Top quark signatures in extended color theories

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We consider the implications of an extended color group $SU(3)_I \times SU(3)_{II}$ spontaneously broken to $SU(3)_c$ at a TeV or lower scale for the hadronic colliders. The associated massive color octet gauge bosons (the colorons) can enhance the $t\bar{t}$ pair production at the Fermilab Tevatron collider. At the CERN LHC, the colorons can be pair produced, each decaying to a $t\bar{t}$ pair. This gives rise to anomalous multi-W production, a clear signature of physics beyond the standard model. We calculate the associated multijet and multilepton final states at the Tevatron and LHC energies, and compare these with the expectations from the standard model.

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I. INTRODUCTION

The Collider Detector at Fermilab (CDF) Collaboration at the Tevatron has reported [1] the observation of two charged dilepton and ten single lepton + $\geq$ 3 jet events which are in excess of those expected in the standard model (SM) excluding $t\bar{t}$ production. A detailed analysis of seven of these events (which have at least one b tag and a fourth jet) yields the central value for top quark mass of 174 GeV and $t\bar{t}$ cross section of 13.9 pb at the Tevatron energy ($\sqrt{s} = 1.8$ TeV). This cross section is about three times larger than expected in the standard model [2] although the error [1] is large. It is entirely possible that, with larger statistics, the values of the mass and the cross section will change to be in agreement with the SM. However, it is also possible that we are seeing the first glimpse of new physics beyond the SM at this TeV scale which is being explored directly for the first time. Several ideas have been proposed for new physics. One is to assume that the color group at high energy is bigger, namely, $SU(3)_I \times SU(3)_{II}$ [3]. The color I is coupled to the first two families of fermions while the color II is coupled to the third family. This group breaks spontaneously to the usual $SU(3)_c$ at a TeV scale or below giving rise to eight massive color octet gauge bosons, called colorons. Because of mixing, these colorons couple to both the ordinary light quarks and to $t\bar{t}$. These colorons are then produced from the ordinary light $q\bar{q}$ as resonances which then decay to $t\bar{t}$, thus enhancing the $t\bar{t}$ production. The second idea assumes the multiscale models of walking technicolor [4]. The color octet technipion, η_T is produced as a resonance in the gluon-gluon channel and decays dominantly to $t\bar{t}$, thus increasing the $t\bar{t}$ production to the level observed by CDF. In the third scenario, a singlet vectorlike, charge $+\frac{2}{3}$ quark is assumed with a mass comparable to the top quark [5]. This singlet quark mixes with the top. Their production and the subsequent decay then effectively double the standard top signals [5]. Another idea proposed is that the top quark may have an anomalous chromomagnetic moment-type tree level coupling with the gluons [6]. A small value of the chromomagnetic moment χ can produce a cross section of the level observed by the CDF Collaboration [6].

In this work, we discuss the hadronic collider implications of the first idea above, an extended color model $SU(3)_I \times SU(3)_{II}$, where the first two families of quarks couple to the $SU(3)_I$, whereas the third family couples to $SU(3)_{II}$, as proposed in Ref. [3]. We calculate the multijet and/or multilepton final-state cross sections arising from production and the subsequent decay of the coloron at the Fermilab Tevatron and CERN Large Hadron Collider (LHC) energies, and compare those with the expectations from the standard model. Hill and Parke have studied the coloron production at the Fermilab Tevatron energy. At the Tevatron, the coloron is singly produced by $q\bar{q}$ annihilation. There is no contribution from gluon-gluon fusion, since there is no gluon-gluon-coloron coupling in this model. Hill and Parke showed that for the extended color symmetry-breaking scale at a TeV or less, the resonant enhancement of the coloron production and their subsequent decay to $t\bar{t}$ is enough to produce the large cross section observed by the CDF Collaboration. They also study the W and top-quark p_T distributions and the $t\bar{t}$ mass distributions and note that the larger p_T in this model can be used to distinguish it from the standard model. In this work we go further by looking at the decay products of the W's and making some simple visibility cuts to test the extent to which the p_T distributions as they would be observed, are really different. However, the main part of our work is to study the implications of the model at the LHC energy ($pp, \sqrt{2} = 14$ TeV). Here, the colorons can be pair produced via gluon-gluon fusion. Each coloron decays to a $t\bar{t}$ or $b\bar{b}$ pair. If we look at the top quarks, we get two top quarks and two top antiquarks whose decays give rise to four W bosons in the final state. The cross sections for these four W final states are much larger than those in the standard model. These anomalous W productions will be a very clean signal for physics beyond the standard model at high energy hadronic colliders such as LHC. We also calculate the branching ratios for the various multijet and/or multilepton final state arising from the subsequent decays of these final-state W's.

We present our work as follows. In Sec. II, we give the formalism for the $SU(3)_I \times SU(3)_{II}$ extended color model and write down the relevant interactions. In Sec. III, we discuss our results for the Fermilab Tevatron. Section IV contains the main part of our work: In A, we calculate the differential and total cross sections for $pp \to$ coloron + coloron + anything at various center of mass energies; in B, we discuss the topology of the events and calculate the branching ratios of the multijet and/or multilepton final states by applying appropriate cuts. Here we discuss our results and important channels for clear signals beyond the standard model. Section V contains our conclusions.

II. FORMALISM FOR THE $SU(3)_I \times SU(3)_{II}$ COLOR MODEL

The gauge part of the $SU(3)_I \times SU(3)_{II}$ extended color model is

$$-L_{\rm gauge} = \tfrac{1}{4}F_{I\mu\nu a}F^{\mu\nu}_{Ia} + \tfrac{1}{4}F_{II\mu\nu a}F^{\mu\nu}_{IIa}, \qquad (1)$$

where

$$F_{I\mu\nu a} = \partial_\mu A_{I\nu a} - \partial_\nu A_{I\mu a} - h_1 f_{abc} A_{I\mu b} A_{I\nu c}$$

and similarly for $F_{II\mu\nu a}$ with h_1 replaced by h_2. h_1 and h_2 are the two color gauge coupling constants. The $SU(3)_I \times SU(3)_{II}$ symmetry is broken spontaneously to the usual $SU(3)_c$ at some scale M at or below a TeV. This is achieved by using a Higgs field, Φ which transform like $(1,3,\bar{3})$ under $(SU(2)_L, SU(3)_I, SU(3)_{II})$ with a vacuum expectation value (VEV)= diag(M,M,M). At low energy, we are left with eight massless gluons $(A_{\mu a})$ and eight massive colorons $(B_{\mu a})$ defined as

$$A_I = A\cos\theta - B\sin\theta,$$
$$A_{II} = A\sin\theta + B\cos\theta, \qquad (2)$$

where θ is the mixing angle, and

$$g_3 = h_1\cos\theta = h_2\sin\theta. \qquad (3)$$

The mass of the coloron is

$$M_B = \left(\frac{2g_3}{\sin 2\theta}\right) M. \qquad (4)$$

In terms of the gluon (A) and the coloron field (B), we can write the gauge part of the interaction schematically as

$$-L_{\rm gauge} = \tfrac{1}{2}g_3[A^3 + 3AB^2 + 2\cot 2\theta B^3] + \tfrac{1}{4}g_3^2[A^4 + 6A^2B^2 + 4(2\cot 2\theta)AB^3 + (\tan^2\theta + \cot^2\theta - 1)B^4]. \qquad (5)$$

In Eq. (5), A^3 and A^4 represent schematically the usual three- and four-point gauge interactions: namely,

$$A^3 \equiv f_{abc}(\partial_\mu A_{\nu a} - \partial_\nu A_{\mu a})A^{\mu b}A^{\nu c}$$

and

$$A^4 = f_{abc}f_{ade}A_{\mu b}A_{\nu c}A^\mu_d A^\nu_e. \qquad (6)$$

We see from Eq. (5) that a single coloron does not couple to two or three gluons. Thus, a single coloron or a coloron in association with a gluon cannot be produced in hadronic colliders from gluon-gluon fusion.

The fermion representations under $(SU(2)_L, SU(3)_I, SU(3)_{II})$ are

$$(u,d)_L, (c,s)_L \to (2,3,1); (u_R,d_R,c_R,s_R) \to (1,3,1),$$
$$(\nu_e,e)_L, (\nu_\mu,\mu), (\nu_\tau,\tau)_L \to (2,1,1); (e_R,\mu_R,\tau_R,\nu_{iR}) \to (1,1,1),$$
$$(t,b)_L \to (2,1,3); (t_R,b_R) \to (1,1,3). \qquad (7)$$

Note that the first two families of quarks couple to the color I while the third family of quarks couples to color II. This assignment is anomaly-free. With the above assignment, the interactions of all the quarks with the gluons are the same as in the usual QCD. The interactions of the colorons are given by

$$-L_{\rm coloron} = g_3\left[z_1\sum_i \overline{q_i}\gamma^\mu\frac{\lambda^a}{2}q_i + z_2\left(\bar{t}\gamma^\mu\frac{\lambda^a}{2}t + \bar{b}\gamma^\mu\frac{\lambda^a}{2}b\right)\right]B_{\mu a}, \qquad (8)$$

where the sum i is over u, d, s, and c quarks,

$$z_1 = -\tan\theta, z_2 = \cot\theta, \qquad (9)$$

so that $z_1 z_2 = -1$.

III. RESULTS FOR FERMILAB TEVATRON

In this section, we discuss $t\bar{t}$ production and the resulting multijet and/or multilepton final states at the $\bar{p}p$ collider at the Fermilab Tevatron, $\sqrt{s} = 1.8$ TeV. The dominant subprocess is the annihilation of ordinary $q\bar{q}$ pair to produce $t\bar{t}$ via coloron exchange in the s channel, in addition to the usual standard model processes. (The contribution of gg subprocess producing two colorons is either kinematically not allowed or negligible.) The total cross sections depends on the coloron mass as well as the coloron width. We use Eq. (8) for our calculations, and following Hill and Parke, present our results for the coloron model, $z_1 z_2 = -1$ [Eq. (9)], as well as for another model which is like the coloron model except the value of $z_1 z_2 = +1$. [The value of $z_1 z_2 = +1$ can be obtained in a color singlet vector resonance model with an extra U(1) [7]]. For parton distributions, we use those produced by the CTEQ Collaboration [8].

Hill and Parke note that in their models the top quark and the W boson have larger p_T than in the standard model and that this could be used to distinguish these models from the standard model with only a relatively small number of top events. Here we go slightly further by looking at the decay products of the W's and making some simple visibility cuts.

In particular we keep the matrix element for top decay into $bl\bar{\nu}$ or $bq\bar{q}$ so as to include the coherent polarization sum of the W's. We then combine the quarks into jets by requiring that final-state quarks be in the same jet if their angular separation is less than $\Delta R = 0.5$ with the standard definition of ΔR. We next require that jets and the charged leptons from the W's be visible by requiring that their p_T be larger than some $p_T^{\min}$ and that their rapidity y be less than some $y^{\max}$. We also require that these leptons be separated from the jets, and from each other, if there is more than one, by $\Delta R \geq 0.5$.

Using these criteria, we find the branching ratios for n jets and m charged leptons where $n = 0, 1, 2, 3, 4, 5, 6$ and $m = 0, 1, 2$. We do this for the standard model and for the following four models of Hill and Parke: (a) $z_1 z_2 = -1, M_B = 400$ GeV, $\Gamma_B = 0.6 M_B$; (b) $z_1 z_2 = +1, M_B = 600$ GeV, $\Gamma_B = 0.2 M_B$; (c) $z_1 z_2 = -1, M_B = 600$ GeV, $\Gamma_B = 0.5 M_B$, and (d) $z_1 z_2 = +1, M_B = 400$ GeV, $\Gamma_B = M_B$.

As can be seen from Fig. 1, these four models each have a total cross section near 14 pb. Table I gives the branching ratios if $y^{\max}$ is 1.5 and $p_T^{\min}$ is 35 GeV. Clearly there is very little difference between these models and the standard model (which is the top number in each set of five) so far as BR's are concerned. Table II gives the same cases for $p_T^{\min} = 50$ GeV. Here the new models do show some p_T behavior (except for model (a)] but the branching ratios for the interesting topologies, four jets and one lepton for example, are quite small. If the detector efficiency is 10% and we have 1000 pb^{-1} of integrated

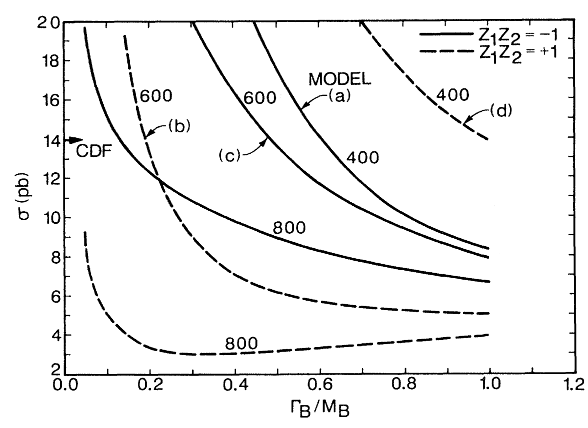

FIG. 1. Cross sections (in pb) for the $t\bar{t}$ pair productions at the Tevatron ($\sqrt{s} = 1.8$ TeV). M_B and Γ_B are the mass and the width of the coloron. The solid curves are for $z_1 z_2 = -1$, the dotted curves are $z_1 z_2 = +1$ as discussed in Sec. III. The numbers indicated with the curves are the coloron masses in GeV. The four models discussed in the text are indicated by (a), (b), (c), and (d). The experimental value of the cross section, as measured by CDF collaboration, is shown by the arrow.

TABLE I. Branching ratios for the various multijet and multilepton final states with each jet and charge lepton (e or μ) having $p_T > 35$ GeV and with other cuts as discussed in the text. The decays of τ to e, μ or quarks have been included. The results are for the Tevatron energy, $\sqrt{s} = 1.8$ TeV. SM stands for the standard model and (a), (b), (c), and (d) are the four different models discussed in Sec. III.

No. of jets \ No. of leptons		0	1	2
0	SM	1.81×10^{-3}	2.32×10^{-3}	9.09×10^{-4}
	(a)	2.17×10^{-3}	2.14×10^{-3}	7.59×10^{-4}
	(b)	2.00×10^{-3}	2.17×10^{-3}	1.27×10^{-3}
	(c)	1.80×10^{-3}	2.20×10^{-3}	1.01×10^{-3}
	(d)	1.95×10^{-3}	2.15×10^{-3}	9.93×10^{-4}
1		0.0251	0.0245	5.93×10^{-3}
		0.0249	0.0259	5.48×10^{-3}
		0.0191	0.0240	7.89×10^{-3}
		0.0231	0.0256	6.45×10^{-3}
		0.0229	0.0253	6.45×10^{-3}
2		0.115	0.0825	9.00×10^{-3}
		0.121	0.0810	8.53×10^{-3}
		0.0874	0.0786	0.0124
		0.107	0.0819	9.92×10^{-3}
		0.106	0.0823	0.0104
3		0.236	0.0897	
		0.240	0.0847	
		0.188	0.106	
		0.225	0.0938	
		0.220	0.0942	
4		0.239	0.0298	
		0.239	0.0270	
		0.230	0.0473	
		0.238	0.0334	
		0.239	0.0361	
5		0.117		
		0.110		
		0.152		
		0.126		
		0.128		
6		0.0209	$\sigma : 4.810 \pm 0.009 +$ pb SM	
		0.0177	13.93 ± 0.03 (a)	
		0.0388	13.49 ± 0.04 (b)	
		0.0241	13.52 ± 0.02 (c)	
		0.0263	13.89 ± 0.03 (d)	

luminosity then the standard model gives 2.4 events of 4 jet, 1 lepton type, while the new models give 4.2 to 23 events. Of course a large part of the extra events in the new models is still just the larger cross section, 14 pb vs 5 pb for the standard model.

We have also investigated other values of M_B and Γ_B/M_B and found similar results. For $p_T^{\min} = 35$ GeV, the additional p_T inherent in these models is of only modest help in increasing the branching ratios of the interesting topologies. For $p_T^{\min} = 50$ GeV the additional p_T is a big help but the branching ratios themselves are quite small.

We note that when we talk about charged leptons we mean electrons or muons. We include the τ lepton by assuming it decays immediately after production into a muon or electron plus neutrinos (35.5% of the time) or into a quark pair plus a neutrino (64.5% of the time). Thus the visible final states of a W decay through a τ have the same particle content as other W decays: an electron, a muon, or a pair of quarks. The possible energies of the visible particles are, of course, different if the decay is through a τ, and that has been included.

TABLE II. Same as in Table I except for $p_T > 50$ GeV.

No. of jets \ No. of leptons		0	1	2
0	SM	0.0155	6.81×10^{-3}	1.36×10^{-3}
	(a)	0.0188	7.30×10^{-3}	1.31×10^{-3}
	(b)	0.0107	5.70×10^{-3}	1.84×10^{-3}
	(c)	0.0148	6.66×10^{-3}	1.53×10^{-3}
	(d)	0.0137	6.85×10^{-3}	1.57×10^{-3}
1		0.105	0.0430	3.48×10^{-3}
		0.109	0.0455	3.04×10^{-3}
		0.0602	0.0395	6.04×10^{-3}
		0.0927	0.0428	3.98×10^{-3}
		0.0876	0.0437	4.32×10^{-3}
2		0.270	0.0670	2.50×10^{-3}
		0.295	0.0631	1.87×10^{-3}
		0.177	0.0795	5.73×10^{-3}
		0.257	0.0696	2.85×10^{-3}
		0.250	0.0720	3.12×10^{-3}
3		0.280	0.0370	
		0.290	0.0304	
		0.258	0.0684	
		0.283	0.0409	
		0.278	0.0447	
4		0.130	4.58×10^{-3}	
		0.121	2.48×10^{-3}	
		0.197	0.0161	
		0.141	5.97×10^{-3}	
		0.150	6.70×10^{-3}	
5		0.0262		
		0.0176		
		0.0722		
		0.0320		
		0.0355		
6		2.29×10^{-3}		
		7.31×10^{-4}		
		9.62×10^{-3}		
		3.14×10^{-3}		
		3.49×10^{-3}		

IV. COLORON SIGNAL AT LHC ENERGY

In this section, we discuss the coloron pair productions in hadronic collisions in the spontaneously broken $SU(3)_I \times SU(3)_{II}$ extended color model. We consider only the case where each coloron decays to top quarks, $t\bar{t}$. Decays of these t(or $\bar{t}$) to a W give rise to four W bosons in the final state. The cross section for these four W productions is much larger than that expected in the standard model. These anomalous W productions will be a very clean signal for physics beyond the standard model. In Sec. IV A, we calculate the differential and total cross sections for the coloron pair production. In IV B, we discuss the multijet and/or multilepton cross sections resulting from the decays of the four tops produced from the coloron pairs.

A. Cross sections for coloron pair productions

The dominant contribution to the coloron pair production at the LHC energy comes from the subprocess

$$g + g \to B + B. \tag{10}$$

The corresponding Feyman diagrams obtained from (5) are shown in Fig. 2. The contribution of the other subprocess $q + \bar{q} \to B + B$ [Eq. (8)] is very small at the LHC

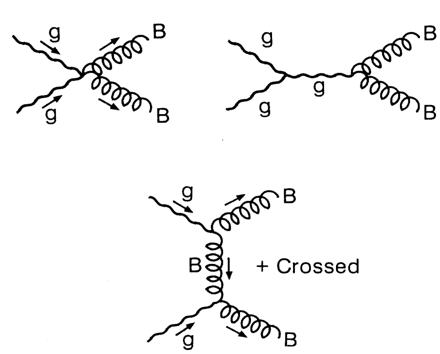

FIG. 2. Feynman diagrams for the process gluon + gluon $\to$ coloron + coloron.

energy because of the low $q\bar{q}$ luminosity.

The differential cross section for the subprocess (10) is obtained to be

$$\frac{d\hat{\sigma}}{dz} = \frac{9\pi\alpha_s^2}{512\,\hat{s}}\beta F(\epsilon, z), \tag{11}$$

where

$$F(\epsilon, z) = \left[\frac{1}{(1+\beta\,z)^2}\left(256 + \frac{48}{\epsilon^2}\right) + \frac{1}{(1+\beta\,z)}\left(-128 - \frac{96}{\epsilon} + \frac{24}{\epsilon^2}\right) + (z \to -z)\right] + 200 + 24\beta^2 z^2 + \frac{48}{\epsilon}. \tag{12}$$

Here, $\hat{s}$ is the total center of mass (c.m.) energy squared for the subprocess, z is the cosine of the c.m. angle, M_B is the mass of the coloron B, α_s is the QCD coupling constant squared over 4π, and

$$\epsilon \equiv \frac{\hat{s}}{4M_B^2}, \quad \beta \equiv \left(1 - \frac{1}{\epsilon}\right)^{1/2}. \tag{13}$$

From Eq. (11), we obtain the total subprocess cross section to be

$$\hat{\sigma} = \frac{9\pi\alpha_s^2}{512\,\hat{s}}\beta\left[\left(1024\epsilon + 416 + \frac{272}{\epsilon}\right) - \left(256 + \frac{192}{\epsilon} - \frac{48}{\epsilon^2}\right)\frac{1}{\beta}\ln\frac{1+\beta}{1-\beta}\right]. \tag{14}$$

The total cross section for the process

$$p + \bar{p} \to B + B + \text{anything} \tag{15}$$

is obtained by folding in the gluon distributions with the above cross section. We have used the distribution produced by the CTEQ Collaboration [8] evaluated at $Q^2 = M_B^2$.

B. Multijet-multilepton final states from coloron pair decays

Using the production cross section above, and assuming the branching ratio for each final state of W decay to be $\frac{1}{9}$, we find the branching ratio for n jets and m charged leptons where $n = 0, \ldots, 12$ and $m = 0, \ldots, 4$. These results depend on the mass of the coloron, the visibility cuts, and the mixing with light quarks [z_1 and z_2 in (8) above]. To isolate the combinations which cannot be produced in lowest order of the SM we consider only the $t\bar{t}\ t\bar{t}$ final state.

As in the Fermilab results above, we combine the quarks into jets using the condition that a quark belongs in an adjacent jet if the angular separation between them is less than ΔR which we take to be 0.5. Once the jets are formed, we require that their transverse momentum be larger than 30 GeV and their rapidity be less 2. For the leptons (electron or muon) we require a transverse momentum of 20 GeV and a maximum rapidity of 2.5. The leptons must be separated from the jets, and from each other by ΔR which is also taken to be 0.5. Thus, for example, if two leptons each satisfy the transverse momentum and rapidity cuts but have ΔR less than 0.5 then they are counted as only one lepton.

If the final state of a W decay is a τ lepton, then we assume the τ has decayed and use its decay products in forming jets and applying the visibility cuts. In other

TABLE III. Branching ratios for the various multijet and multilepton (e or μ) final states at the LHC energy, $\sqrt{s}$ = 14 TeV for the coloron model with coloron mass M_B = 400 GeV. The cuts are $(p_T^{\text{jets}})_{\text{min}}$ = 30 GeV, $(p_T^{\text{leptons}})_{\text{min}}$ = 20 GeV, $y_{\text{jet}} \leq 2.0, y_{\text{lepton}} \leq 2.5$, and $\Delta R = 0.5$ everywhere as discussed Sec. IV B. The top mass has been taken to be 175 TeV. The decays of τ to e, μ or quarks have been included. Each branching ratio in the table should be multiplied by $[0.6695/(4z_1^2/z_2^2 + 1.6695)]^2$.

No. of jets \ No. of leptons	0	1	2	3	4
0				1.18×10^{-5}	1.80×10^{-6}
1				1.76×10^{-4}	3.55×10^{-5}
2				1.15×10^{-3}	1.67×10^{-4}
3				3.30×10^{-3}	3.50×10^{-4}
4				5.05×10^{-3}	2.43×10^{-4}
5			0.0326	3.86×10^{-3}	
6			0.0258	1.04×10^{-3}	
7		0.0770	0.0103		
8		0.0391	1.69×10^{-3}		
9	0.0589	0.0106			
10	0.0192	1.11×10^{-3}			
11	4.01×10^{-3}		$\sigma = 758 \pm 2$ pb		
12	3.51×10^{-4}				

TABLE IV. Same as in Table III, except for $M_B = 600$ GeV. Each branching ratio in the table should be multiplied by $\left[0.9504/(4z_1^2/z_2^2+1.9504)\right]^2$.

No. of jets \ No. of leptons	0	1	2	3	4
0				4.75×10^{-6}	1.37×10^{-6}
1				9.65×10^{-5}	2.45×10^{-5}
2				7.94×10^{-4}	1.66×10^{-4}
3				3.13×10^{-3}	4.29×10^{-4}
4				6.03×10^{-3}	3.65×10^{-4}
5			0.0347	5.40×10^{-3}	
6			0.0335	1.86×10^{-3}	
7		0.0942	0.0173		
8		0.0607	3.73×10^{-3}		
9	0.0792	0.0207			
10	0.0350	3.22×10^{-3}			
11	9.75×10^{-3}		$\sigma = 67.32 \pm 0.16$ pb		
12	1.09×10^{-3}				

words in case of a τ, we go one level further in the decay chain to find the particles we treat as the final state.

We keep a coherent sum over the polarizations of the W's from the top decays but not for the W's in the τ decays. We do not keep a coherent spin sum for the top quarks.

Our results are given in Tables III–V for a coloron mass of 400, 600, and 800 GeV. We give results only for the branching ratios for events with more jets or leptons than can be straightforwardly produced in the SM, or by other final states of the colorons, $t\bar{t}\,b\bar{b}$ for example. To include mixing with the lighter quarks each branching ratio should be multiplied by

$$\left[\frac{z_2^2 I}{4z_1^2+z_2^2+z_2^2 I}\right]^2 ,$$

where I is given by

$$I=\left(1+2\frac{m_t^2}{M_B^2}\right)\left(1-4\frac{m_t^2}{M_B^2}\right)^{1/2} .$$

These branching ratios are rather small; fortunately the production cross sections are large so the actual number of events with these topologies can be large.

V. CONCLUSION

At Fermilab energies we have calculated the branching ratios for the various final states possible from a $t\bar{t}$ pair produced through resonant coloron. This is quite model dependent; however, the motivation for these models is

TABLE V. Same as in Table III except for $M_B = 800$ GeV. Each branching ratio in the table should be multiplied by $\left[0.9853/(4z_1^2/z_2^2+1.9853)\right]^2$.

No. of jets \ No. of leptons	0	1	2	3	4
0				1.71×10^{-6}	7.62×10^{-7}
1				6.02×10^{-5}	1.70×10^{-5}
2				5.92×10^{-4}	1.29×10^{-4}
3				2.76×10^{-3}	3.61×10^{-4}
4				5.51×10^{-3}	3.23×10^{-4}
5			0.0334	4.76×10^{-3}	
6			0.0302	1.55×10^{-3}	
7		0.0879	0.0142		
8		0.0509	2.95×10^{-3}		
9	0.0687	0.016			
10	0.0287	2.29×10^{-3}			
11	6.71×10^{-3}		$\sigma = 9.448 \pm 0.024$ pb		
12	8.79×10^{-4}				

that they can give a larger cross section than the SM. Thus we choose sets of parameters which give a production cross section of about three times the SM cross section. Our results are shown in Tables I and II. We see that the branching ratios for the interesting final states are not very different from those of the standard model unless we take a large value for the minimum p_T. This seems to be in agreement with Ref. [3]. We have chosen to require a large transverse momentum for the jets and leptons because it was hoped that these models would be distinguished by larger branching ratios for large transverse momentum.

The only check we have on the accuracy of the numbers in any of the tables is to rerun the Monte Carlo integration which generates the histograms with different sets of random numbers. When we do this the branching ratios, even those whose values are very small, remain very stable; nevertheless we feel that the very small numbers should not be trusted.

At LHC energies we have calculated the branching ratios for the various final states of coloron-coloron $\to t\bar{t}\, t\bar{t}$ production, these are given in Tables III–V. Here we have many final states that are only possible in higher order in the SM; if n is the number of jets and m is the number of electron or muons these final states are $m > 2$ if $n \leq 2, m > 1$ if $3 \leq n \leq 4, m > 0$ if $5 \leq n \leq 6$. Even when the branching ratios for these states are rather small, this is compensated by a large production cross section if the coloron mass is not too large. Detection of these states would be a very strong signal for the coloron.

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