Fermi National Accelerator Laboratory

FERMILAB-Pub-93/105-T
May, 1993

HEAVY TOP QUARK SEARCHES IN THE DI-LEPTON MODE AT THE TEVATRON

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ABSTRACT

We present the results of a detailed study of the effects of b-tagging on the heavy top-quark signal and backgrounds for the modes of the di-lepton plus two high transverse energy jets at the Fermilab Tevatron. The general characteristics of the heavy top-quark signal events are also discussed so that a comparison can be made between b-tagging and imposing stringent kinematical cuts to eliminate backgrounds.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

In spite of the tremendous success of the Standard Model (SM) up to the highest energies accessible today, the top quark has not yet been observed. To experimentally establish the existence of the top quark (t) and measure its mass (m_t) is not only crucial to completing the pattern of the three generations of fermion families, but it is also important as a probe of new physics beyond the SM [1].

Precision measurements of electroweak parameters imply that in the SM, $m_t = 150^{+19+15}_{-24-20}$ GeV [2]. The current direct experimental mass limits on the SM top quark are $m_t > 108$ GeV from CDF Collaboration [3] and $m_t > 103$ GeV from D0 Collaboration [4]. With an integrated luminosity of 25 pb^{-1} for the Tevatron, CDF/D0 should be able to search for the top quark up to $m_t \approx 130$ GeV; and to $m_t \approx 170$ GeV with 100 pb^{-1}. With the new Main Injector an integrated luminosity of 10^3 pb^{-1} should be easily obtained, pushing the reach of the Tevatron to top-quark masses greater than 200 GeV.

Standard Model top quarks, with masses greater than the W-boson mass, are produced at Tevatron energies, $\sqrt{s} = 1.8$ TeV, predominantly by $q\bar{q} \to t\bar{t}$ and decay into Wb final state with almost a 100% branching fraction. The experimental signature of a top quark will therefore be two energetic b-quark jets plus a pair of W's. The hadronic decays of the W-boson pair are of the largest rate for the top-quark signal, with a branching fraction $\text{BF}(t\bar{t} \to b\bar{b} + 4 \text{ jets}) = (2/3)^2$. However, the QCD 6-jets background swamps this signal [5]. Even with an efficient b-tagging, the experimental searches in this channel are still difficult [6]. The single leptonic modes also have a large rate, with $\text{BF}(t\bar{t} \to b\bar{b}\ell^{\pm}\nu + 2 \text{ jets}) = 2(2/9)(2/3)$, where $l = e, \mu$. The continuum $W^{\pm}+$ 4-jets background is also large. For a top quark of $m_t < 170$ GeV, it is possible after some optimized kinematical cuts to reach a signal/background ratio of order one [7,8]. Additional information can be obtained from b-tagging to improve the situation [9], however more comprehensive studies including the effects of c-quark production and jet smearing are required. The di-lepton modes are considered to be the cleanest channel for top quark searches, though with a smaller branching fraction $\text{BF}(t\bar{t} \to b\bar{b}\ell^+\ell^-\nu\bar{\nu}) = (2/9)^2$. For a very heavy top quark this channel is not background free.

In this letter, we study the effects of b-tagging to purify the top-quark signal in the di-lepton decay modes. For simplicity, only $e^{\pm}\mu^{\mp}$ final states are counted in the numerical presentation. An additional factor of two is needed to include ee and $\mu\mu$ channels but slightly more care is necessary to separate the backgrounds. We present for the first time the calculation of the background processes, $p\bar{p} \to e^{\pm}\mu^{\mp}\ \not{p}_T\ b\bar{b}$, $e^{\pm}\mu^{\mp}\ \not{p}_T\ c\bar{c}$, and $e^{\pm}\mu^{\mp}\ \not{p}_T\ cq(g)$ (where $\not{p}_T$ denotes the missing transverse momentum), which are relevant to the b-tagged signal. A comparison is made between the effects of tagging one b-quark jet versus imposing stringent kinematical cuts to eliminate backgrounds.

The experimental signature of a heavy top quark in the di-lepton mode under consideration is

$$t\bar{t} \ \to\ e^{\pm}\mu^{\mp}\ \not{p}_T jj\ , \tag{1}$$

where $e^{\pm}\mu^{\mp}$ are well isolated charged leptons coming from the W decays; $\not{p}_T$ is mainly from the missing neutrinos; and j's are the jets resulting from the b-quark hadronization and decay.

Without identifying the b-quark flavor, the major backgrounds to process (1) are the Drell-Yan process (called $\tau^+\tau^- jj$ background)

$$Z^*(\gamma^*)jj \ \to\ \tau^+\tau^- jj \ \to\ e^{\pm}\mu^{\mp}\ \not{p}_T jj\ , \tag{2}$$

and the W-pair production (called $W^+W^- jj$ background),

$$W^+W^- jj \ \to\ e^{\pm}\mu^{\mp}\ \not{p}_T jj\ . \tag{3}$$

We have calculated the cross section for these three processes using the fully spin-correlated matrix elements [10-12]. For the production of a pair of top quarks, heavier than 100 GeV at Tevatron energies, the typical momentum fraction of a parton inside a proton is in the range 0.1 - 0.3. Therefore, the theoretical uncertainty from the parton distribution functions is small. However, since our calculations are at tree level, $\mathcal{O}(\alpha_s^2(Q))$, the results are sensitive to our choice of the renormalization scale, Q. We normalize our signal cross section to the full $\mathcal{O}(\alpha_s^3)$ results [13], which has a small uncertainty, approximately 25%. For the backgrounds, we estimate the uncertainties by varying the scale in the range $M_Z/2 < Q < 2M_Z$ for $\tau^+\tau^- jj$ and $M_W/2 < Q < M_{WW}$ for $W^+W^- jj$, where M_{WW} is the invariant mass of the W^+W^- system. The HMRS Set-B parton distribution functions [14] have been used for these calculations with the factorization scale set equal to the renormalization scale, Q.

To calculate the cross sections for both the signal and background processes we first impose the following minimal acceptance cuts,

$$
\begin{aligned}
p_T(\ell) &> 15 \text{ GeV}, & |y(\ell)| &< 2, & \not{p}_T &> 20\text{GeV}, \\
E_T(j) &> 15 \text{ GeV}, & |y(j)| &< 2, \\
\Delta R(jj) &> 0.7, & \Delta R(\ell j, \text{or } \ell\ell) &> 0.4,
\end{aligned}
\tag{4}
$$

where $p_T(E_T)$, y, and $\Delta R(ij)$ are the transverse momentum (energy), pseudorapidity, and the separation between i and j in the pseudorapidity-azimuthal angle plane, respectively. These cuts cover most of the phase space region for the signal events and roughly simulate the CDF/D0 detector acceptance.

Figure 1 shows the total cross sections for the processes (1)-(3). For $m_t < 120$ GeV, we see that the signal rate (dashes) is larger than the backgrounds (dots) by about an order of magnitude. The total background cross section is less than 46 fb (38 fb from $\tau^+\tau^- jj$ channel), corresponding to 1.1 $e\mu$ events for an integrated luminosity of 25 pb^{-1}. In searching for a heavier top quark additional handles to suppress these backgrounds are desirable.

Since CDF has a working Silicon microvertex detector, it is natural to ask how advantageous it is to tag on one of the b-quarks to enhance the top-quark signal over the background. If the jets in background processes were all from light quarks (or gluons), then the backgrounds would be highly suppressed by tagging one of the two b-quarks in the signal, assuming a 1% misidentification for the light quark jets. However, there is open flavor $b\bar{b}$ production via

$$\begin{aligned} gg,\ q\bar{q} &\to Z^*(\gamma^*)b\bar{b} \ \to\ \tau^+\tau^- b\bar{b} \to\ e^\pm\mu^\mp\ \not{p}_T b\bar{b}\ , \\ gg,\ q\bar{q} &\to W^+W^- b\bar{b} \ \to\ e^\pm\mu^\mp\ \not{p}_T b\bar{b}\ . \end{aligned} \tag{5}$$

which have to be carefully studied when b-tagging is applied. We have calculated these cross sections using the full Standard Model matrix elements, in the limit $m_b = 0$. The contribution from the b-parton distribution in the protons has been ignored [15]. The b-quark mixings with the first two generation quarks are small (*e. g.*, $V_{cb}^2 \approx 3 \times 10^{-3}$) and hence negligible. With the cuts of Eq. (4), we find that the cross section for $e^\pm\mu^\mp\not{p}_T b\bar{b}$ is 0.21 fb from W^+W^-jj process and 0.47 fb from $\tau^+\tau^-jj$. These background rates are significantly smaller than the signal, making the b-tagging scheme very promising for enhancing the signal to background ratio.

However, due to the comparable lifetime of the charmed-mesons to the b-mesons, it is difficult to experimentally distinguish the b's and c's on an event by event basis. We are therefore forced to consider the c-quark production. Besides the open flavor $c\bar{c}$ pair production similar to Eq. (5), there are single c contributions, such as

$$gc \to e^\pm\mu^\mp\not{p}_T gc, \qquad qc,\ qq' \to e^\pm\mu^\mp\not{p}_T qc, \tag{6}$$

that must be evaluated if single b-tagging is to be used. Again, we have ignored the generation mixings among quarks. The largest error in this approximation is from the valence quark transition $d \to cW$, proportional to $V_{cd}^2 = 0.048$. The cross section from this transition is only about 10^{-3} fb, which is negligible.

In Table (1) we list the contributions from the individual channels. Figure 1 compares the cross sections of $e^\pm\mu^\mp\not{p}_T jj$ with at least one heavy quark (b, c) in the jets from the $t\bar{t}$ signal, W^+W^-jj and $\tau^+\tau^-jj$ background processes. From this figure it is clear that

Table 1: The central value for the QCD b-quark and c-quark associated production rates with $e^\pm\mu^\mp$ and $\not{p}_T$ at $\sqrt{s}$ = 1.8 TeV (in units of fb). W^+W^- and $\tau^+\tau^-$ indicate the source of the final state $e^\pm\mu^\mp$.

	W^+W^-	$\tau^+\tau^-$
$q\bar{q} \to e^\pm\mu^\mp \not{p}_T b\bar{b}$	0.20	0.33
$gg \to e^\pm\mu^\mp \not{p}_T b\bar{b}$	0.01	0.14
$q\bar{q} \to e^\pm\mu^\mp \not{p}_T c\bar{c}$	0.10	0.30
$gg \to e^\pm\mu^\mp \not{p}_T c\bar{c}$	0.01	0.11
$gc \to e^\pm\mu^\mp \not{p}_T gc$	0.02	0.30
$qc(q') \to e^\pm\mu^\mp \not{p}_T qc$	0.01	0.15

the signal rate is higher than the backgrounds by more than an order of magnitude up to $m_t \approx$ 200 GeV. Assuming a 30% tagging efficiency, independent of E_T, for a b-quark to be identified having a second vertex (50% for tagging one of the two b's), the signal cross section for $m_t \approx$ 200 GeV is 16 fb, while the summed background is less than 1.0 fb. Now, the signal to background ratio is better than 16:1. To achieve this high S/B ratio, the signal has been reduced by a factor of two. However, the experimentalists could loosen the b-tagging requirement to retain a larger fraction of the signal. since the background is so much smaller than the signal. Table (1) can be used to calculate the backgrounds for tagging efficiencies other than the 30% assumed here. Of course in reality the b-tagging efficiency is higher for more energetic jets. Since the signal jets are typically stiffer than the background jets, the signal to background ratio will be higher than indicated here.

An alternative technique for separating the di-lepton signal from the backgrounds is to tighten the kinematical cuts [16]. Since the $\tau^+\tau^-jj$ background is predominantly from an on-shell Z decay, the cluster transverse mass variable M_T is limited by the Z mass, where M_T is defined as

$$M_T^2 = [(M_{\ell\ell}^2 + p_{T\ell\ell}^2)^{1/2} + |\not{p}_T|]^2 - (\mathbf{p}_{T\ell\ell} + \not{\mathbf{p}}_T)^2 \tag{7}$$

with $M_{\ell\ell}$ and $p_{T\ell\ell}$ the the invariant mass and the transverse momentum of the charged lepton pair. As suggested in Ref. 16, requiring $M_T > M_Z$ would therefore substantially reduce the $\tau^+\tau^-$ background. In Figure 2(a) and (b) we have plotted the signal and background differential cross sections versus the minimum transverse momentum of the charged leptons, $p_T^{min}(l) = min(p_T(l_1), p_T(l_2))$, and the leptonic cluster transverse mass, M_T. For the $e^\pm\mu^\mp$ modes with two high E_T jets, the distributions of the azimuthal separation between the two charged leptons does not provide a clear distinction between the signal and backgrounds. In particular the high transverse energy of the jets smears out the peak in the $\tau^+\tau^-jj$ background at 180 degrees.

Furthermore, the QCD jets in the backgrounds discussed here tend to be soft, in contrast to the rather hard b-quark jets from heavy top decays. A higher jet threshold would be helpful in reducing the backgrounds. To see this, in Figure 3(a) and (b) we have plotted the signal and background differential cross sections versus the minimum transverse energy of the two jets, $E_T^{min}(j) = min(E_T(j_1), E_T(j_2))$, and the scalar sum of the transverse jet energies, $E_T^{sum} = E_T(j_1) + E_T(j_2)$.

Figure 4 shows the total cross section with the additional cuts

$$M_T > 90 \text{ GeV}, \qquad p_T(j) > 30 \text{ GeV}. \tag{8}$$

With these stringent cuts, Eq. (4) and (8), the signal rate is larger than the backgrounds by an order of magnitude up to $m_t = 200$ GeV, with only a moderate reduction in the signal; about 30% reduction for $m_t = 150$ GeV, and 10% for $m_t = 200$ GeV. Further kinematic cuts could also be applied, if necessary, such as a cut on the scalar sum of the transverse jet energies.

In conclusion, we have demonstrated that in the search for the heavy top quark in the di-lepton mode that the signal can be easily distinguished from the W^+W^-jj and $\tau^+\tau^-jj$ physics backgrounds by either tagging one of the jets as a b-quark jet or by making stringent kinematical cuts for top quark masses up to 200 GeV. Of course, events that are b-tagged and also pass the stringent kinematical cuts are truly platinum candidates for the discovery of the heavy top quark.

Acknowledgements:

The authors wish to thank V. Barger, W. Giele, J. Ohnemus, M. Peskin, R. Phillips, S. Willenbrock and G.-P. Yeh for discussions. Fermilab is operated by the Universities Research Association Inc. under contract with the United States Department of Energy.

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FIGURE CAPTIONS

1) Total cross sections at $\sqrt{s} = 1.8$ TeV, with the minimal cuts, Eq. (4), for the $t\bar{t}$ signal (dashes), and backgrounds from $\tau^+\tau^- jj$ and $W^+W^- jj$ (dots). The solid lines are for the processes, $\tau^+\tau^- jj$ and $W^+W^- jj$, with at least one of the jets a b-quark or c-quark jet. The range corresponds to the scale choices of $M_Z/2 < Q < 2M_Z$ for $\tau^+\tau^- jj$ and $M_W/2 < Q < M_{WW}$ for $W^+W^- jj$.

2) Differential cross sections, at $\sqrt{s} = 1.8$ TeV, for the signal (solid) with $m_t = 150$ GeV and 200 GeV and the backgrounds $\tau^+\tau^- jj$ (dot-dashed) and $W^+W^- jj$ (dashed); (a). Minimum p_T distribution of the two charged leptons, (b). Leptonic cluster transverse mass, M_T, distribution. The minimal cuts of Eq. (4) have been imposed.

3) Differential cross sections, at $\sqrt{s} = 1.8$ TeV, for the signal (solid) with $m_t = 150$ GeV and 200 GeV and the backgrounds $\tau^+\tau^- jj$ (dot-dashed) and $W^+W^- jj$ (dashed); (a). Minimum E_T distribution of the two jets, (b). The scalar sum of the transverse jet energies, E_T^{sum}, distribution. The minimal cuts of Eq. (4) have been imposed.

4) Total cross sections at $\sqrt{s} = 1.8$ TeV, with stringent cuts, Eq. (4) and (8), for the $t\bar{t}$ signal (dashes), and backgrounds from $\tau^+\tau^- jj$ and $W^+W^- jj$ (dots). The range corresponds to the same choices of scale as Fig. 1.

fig. 1

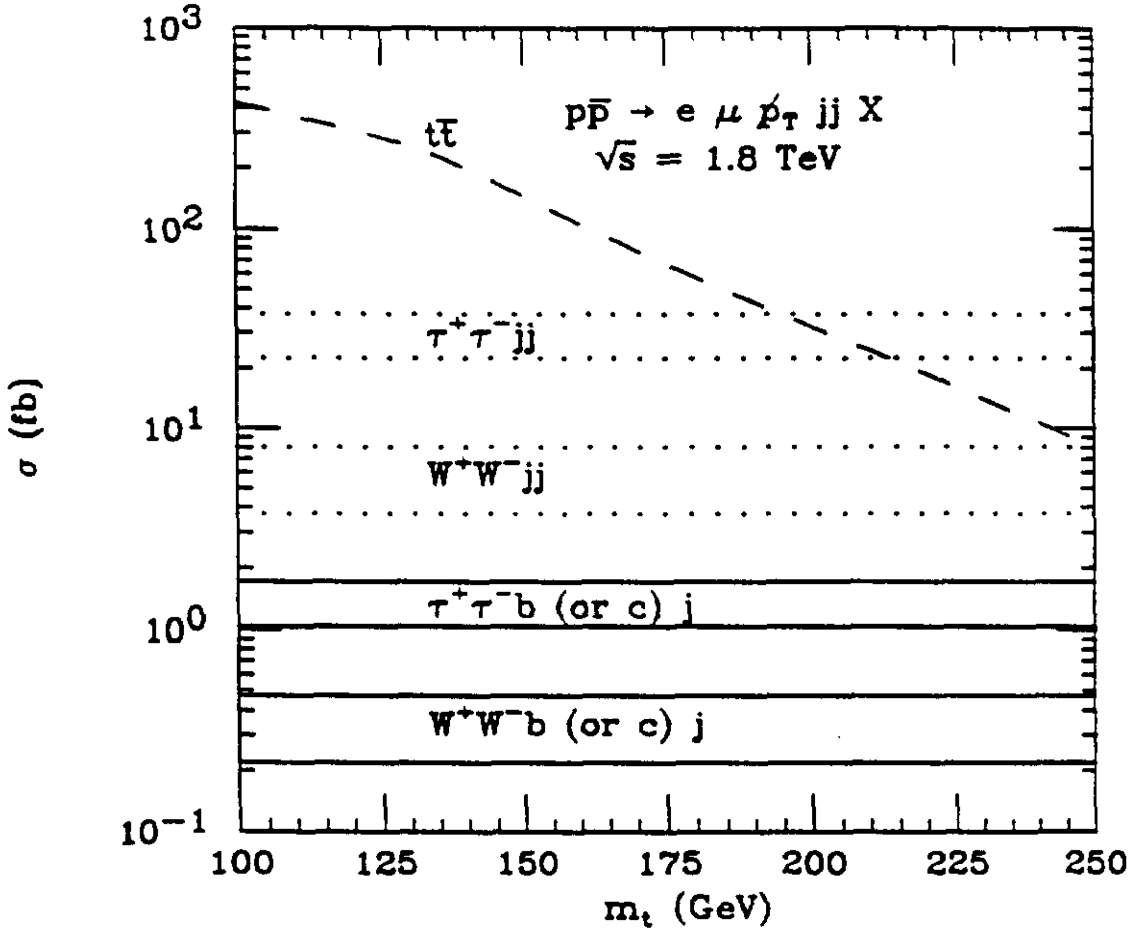

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fig. 2

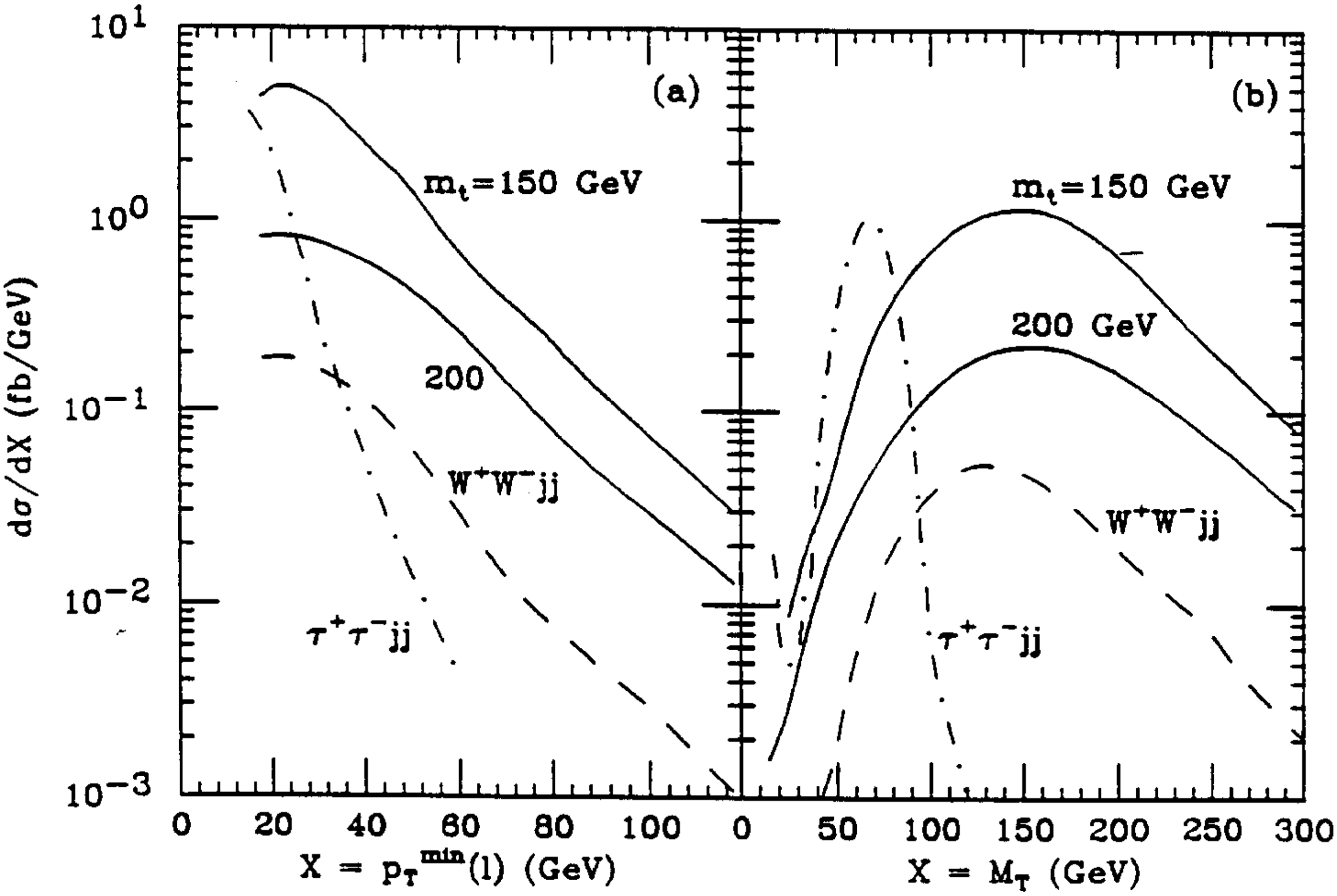

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fig. 3

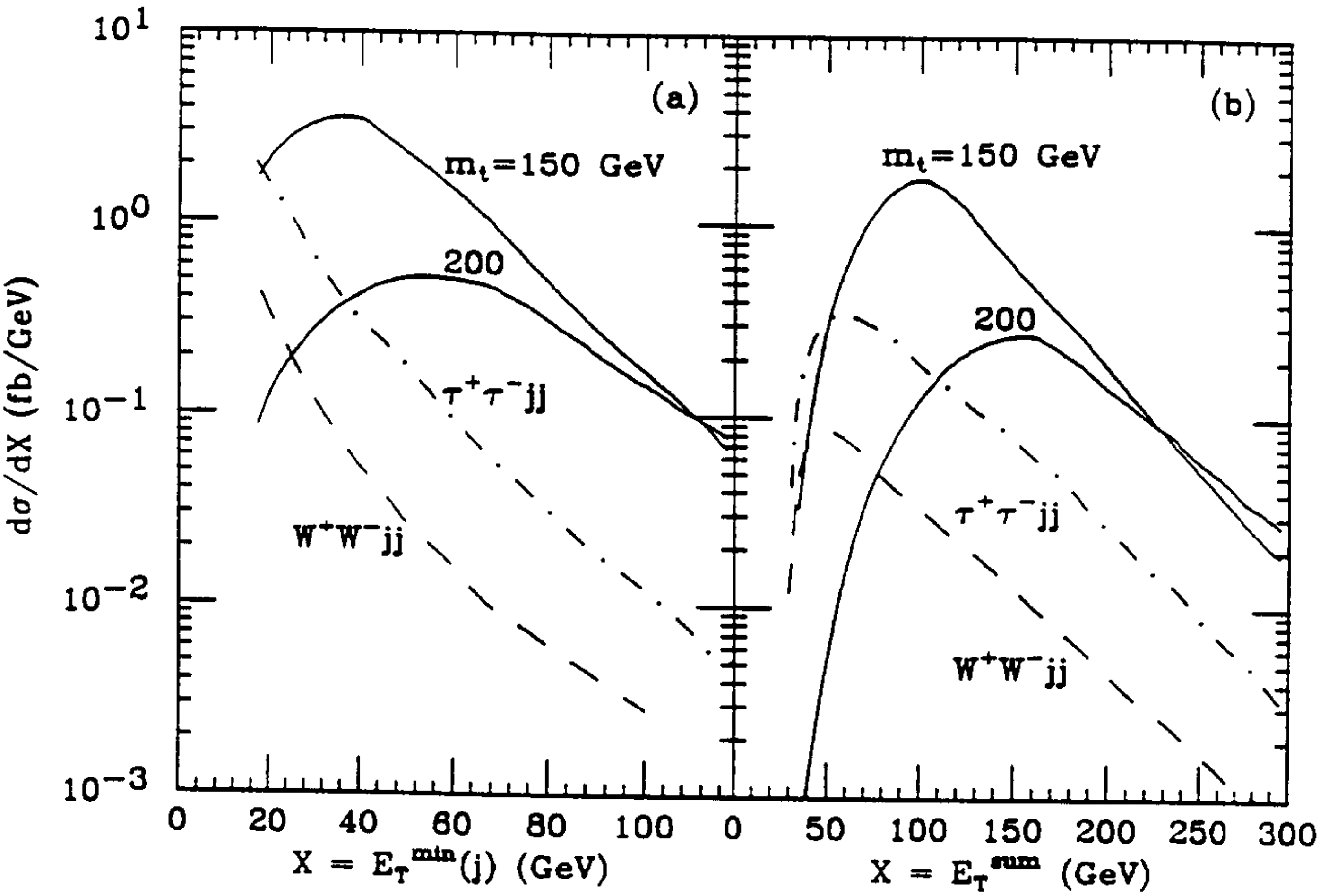

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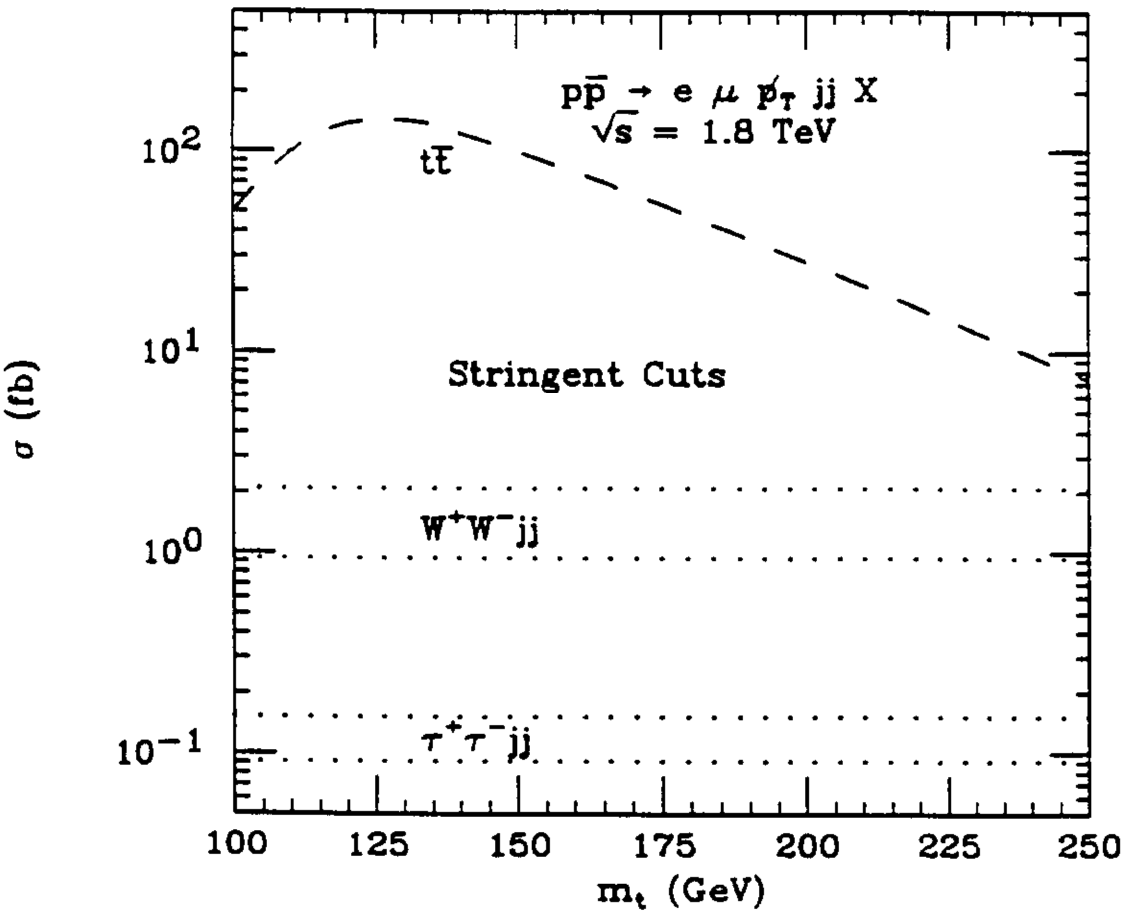
fig. 4



4) Total cross sections at $\sqrt{s} = 1.8$ TeV, with stringent cuts, Eq. (4) and (8), for the $t\bar{t}$ signal (dashes), and backgrounds from $\tau^+\tau^- jj$ and $W^+W^- jj$ (dots). The range corresponds to the same choices of scale as Fig. 1.