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A Preliminary Calculation of the Background to t Detection With Tagged bs*

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We investigate the utility of using tagged b jets as a probe for the top quark. We present an approximate calculation of the QCD rate at Tevatron energies for the production of six jets where one of the jets is required to contain a b quark, along with the corresponding rate involving an intermediate $t\bar{t}$ pair. With a minimal set of cuts, the signal-to-background is expected to be of order one-to-one, in contrast to the case where no jets are tagged, when the signal-to-background is at least fifty times worse.

The top quark is one of two missing pieces in the experimental verification of the standard model, and the one whose discovery at the Tevatron — long before either the LHC or the SSC turns on — is most likely. Given the current CDF limit of approximately 90 GeV on the t quark mass, each top will decay into a W plus a b quark; the W in turn will decay primarily into jets and partially into leptons + corresponding neutrinos. Once the top is sufficiently heavy, the b quarks will produce observable jets, and the dominant observed configurations for $t\bar{t}$ production will thus be either 5 jets + lepton + missing energy or 6 jets. A somewhat smaller mode, which may also be promising for detection of the top quark if it is not too heavy, is the one where both Ws decay leptonically, into different leptons. The lepton + 5 jets mode will be discussed in detail elsewhere by Berends, Giele, Kuijf, and Tausk[7].

Here we shall concern ourselves with the detection of the top in pure jet modes. Kunszt and Stirling[1] examined the expected QCD background in the six-jet mode at LHC energies, using an approximation based on the $gg \to 6g$ process, and found that the raw signal-to-background was of order 1 to 3000; even after a list of cuts, the signal-to-background remained of order 1 to 50, which is to say with the expected statistics, detection without further cuts would be hopeless.

The advent of silicon strip microvertex detectors may however enable experimenters to 'tag' jets containing b quarks. The b has a sufficiently long lifetime that it creates a displaced vertex; thus one may be able to create a sample of jet events containing a b-quark (or at least substantially enriched in b quarks) by demanding the presence of a displaced vertex.

One might expect that as every signal event contains a b, but not every background event does, that this might improve the signal-to-background ratio. We should therefore ask how such tagging would affect the background rates, and how the backgrounds with b's compare with the signal from $t\bar{t}$ events. To answer these questions, one must be able to compute both processes. The top signal is relatively easy; we have employed the formulæ of Kleiss and Stirling[2] (correcting a few minor typos), which fold the decays of the top-antitop pair and the daughter Ws in with the production matrix elements. The calculation of the QCD background is much harder, in terms of the calculation, the programming, and the amount of computer time required. We have therefore chosen to use a set of approximations based on the infrared reduction technique of Maxwell[3, 4]. Such approximations have been compared with exact tree-level matrix elements for pure gluon matrix elements, and are known to work quite well. The errors are perhaps larger in matrix elements involving quarks, but for the purposes of obtaining a rough estimate, to say 50%, of the expected signal-to-background ratio, they should be quite adequate. We have also compared the approximations for the various subprocesses of interest with the exact matrix elements for 5 jets.

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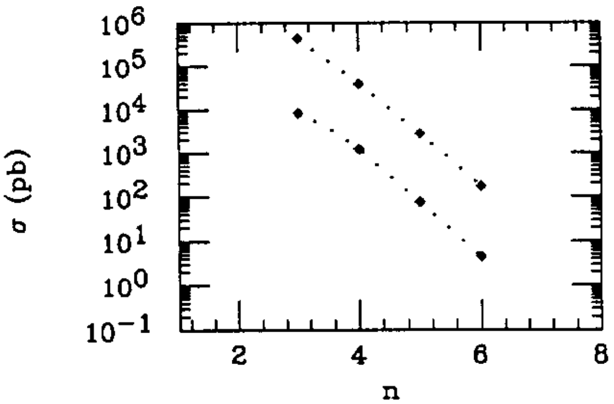

Figure 1: n-jet cross-sections at the Tevatron. Upper curve: all jets; lower curve: jets with one tagged b.

We model the CDF detector cuts by parton-level cuts on the rapidity, and minimum transverse energy of the outgoing partons, and on the $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ between pairs of outgoing partons. We ignore the mass of the b in the background calculations; this is expected only to underestimate the signal-to-background ratio. The vertex detector to be employed by CDF will have a narrower rapidity coverage than the hadron calorimeter, but we overlook this fact as well; it should not affect the estimate of the signal-to-background, since the background is expected to be dominated by processes that involve the production of a single $b\bar{b}$ pair, the same as for the signal. We have also not included a factor for the efficiency of the vertex detector, but this again will be the same for the signal and the backgrounds.

In the calculations presented here, we will use the following cuts: parton $p_T > 25$ GeV, $\Delta R > 0.8$, and $|\eta| < 3.5$. We will use the MRS-2 set of structure functions ($\Lambda = 0.2$ GeV). The first thing we should do is examine the fraction of n-jet events that contain b-quarks. In fig. 1, we compare the cross section for n jets with the cross section for n jets with one tagged b. One should expect a factor of fifty reduction in the background with the tag.

The idea behind Maxwell's infrared reduction technique is to write the amplitude for a given $2 \to (n-2)$ subprocess in the form

$$\mathcal{A}_n = A_n^{\text{simple}} \frac{\mathcal{A}_n}{A_n^{\text{simple}}}$$

where A^{simple} is a simple analytical function that captures the important pole structure of the full amplitude – for example, the Parke-Taylor formula[5], or corresponding formulæ for special helicity amplitudes with one or two quark pairs. One then approximates the ratio $\mathcal{A}_n/A_n^{\text{simple}}$ by evaluating it for a configuration of outgoing momenta which has one *collinear* pair of momenta k_i, k_j but is otherwise 'near' the original configuration, and using the Altarelli-Parisi behavior of the amplitudes and the corresponding collinear behavior of A^{simple},

$$\frac{\mathcal{A}_n}{A_n^{\text{simple}}} = \frac{\mathcal{A}_{n-1}}{A_{n-1}^{\text{simple}}} \frac{\mathrm{AP}(z)}{\mathrm{Collinear}_{\text{simple}}(z)}$$

where $z = E_i/(E_i+E_j)$. One repeats this process until n is small enough to evaluate the ratio $\mathcal{A}_n/A_n^{\text{simple}}$ exactly. There are a variety of choices that can be made for A^{simple} — we have used the Parke-Taylor amplitude, even for the reduction of amplitudes containing quarks, as this seems to give a more stable behavior; for the legs to reduce — we have chosen to reduce pairs of outgoing gluons, or outgoing quarks with gluons, at each stage of the infrared reduction process; and for the n at which to terminate the reduction — we stop at $n = 5$.

This last choice implies that we cannot use this approximation scheme to estimate the contribution of six-quark processes, in particular for the subprocess in which valence quarks scatter and produce a new $b\bar{b}$ pair in the final state (in addition to two gluons). This process could be approximated using a reduction to $n = 6$, and we are planning to do so; for the preliminary investigation reported here, we have estimated the six-quark processes by taking the leading four-quark process ($q\bar{q} \to q\bar{q}gggg$, where the incoming quarks are valence quarks), and adjusting only for the color factor.

In order to check these approximations, we have compared the cross-sections for five-jet production with the results obtained from exact tree-level matrix elements using the NJETS code[6]. The results of this comparison are given in the following table,

Process	Cross Section (pb)	
	Exact	Approximation
$gg \to ggggg$	$(7.2 \pm 0.9) \cdot 10^2$	$(9.11 \pm 0.07) \cdot 10^2$
$qg \to qgggg$	$(1.1 \pm 0.2) \cdot 10^3$	$(1.79 \pm 0.07) \cdot 10^3$
$gg \to q\bar{q}ggg$	$(1.6 \pm 0.2) \cdot 10^2$	$(1.16 \pm 0.01) \cdot 10^2$
$q\bar{q} \to ggggg$	4.0 ± 0.8	2.75 ± 0.02
$q_1\bar{q}_1 \to q_2\bar{q}_2ggg$	1 to 6	8.85 ± 0.08
$q_1g \to q_1q_2\bar{q}_2gg$	50 ± 15	95 ± 1
Six – quark	$(1.4 \pm 0.5) \cdot 10^2$	$(1.47 \pm 0.01) \cdot 10^2$

and indicate that the approximations are trustworthy to better than a factor of 2. The computational complexity of the exact matrix element, especially for subprocesses involving two quark pairs, is evident in the larger statistical errors.

Jet calculations suffer from a systematic uncertainty due to the choice of the scale for the QCD running coupling. In our calculations, we have used the (standard) choice of average outgoing jet E_T. It is presumably possible (and desirable) to fix this uncertainty by comparing the *total* six-jet rate to that measured at CDF, as jet results emerge from the 1988–89 run.

We estimate the background as follows,

$gg \to b\bar{b}gggg$	1.1 pb
$q\bar{q} \to b\bar{b}gggg$	0.15 pb
$qg \to qb\bar{b}ggg$	0.92 pb
$q\bar{q} \to q\bar{q}b\bar{b}gg$	2.2 pb

with statistical errors of a few percent. The background from intrinsic b in the proton is negligible at the Tevatron (less than 0.3 pb). Thus the total background is estimated at about 4.4 pb, to be contrasted with a signal of 0.77 pb (for $m_t \sim 140$ GeV). The signal is shown as a function of top quark mass in fig. 2. At low masses, it drops because the daughter bs become too soft to survive the transverse energy cut, whereas at high masses, the production cross section falls.

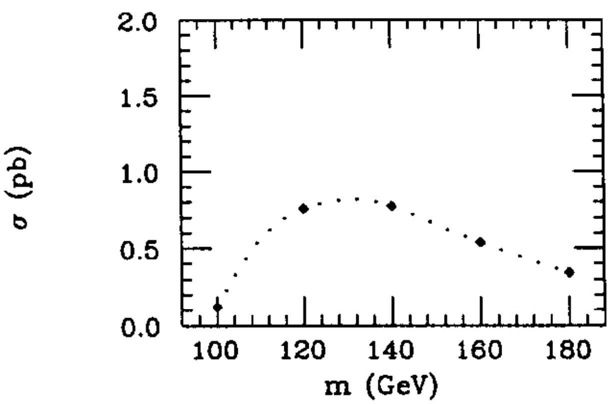

Figure 2: Cross section for six jets from $t\bar{t}$ decay, as a function of the top quark mass.

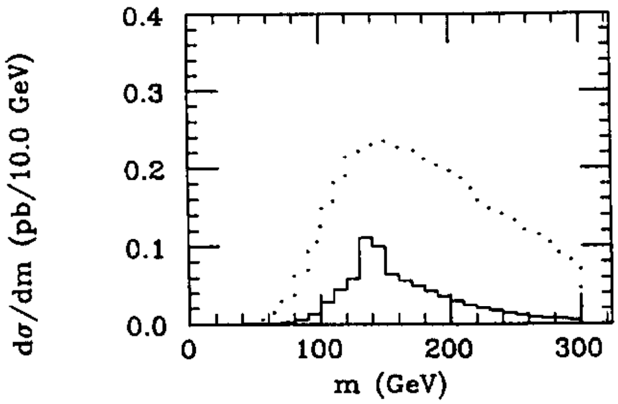

Figure 3: Three-jet invariant mass distribution, averaged over all possible assignments. Upper curve: background; lower curve: signal, for $m_t = 140$ GeV.

However, the background is expected to be rather featureless, whereas the signal is known to contain peaks in the three-jet invariant mass distribution (the top quarks!). We can use a relatively simple cut based on this to improve the signal-to-background to $O(1)$ (in the bin containing the top quark), as follows: for each event, we consider all ten possible assignments of the six jets to two trios. We form the invariant masses of the two trios m_1 and m_2, and retain only assignments satisfying $|m_1 - m_2| < 25$ GeV. If there is no assignment satisfying this requirement, we reject the event; if there are multiple assignments satisfying the requirement (and there often are), we pick the assignment with the lowest possible m_1 or m_2. Were we to consider all possible assignments, we would end up with broad peaks for both the background and the signal, as shown in fig. 3; the background has a peak because the cuts eliminate low-mass trios, while the rate for high-mass trios falls off for the usual dimensional reasons. The peak for the signal is smeared out by the *incorrect* reconstructions. Imposition of

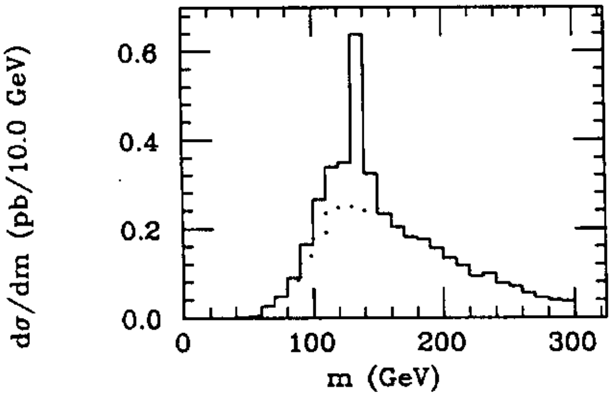

Figure 4: Three-jet invariant mass distribution, after matched-trio cut. Solid curve background+signal (m_t = 140 GeV); dotted curve: background.

the 'matched-trio' cuts given above has two effects: it cuts down on the background, and also concentrates the signal in a single 20 GeV interval. The combined signal and background are shown in fig. 4 for a top of 140 GeV. It is also possible to impose additional cuts, say by demanding that within each trio, a pair of jets reconstruct to with 15 GeV of the W mass; but this does not seem to improve the signal-to-background much. The combined signal and background with this additional cut are shown in fig. 5 for a top of 160 GeV.

These results suggest that the tagged-jet mode may well be promising for detecting and studying the top quark, and deserves further study. We thank E. Eichten and W. J. Stirling for helpful discussions.

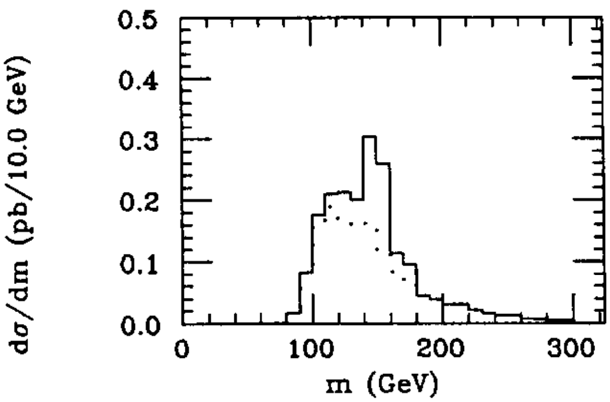

Figure 5: Three-jet invariant mass distribution, after matched-trio and W-mass cuts. Solid curve background+signal (m_t = 160 GeV); dotted curve: background.

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