{b}$	$m_t=25$	3.1	0.25	0.32
	$m_t=40$	2.2	0.22	0.26
$t\bar{t}$	$m_t=25$	13.5	0.93	1.09
	$m_t=40$	2.2	0.17	0.20
$v\bar{v}$	$m_v=23$	4.2		

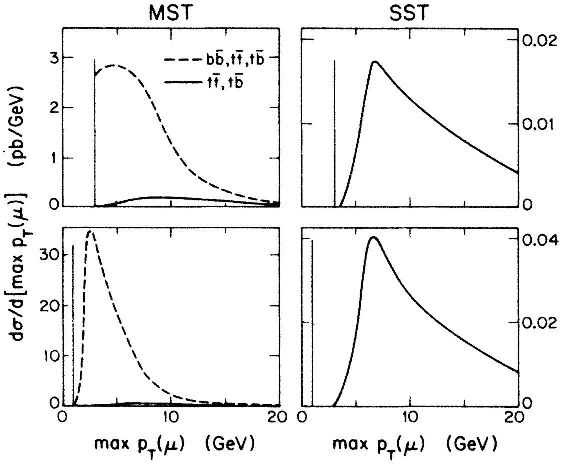

FIG. 3. Predicted distributions of mixed-sign trimuons (MST) and same-sign trimuons (SST) at $\sqrt{s}=630$ GeV, vs the maximum muon p_T in each event. The upper pair of figures refer to the "tight cuts," the lower pair of figures refer to the "loose cuts" described in Sec. I. Solid curves denote t-quark contributions (with $m_t=40$ GeV and $\epsilon_b=0$); dashed curves denote b- plus t-quark contributions.

The figures above represent the standard expectations, with the suggested[1] t-quark mass 40 GeV. There is also interest, however, in possible exotic contributions that might appear in the special trimuon channels (i) and (ii) of Sec. I in future high-luminosity measurements.

Figures 6 and 7 show how $b\bar{b}$ contributions would appear in SST maxp_T and $m(3\mu)$ distributions, if there were D^0-$\bar{D}^0$ mixing at the level $\epsilon_c=0.01$. The t-quark contributions for mass $m_t=25$ or 40 GeV are shown for comparison.

Figure 8 shows how $b\bar{b}$ contributions would appear in class (ii) MST if there were D^0-$\bar{D}^0$ mixing with $\epsilon_c=0.01$. The MST cross section is plotted versus min$[m(\mu^+\mu^-)]$ in the relevant range above 5 GeV. The contributions from t quarks ($m_t=25$ or 40 GeV) and from a fourth-generation v quark of mass 23 GeV are also shown (loose

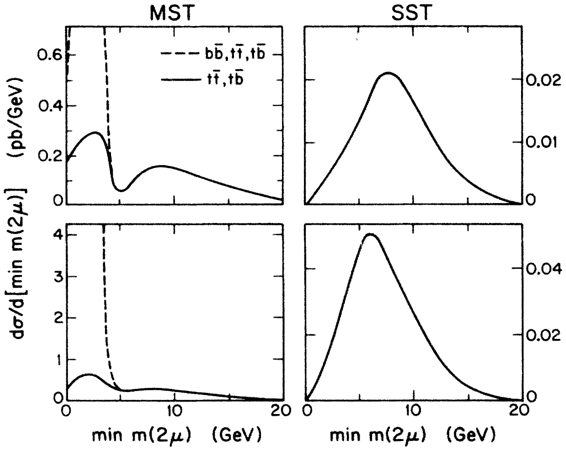

FIG. 4. Predicted trimuon distributions vs minimum dimuon mass (SST) and minimum unlike-sign dimuon mass (MST). Notation as in Fig. 3.

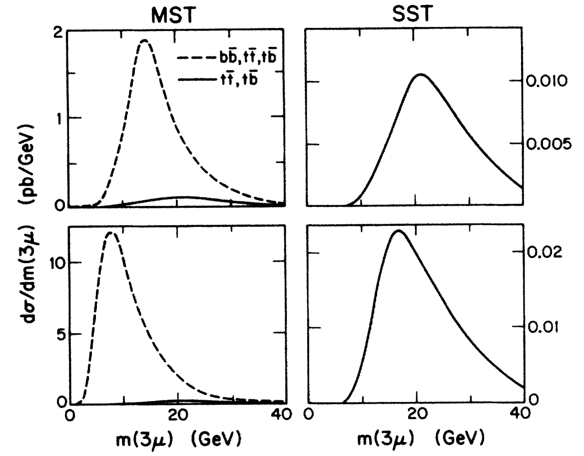

FIG. 5. Predicted trimuon distributions vs trimuon mass: notation as in Fig. 3.

cuts assumed). The cross sections are listed in Table III.

Finally we record the SST/MST ratios and fractions of class (ii) MST events (i.e., those with $\min[m(\mu^+\mu^-)]>5$ GeV) arising from the two crude models for $b\bar b$ plus $c\bar c$ creation.

Model (a), "b fragmentation":

SST/MST=0.03 (tight cuts), 0.05 (loose cuts),

MST(ii)/(all MST)=0.11 (tight cuts), 0.11 (loose cuts);

model (b), "g fragmentation":

SST/MST=0.02 (tight cuts), 0.03 (loose cuts),

MST(ii)/(all MST)=0.08 (tight cuts), 0.09 (loose cuts).

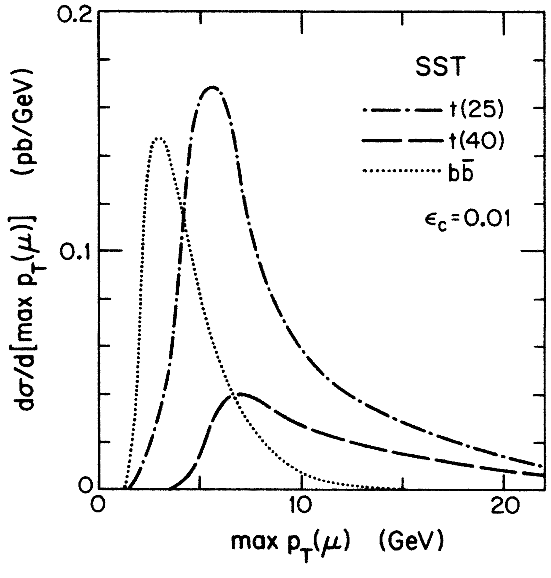

FIG. 6. Effects of D^0-$\bar D^0$ mixing with $\epsilon_c=0.01$ on SST production. The induced $b\bar b$ contribution to the cross section is plotted vs $\max p_T(\mu)$ and compared with t-quark contributions, for the case of loose cuts. Dotted, dashed, and dot-dashed curves denote $b\bar b$, $t(40)$, and $t(25)$ cases, respectively, with $\epsilon_b=0$.

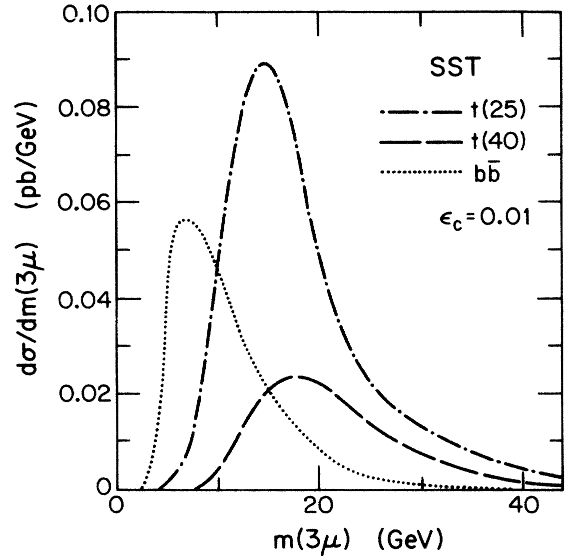

FIG. 7. Effects of D^0-$\bar D^0$ mixing with $\epsilon_c=0.01$ on the SST production cross section, plotted vs the trimuon mass. Notation as in Fig. 6.

With no cuts at all, both models would give the ratio SST/MST=0.10. These results are insensitive to ϵ_b.

IV. DISCUSSION

Our results show that the overwhelmingly dominant expected trimuon signal at $\sqrt{s}=630$ GeV is from $b\bar b$ pro-

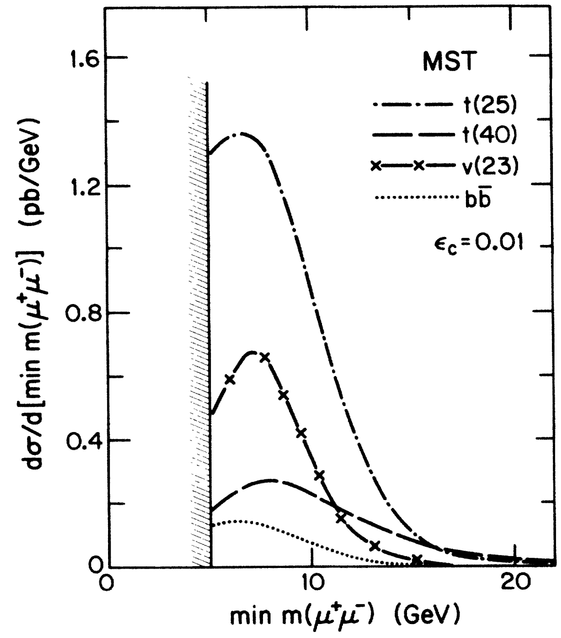

FIG. 8. Cross section for class (ii) MST events vs $\min[m(\mu^+\mu^-)]$ from $b\bar b$ production with D^0-$\bar D^0$ mixing ($\epsilon_c=0.01$) for the case of loose cuts. The range of interest $\min[m(\mu^+\mu^-)]>5$ GeV is shown. Also shown are contributions from $v\bar v$ production and $t\bar t$, $t\bar b$. Dotted, dot-dashed, dashed, and dash-cross curves denote the $b\bar b$, $t(25)$, $t(40)$, and $v(23)$ cases, respectively.

TABLE III. MST cross sections (in pb) with $\min[m(\mu^+\mu^-)] > 5$ GeV from b-, t-, and v-quark sources.

	Source	Tight cuts	Loose cuts
$b\bar{b}$	$\epsilon_c = 0$		
	$\epsilon_c = 0.01$	0.1	0.7
$t\bar{b}$	$m_t = 25$	0.7	1.1
	$m_t = 40$	0.6	0.9
$t\bar{t}$	$m_t = 25$	4.2	8.5
	$m_t = 40$	1.0	1.5
$v\bar{v}$	$m_v = 23$	1.6	3.3

duction, with distributions shown in Figs. 3—5. MST events with $\min[m(\mu^+\mu^-)] < 5$ GeV dominate at least 40:1 over SST events.

In the UA1 dimuon analysis,[3] efficiency factors $0.45 \times 0.58 = 0.26$ are quoted for geometry and track acceptance. If the trimuon efficiency is comparable to this, then with the present integrated luminosity 0.7 pb^{-1} we expect up to 25 (4) MST events with loose cuts (tight cuts). This prediction is relatively firm since the $b\bar{b}$ model on which it is based gives the correct heavy-quark dimuon rates. The first thing to check will be whether these gross expectations are correct.

For MST with $\min[m(\mu^+\mu^-)] > 5$ GeV, only a small fraction of an event is expected—except for the case m_t or $m_v \simeq 25$ GeV. The present luminosity is too low to explore a v-quark signal, although in principle it might be distinguished through its mass dependence. Note incidentally that $v\bar{v}$ is a weaker source of trimuons than $t\bar{t}$ production with comparable mass. This is largely because the secondary b quarks from $t \to b$ decays have harder fragmentation functions and harder $b \to \mu$ spectra than the corresponding secondary c quarks appearing in $v \to c$ decays; here we have assumed Peterson *et al.*[12] fragmentation in the decaying t- (v-) quark rest frame.

The cross sections for SST are even smaller, with the realistic cuts we have studied. It is too soon for the systematic study of such events if the new physics they contain comes from t quarks or D^0-$\bar{D}^0$ mixing. However, if one event were to be found and attributed to such kinds of physics, there would be immediate implication; e.g., if the minimum dimuon mass were greater than 5 GeV, this would be a lower bound on m_t.

Finally there remains the question of SST and class (ii) MST production via $b\bar{b} + c\bar{c}$ double-pair processes. The crude b-fragmentation and g-fragmentation models we studied suggest that SST/MST ratios from this source would be of the order of 3—5%. The fact that $c\bar{c}$ pairs are much more massive than $s\bar{s}$ pairs suggests that they will be produced much less readily—perhaps in only a few percent of events. Multiplying these factors suggests an overall SST/MST ratio from this source of order 10^{-2}—10^{-3} at most, comparable perhaps to t-quark sources but not much bigger. The class (ii) MST are estimated to be about 2—4 times more than SST events, from these $b\bar{b}c\bar{c}$ sources; again this might at most be comparable to the calculated t- and v-quark examples.

ACKNOWLEDGMENTS

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