

## Top Spin and Experimental Tests\*

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### Abstract

We examine pair mass dependence near threshold as a means to measure the spin of the top quark in hadron collisions, and we discuss the possibility that a top squark signal could be hidden among the top events.

### I. INTRODUCTION

Evidence to date is circumstantial that the top events analyzed in Tevatron experiments are attributable to a spin-1/2 parent. The evidence comes primarily from consistency of the distribution in momentum of the decay products with the pattern expected for the weak decay  $t \rightarrow b + W$ , with  $W \rightarrow l + \nu$  or  $W \rightarrow \text{jets}$ , where the top  $t$  is assumed to have spin-1/2.

It is valuable to ask whether more definitive evidence for spin-1/2 might be obtained in future experiments at the Tevatron and LHC. We take one look at this question by studying the differential cross section  $d\sigma/dM_{t\bar{t}}$  in the region near production threshold. Here  $M_{t\bar{t}}$  is the invariant mass of the  $t\bar{t}$  pair. We contrast the behavior of  $t\bar{t}$  production with that

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expected for production of a pair of spin-0 objects. We are motivated by the fact that in electron-positron annihilation,  $e^+ + e^- \rightarrow q + \bar{q}$ , there is a dramatic difference in energy dependence of the cross section in the near-threshold region for quark spin assignments of 0 and 1/2.

For definiteness, we compare top quark  $t$  and top squark  $\tilde{t}$  production since a consistent phenomenology exists for top squark pair production, obviating the need to invent a model of scalar quark production. Moreover, top squark decay may well mimic top quark decay. Indeed, if the chargino  $\tilde{\chi}$  is lighter than the light top squark, as is true in many models of supersymmetry breaking, the dominant decay of the top squark is  $\tilde{t} \rightarrow b + \tilde{\chi}^+$ . If there are no sfermions lighter than the chargino, the chargino decays to a  $W$  and the lightest neutralino  $\tilde{\chi}^0$ . In another interesting possible decay mode, the chargino decays into a lepton and slepton,  $\tilde{\chi}^+ \rightarrow \ell^+ \tilde{\nu}$ . The upshot is that decays of the top squark may be very similar to those of the top quark, but have larger values of missing energy and softer momenta of the visible decay products. A recent study for Run II of the Tevatron [1] concluded that even with  $4 \text{ fb}^{-1}$  of data at the Tevatron, and including the LEP limits on chargino masses, these decay modes remain open (though constrained) for top squarks with mass close to the top quark mass.

## II. CALCULATION AND RESULTS

At the energy of the Fermilab Tevatron, production of  $t\bar{t}$  pairs and of  $\tilde{t}\tilde{t}^*$  pairs is dominated by  $q\bar{q}$  annihilation, where the initial light quarks  $q$  are constituents of the initial hadrons. The subprocess proceeds through a single intermediate gluon at leading-order in QCD perturbation theory. The analogy to  $e\bar{e} \rightarrow q\bar{q}$  through an intermediate virtual photon is evident. We choose to work at leading-order in the  $t\bar{t}$  and  $\tilde{t}\tilde{t}^*$  partonic cross sections.

In Fig. 1(a) we display the partonic cross sections  $\hat{\sigma}(\sqrt{\hat{s}})$  as functions of the partonic subenergy  $\sqrt{\hat{s}}$  for the  $q\bar{q}$  channel, where  $q$  represents a single flavor of massless quark. We use the nominal value  $m_t = 175 \text{ GeV}$  for the mass of the top quark. We select  $m_{\tilde{t}} =$

165 GeV for the mass of the top squark so that the maximum values of the partonic cross sections occur at about the same value of  $\sqrt{\hat{s}}$  in  $t\bar{t}$  and  $\tilde{t}\tilde{t}$  production. Although the coupling strengths  $g$ , where  $\alpha_s = g^2/(4\pi)$ , are the same in the amplitudes for  $t\bar{t}$  and  $\tilde{t}\tilde{t}$  production, the magnitude of the  $\tilde{t}\tilde{t}$  partonic cross section is a factor of  $\simeq 0.015$  smaller at the peak. The reduction comes in part from the final-state sum over spins and in part from the momentum dependence of the p-wave coupling for  $\tilde{t}\tilde{t}$  production.

If we ignore relative normalization, the very different threshold energy dependences of the  $t\bar{t}$  and  $\tilde{t}\tilde{t}$  cross sections in Fig. 1(a) suggest that spin discrimination might be possible if one could study the pair mass distribution,  $d\sigma/dM_{t\bar{t}}$ . However, in hadron reactions, one observes the cross section only after convolution with parton densities.

In Fig. 1(b), we display the hadronic cross sections for  $p\bar{p} \rightarrow t\bar{t}X$  and  $p\bar{p} \rightarrow \tilde{t}\tilde{t}X$  at proton-antiproton center-of-mass energy 2 TeV as a function of pair mass. We use the CTEQ5L parton densities [2] with the factorization scale  $\mu$  chosen equal to the top quark mass for  $t\bar{t}$  production, and the top squark mass for  $\tilde{t}\tilde{t}$  production. We include the relatively small contributions from the glue-gluon initial state. The parton luminosities fall steeply with subenergy so the tails at high pair mass evident in Fig. 1(a) are cut-off sharply in Fig. 1(b). Indeed, the convolution with parton densities sharpens the peak of the  $\tilde{t}\tilde{t}$  pair mass distribution significantly and makes it resemble a background that is similar to  $t\bar{t}$  production. The top squark cross section is approximately 12% of the top cross section. The smaller value is due in part to the fact that the p-wave top squark production reduces the partonic cross section for low  $M_{t\bar{t}}$ , where the parton luminosities are largest.

At the energy of the CERN LHC, production of  $t\bar{t}$  pairs and of  $\tilde{t}\tilde{t}$  pairs is dominated by  $gg$  subprocess, and the threshold behaviors in the two cases do not differ as much as they do for the  $q\bar{q}$  incident channel. In Fig. 2(a), we show the partonic cross sections  $\hat{\sigma}(\sqrt{\hat{s}})$  as functions of the partonic subenergy  $\sqrt{\hat{s}}$  for the  $gg$  channel. In Fig. 2(b), we display the hadronic cross sections for  $pp \rightarrow t\bar{t}X$  and  $pp \rightarrow \tilde{t}\tilde{t}X$  at proton-proton center-of-mass energy 14 TeV as a function of pair mass. We include the relatively small contributions from the  $q\bar{q}$  initial state. After convolution with parton densities, the shape of the  $\tilde{t}\tilde{t}$  pair mass distribution is

remarkably similar to that of the  $t\bar{t}$  case.

### III. DISCUSSION

Based on shapes and the normalization of cross sections, it is difficult to exclude the possibility that some fraction (on the order of 10%) of top squarks with mass close to 165 GeV is present in the current  $t\bar{t}$  sample. The invariant mass distribution of the produced objects,  $M_{t\bar{t}}$ , is quite different at the partonic level for the  $q\bar{q}$  initial state (dominant at the Tevatron), but much less so for the  $gg$  initial state (dominant at the LHC). However, after one folds with the parton distribution functions, the difference in the  $q\bar{q}$  channel at the Tevatron is reduced to such an extent that the  $M_{t\bar{t}}$  distribution is not an effective means to isolate top squarks from top quarks.

Ironically, the good agreement of the absolute rate for  $t\bar{t}$  production with theoretical expectations [3,4] would seem to be the best evidence now for the spin-1/2 assignment in the current Tevatron sample.

A promising technique to isolate a top squark with mass close to  $m_t$  would be a detailed study of the momentum distribution of the top quark decay products (presumably in the top quark rest frame). One could look for evidence of a chargino resonance in the missing transverse energy and charged lepton momentum, or for unusual energy or angular distributions of the decay products owing to the different decay chains. One could also look for deviations from the expected correlation between angular distributions of decay products and the top spin [5].

As a concrete example of an analysis of this type, in Fig. 3 we present the distribution in the invariant mass  $X$  of the bottom quark and charged lepton, with  $X^2 = (p_b + p_{\ell^+})^2$ , where the bottom quark and lepton are decay products of either a top quark with  $m_t = 175$  GeV or a top squark  $\tilde{t} \rightarrow \tilde{\chi}^+ b \rightarrow W^+ \tilde{\chi}^0 b \rightarrow \ell^+ \nu_\ell \tilde{\chi}^0 b$ , with  $m_{\tilde{t}} = 165$  GeV,  $m_{\tilde{\chi}^+} = 130$  GeV,  $m_{\tilde{\chi}^0} = 40$  GeV, and  $m_b = 5$  GeV. The  $X$  distribution is a measure of the degree of polarization of the  $W$  boson in top quark decay [6], and the figure shows that the different

dynamics responsible for top squark decay result in a very different distribution, peaked at much lower  $X$ . The areas under the curves are normalized to the inclusive  $t\bar{t}$  and  $\tilde{t}\bar{\tilde{t}}$  rates at the Tevatron and LHC, respectively. At the LHC there is relatively more top squark in the sample, and thus the difference is more prominent.

In this simple demonstration potentially important effects are ignored such as cuts to extract the  $t\bar{t}$  signal from its backgrounds, detector resolution and efficiency, and ambiguities in identifying the correct  $b$  with the corresponding charged lepton from a single decay. Detailed simulations would be required to determine explicitly how effective this variable would be in extracting a top squark sample from top quark events. Nevertheless, such techniques, combined with the large  $t\bar{t}$  samples at the Tevatron Run II and LHC, should prove fruitful in ruling out the possibility of a top squark with mass close to the top quark mass, or alternatively, in discovering a top squark hidden in the top sample.

#### ACKNOWLEDGMENTS

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# FIGURES

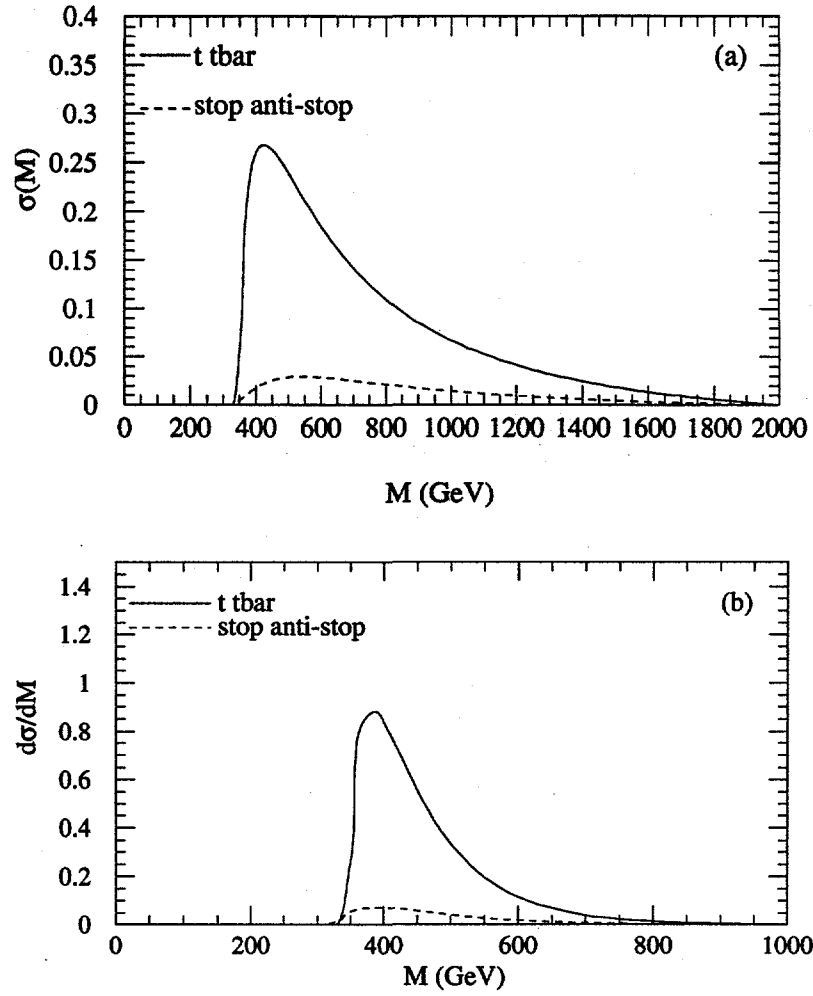


FIG. 1. (a) Partonic cross sections  $\hat{\sigma}(M)$  as functions of partonic subenergy  $M$  for the  $q\bar{q}$  channel. (b) Hadronic cross sections  $d\sigma/dM$  in proton-antiproton collisions at 2 TeV as functions of pair mass. The top quark mass  $m_t = 175$  GeV, and the top squark (stop) mass  $m_{\tilde{t}} = 165$  GeV.

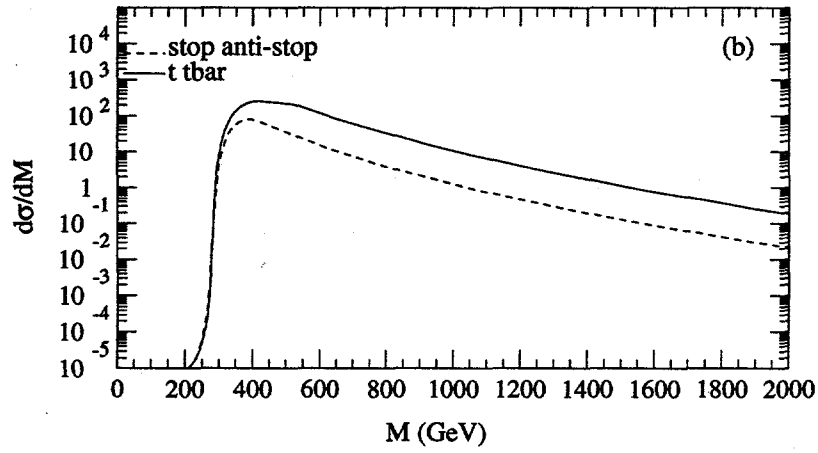
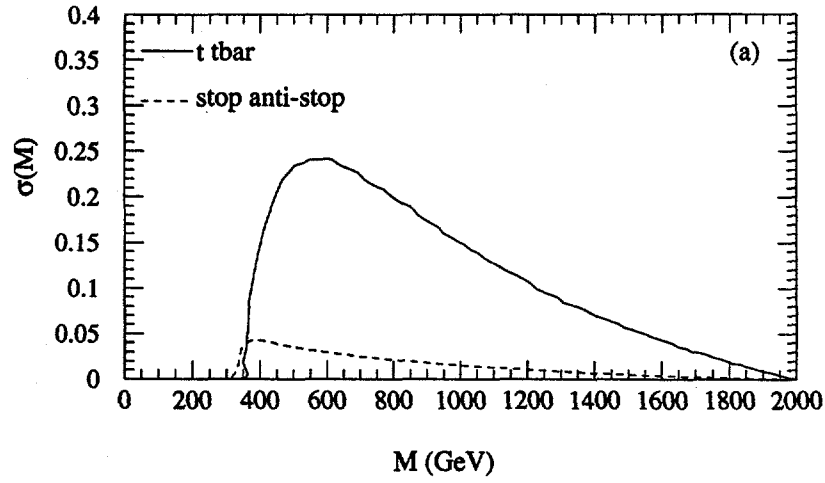


FIG. 2. (a) Partonic cross sections  $\hat{\sigma}(M)$  as functions of partonic subenergy  $M$  for the  $gg$  channel. (b) Hadronic cross sections  $d\sigma/dM$  in proton-proton collisions at 14 TeV as functions of pair mass. The top quark mass  $m_t = 175$  GeV, and the top squark (stop) mass  $m_{\tilde{t}} = 165$  GeV.

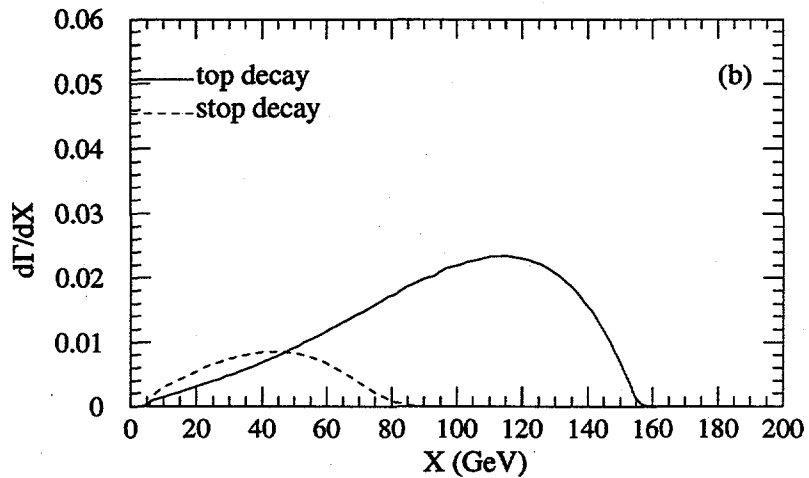
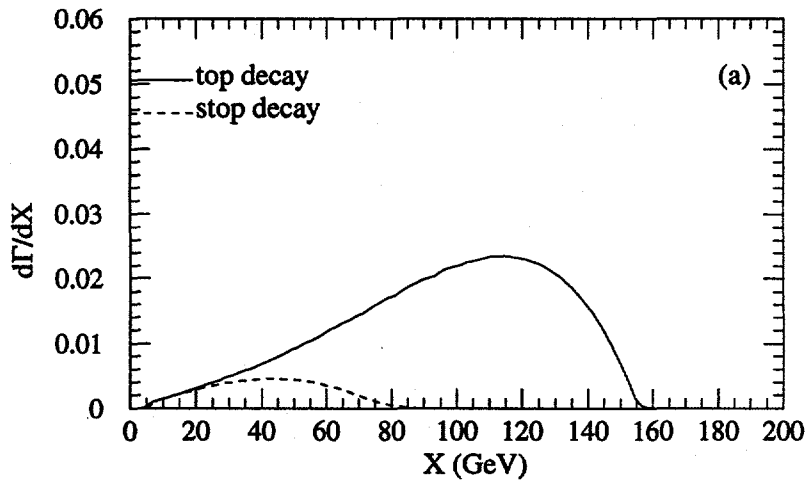


FIG. 3. Distribution of the invariant mass of a bottom quark and charged lepton ( $X$ ) for a top quark or top squark decay, with relative size normalized to the cross sections at (a) the Tevatron Run II and (b) the LHC. The top squark decay and sparticle masses are discussed in the text.