CDF note 7113

Search for $t' \rightarrow Wq$ Using Lepton Plus Jets Events

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We describe here a search for a t' quark decaying to Wq final states in CDF Run 2. Using the lepton+jets sample, we fit the observed H_T spectrum to discriminate the t' signal from Standard Model backgrounds. Using 200 pb^{-1} of integrated luminosity we set limits on the cross section times branching ratio for pair producing t' as a function of t' mass.

Preliminary Results for Summer 2004 Conferences

I. MOTIVATION

The cross section for $t\bar{t}$ production has been measured in Run 2 using the observed H_T distribution. [1] The result in the three or more jets case is $\sigma_{t\bar{t}} = 4.8 \pm 1.8 \pm 1.7$ pb, in good agreement with the standard model prediction of 6.7 pb in the most recent NNLO calculations [2, 3].

It is of interest to ask whether the present data allow or preclude the production of hypothetical new quarks which decay to final states with a high-p_T lepton, large $\not\!\!E_T$, and multiple hadronic jets, having large total transverse energy H_T. As discussed below there are several possibilities arising from extensions to the standard model in which this may be the case, and are not excluded by precision electroweak data or other direct searches.

We refer here to the hypothetical new quark as t', but in fact it need not be a standard fourth-generation up-type heavy quark. For the purposes of this analysis we simply consider a new quark which

- is pair-produced strongly,
- has mass greater than the top quark, and
- decays promptly to Wq final states.

In particular we need not demand the charge of the quark be +2/3, nor need we even demand that the quark be a fermion. (In the case of a new scalar quark, however, the production rate will be reduced due to the β^3 factor in its production cross section.)

A fourth generation of matter fermions with light neutrino ν_4 with mass $m(\nu_4) < m_Z/2$ is excluded by precision data from LEP 1. However, as pointed out by He *et al.* [4], and Okun *et al.* [5] a heavier fourth generation of fermions with $m_Z/2 < m_f < \mathcal{O}(< H >)$ is consistent with existing precision electroweak data. Indeed, the authors conclude that the present bounds on the Higgs in such scenario are relaxed; the Higgs mass could be as large as 500 GeV.

He *et al.* point out that additional fermion families can be accomodated in two-Higgs-doublet scenarios and $N = 2$ SUSY models, and possibly remove the requirement of the weak-mixing assumption above. In that case, the decay $t' \to Wq$ may predominate, assuming $m(t') > m(b') + m(W)$ for example.

Other theoretical possibilites lead directly to the scenario in which we are interested. In one version of the "beautiful mirrors" model of Wagner *et al.* [6] there exists an up-type quark with the same quantum numbers as the top, which decays as $\chi \to Wb$. In this scenario, the slightly anomalous results from LEP on the b forward-backward asymmetry are accomodated naturally, and the electroweak fits are improved (with a relaxed upper limit on the Higgs boson mass).

Recent theoretical developments lead one to hypothesize the existence of a heavy t'. Little Higgs models [7] evade the hierarchy problem by introducing a minimal set of gauge and fermion fields in the context of a large-extra-dimension framework. The minimal versions of these models, however, result in new quarks which have mass of order 1 TeV, too heavy for Tevtron studies. Non-minimal Little Higgs scenarios, however, are of course possible.

The basic conclusion is that there exist enough theoretical scenarios and ideas involving new heavy quarks that, as experimentalists, we are compelled to perform the search for them in as many channels as possible. In order to allow the widest possible theoretical interpretation we need to express our results in as model-independent a fashion as possible. Here we set limits on the t' pair production cross section times branching ratio $t' \to Wq$, leading to the high-H_T lepton+jets+$\not\!\!E_T$ signature with an acceptance determined from a generic fourth generation quark decaying to Wb. Inevitably, however, different proposed models will have different kinematic distributions and hence have acceptance different from a generic fourth-generation quark.

II. ANALYSIS METHOD

The CDF detector is described in detail in [8]. We use a data sample corresponding to 195 pb^{-1} of integrated luminosity. The t' analysis uses exactly the same event selection as in the kinematic top cross section measurement [1], using the requirement of $\geq$4 jets. These cuts demand

- one and only one isolated lepton (e or μ) with $p_T > 20$ GeV,
- at least 20 GeV missing transverse energy, and
- at least four jets with $E_T > 15$ GeV and $|\eta| < 2$.

We then use the observed distribution of total transverse energy in the event, H_T, to distinguish the t' signal from the backgrounds by fitting it to a combination of t' signal, $t\bar{t}$, W+jets, and QCD background shapes.

We use a likelihood method to extract the t' signal and/or set an upper limit on its production rate. As in the top cross section measurement we use a binned likelihood in H_T.

The technique here is to calculate the likelihood as a function of the t' cross section, and use Bayes' Theorem to convert this into a posterior density in $\sigma_{t'}$. We can then use this posterior density to set an upper limit on (or if we get lucky, measure) the production rate of t'.

However, there are unknown parameters, such as the production rate for W+jets, the $t\bar{t}$ production cross section, lepton ID data/MC scale factors, true integrated luminosity, etc. All such factors are in fact related to systematic errors, and can be treated in the likelihood as nuisance parameters which float, but may be constrained within their expected distributions. The treatment of these parameters is discussed in the next section.

III. SYSTEMATIC ERRORS

The method we use in this analysis to incorporate the effects of systematic uncertainties is to introduce constraint functions on the unknown (nuisance) paramaters in which we are not interested. These might include, for example, the rates for various background processes, the signal acceptance, etc. In calculating the likelihood versus signal cross section we maximize the likelihood with respect to all these parameters; the effect of the constraint functions is (in the absence of a signal) to broaden the shape of the likelihood, leading to a larger (weaker) limit in the end.

In general we use Gaussians as the shape of the contraint functions for the nuisance parameters. However, for certain errors, namely the jet energy scale and Q^2 scale, we do not believe a Gaussian reflects the true nature of our prior probability, and we use an alternate constraint function. This is discussed in more detail below.

Jet Energy Scale

Because the sensitivity to t' depends on knowing accurately the distribution of H_T, the largest source of uncertainty is that due to the jet energy scale. Jets in the data and Monte Carlo are corrected for various effects, leaving some residual uncertainty.

The effect of this uncertainty on the analysis is evaluated by first measuring the resulting change in the measured t' cross section if the t' existed. The expected 1σ change in the measured cross section is then interpreted as the uncertainty on the t' cross section itself.

We use pseudoexperiments to measure this shift and find that for a given t' mass it rises linearly. Figure 1 shows the shift in the case of a 250 GeV t'. The offset and slope of the upward shift is taken as the uncertainty, since the downward shift has been constrained in the fit to not result in a cross section less than zero, which is unphysical.

Both the slopes and offsets of the linear fit to the shift in t' cross section as a function of $\sigma_{t'}$ decrease as a function of t' mass. Table I shows the parameters used in the likelihood.

The uncertainty can be represented as a parameter which adds to the t' cross section in the likelihood. It is nominally zero with a constraint function related to the uncertainty. The magnitude of this uncertainty is large enough that if we were to use a gaussian constraint as described above, the likelihood as a function of t' cross section never reaches zero, making the integral of the likelihood diverge linearly with $\sigma_{t'}$.

A gaussian constraint leads to a "penalty" term in the log likelihood of the form

$$\frac{(f-f_0)^2}{2\sigma_f^2} \quad . \tag{1}$$

For the jet energy scale systematic error, it turns out that the "1-sigma" shift should not be taken as a gaussian-style uncertainty, but more of an upper limit on the residual difference in data and MC scales. It should be noted here that the current jet energy scale errors (for 4.11.1 jet corrections) were determined not as a statistical "1-sigma", but rather were meant to cover all possible deviations, to the best of our knowledge. Allowing the nuisance parameter associated with the these errors to float very far outside the given shift boundaries would over-estimate any possible effect, and would not reflect our current knowledge of this systematic. Thus we use a constraint function that goes to zero much more rapidly near the boundaries: this corresponds to a penalty in the log likelihood which rises rapidly. Using the form

$$\frac{2(f-f_0)^4}{\sigma_f^4} \tag{2}$$

accomplishes this, and gives a constraint function as shown in figure 2. As the figure shows, the function has a flatter central region and goes rapidly to zero outside a deviation of "1 sigma". This better represents our belief in the nature of the uncertainty on the jet energy scale, and leads to a convergent likelihood intergral.

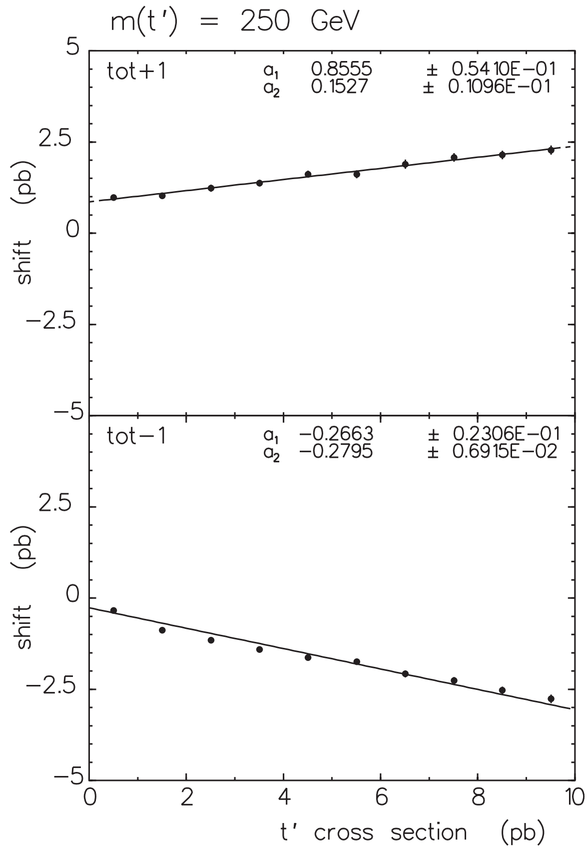

FIG. 1: Shift in measured t' cross section as a function of true t' cross section, due to a 1σ shift in jet energy scale, for a t' mass of 250 GeV.

$m(t')$ (GeV)	a_1	a_2
175	1.94	0.24
200	1.63	0.19
225	1.30	0.16
250	0.86	0.15
300	0.46	0.14
350	0.29	0.10

TABLE I: Linear parameters describing the uncertainty in t' cross section due to jet energy scale. The shift can be expressed as $\delta\sigma_{t'} = a_1 + a_2\sigma_{t'}$.

W+jets Q^2 Scale

In the top kinematic cross section analysis the uncertainty in the appropriate Q^2 scale for W+jets production is taken into account by studying the shift in apparent top cross section for different choices of Q^2 scale. The choice of the size of this variation is somewhat arbitrary, but the effect of rather conservative changes in the scale is much smaller than the effects of the jet energy scale uncertainty. Furthermore the effect is independent of the signal cross section; we simply add it in quadrature to the offfset term in the linear function representing the jet energy shifts.

ISR and FSR

To take into account the uncertainty in modelling the effects of initial and final state radiation, we measured the shifts in apparent cross section using templates generated with varied ISR and FSR. The resulting differences in measured cross section corresponds to a 1.3% effect for ISR and a 0.5% effect for FSR for shape and acceptance systematics combined. These are incorporated into the same parameter encoding as the integrated luminosity uncertainty, described below.

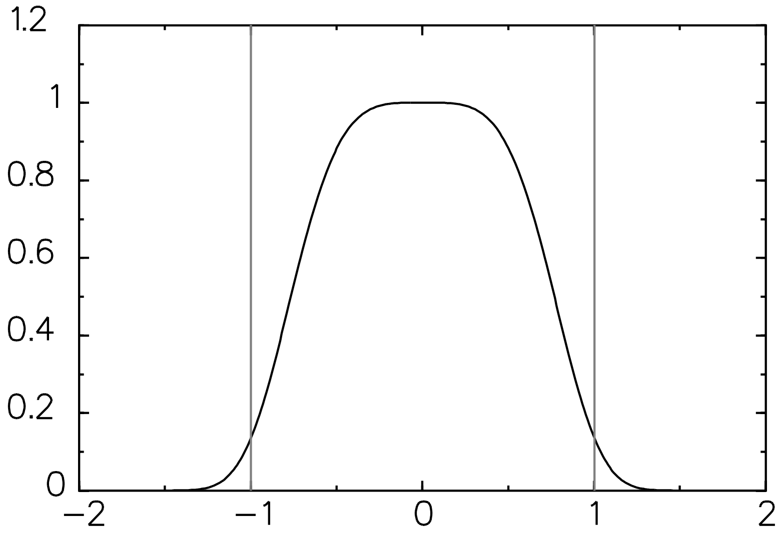

FIG. 2: Constraint function used in representing the jet energy scale systematic uncertainty. This function can be written $exp[-2(f-f_0)^4/\sigma_f^4]$.

Lepton ID

Our lepton identification is not perfectly modeled in the simulation, and leads to data/MC scale factors which are applied as a correction. The values of these factors have a residual systematic uncertainty of 7%.

QCD Background

The QCD background shape, determined from the top kinematic cross section analysis, is assumed to have a relative normalization uncertainty of 30%, represented by a gaussian-constrained parameter in the likelihood. This leads to a negligible effect on the t' limit.

Integrated Luminosity

The integrated luminosity uncertainty is taken to be 6%, and represented by an additional gaussian-constrained parameter multiplying all contributions except for the QCD background, which is normalized independently.

PDF Uncertainty

The parton distribution functions (PDFs) are not precisely known, and this uncertainty leads to a corresponding uncertainty in the predicted t' cross sections, as well as smaller effects on the t' acceptance and the H_T distribution.

By comparing various PDF sets and their uncertainties, ee estimate the systematic uncertainty due to PDF as follows: 2.3% due to CTEQ5,6 differences, 0.8% due to CTEQ5 vs. MRST72, and 2.5% due to α_s variation. We add these in quadrature and get a 3.5% overall systematic uncertainty.

Top Mass and Cross Section

The top mass is assumed to be 175 GeV in the likelihood fit, and the $t\bar{t}$ cross section is constrained to be 6.7±0.9 pb. Clearly, however, a higher true top mass will result in a harder H_T spectrum than we assume, and will result in additional apparent signal.

To asses the magnitude of this effect we perform the final limit calculations using different values for the top mass (and corresponding cross section, taken from Reference [3]) and display the limits on the final plot. The cross sections and errors as a function of top mass appear in Table II

top mass (GeV)	cross section constraint
170	7.83±1.0
175	6.70±0.9
180	5.75±0.7

TABLE II: Top quark pair production cross section and uncertainty versus top quark mass.

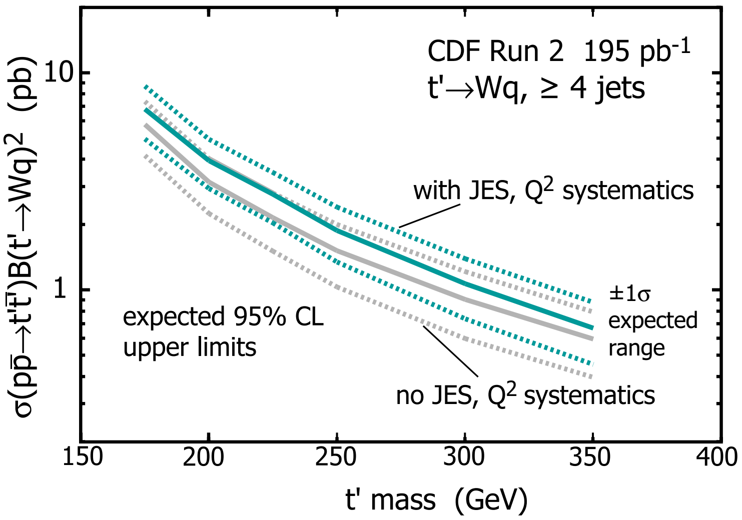

FIG. 3: Expected 95% CL upper limits on cross section times branching ratio for t' pair production, where $t' \to Wq$. The dim (grey) curves incorporate the effects of all systematic errors except that due to the jet energy scale; the dark (blue) curves incorporate this one as well. The central curve is the mean expected limit, and the other two curves in each triplet are the one standard deviation ranges of the expected limit.

IV. EXPECTED LIMITS

Figure 3 shows the expected limit on cross section times branching ratio for t' as a function of t' mass. The dim (grey) curves represent all systematic errors except that due to our parametrization of the jet energy scale uncertainty. The dark (blue) curves include the effect of this uncertainty in addition.

As the figure shows, the relative change in the limit due to incorporation of the jet energy scale uncertainty is largest at high t' masses. In the lower range, which is of more interest at our level of statistics, the effect is smaller.

V. RESULTS AND CONCLUSION

After performing the analysis on the selected data set, we find no evidence of a t' signal. Figure 4 shows the likelihood versus cross section for the example mass point $m(t')$ =225 GeV. The fit slightly prefers a small signal, but with small statistical significance. Figure 5 shows the observed H_T distribution and the best fit to the distribution at the t' cross section point where we set the 95% CL upper limit. In this case the $t\bar{t}$ cross section has floated to 6.1 pb.

Hence we proceed to determine upper limits on the t' signal. Figure 6 shows the final result, expressed as a 95% CL upper limit on the t' production rate as a function of t' mass. The result includes three curves, that in general overlap, for assumed top mass of 170, 175, and 180 GeV. Table III shows the individual calculated limits for reference.

We also include on the final plot a curve with the theoretical prediction from PYTHIA, multiplied by the factor 1.055 to account for the fact that PYTHIA's prediction is smaller than the ones we take from Kidonakis and Mangano [2, 3]. The PYTHIA curves were obtained using the CTEQ5L parton density functions, the same used to model t' and $t\bar{t}$.

Thus we conclude that we can rule out at 95% CL a t' with mass greater than about 175 GeV, if the true top mass is about the same value. For a smaller top mass the excluded mass is lower, and vice versa for higher mass.

As CDF records more data in Run 2 the limit on the t' will steadily improve, and eventually pass out of the region where its presence would have affected the top mass. Figure 7 shows the mean expected limit as a function of t' mass for various integrated luminosities. This is a conservative estimate in that we expect the systematic errors to improve greatly very soon.

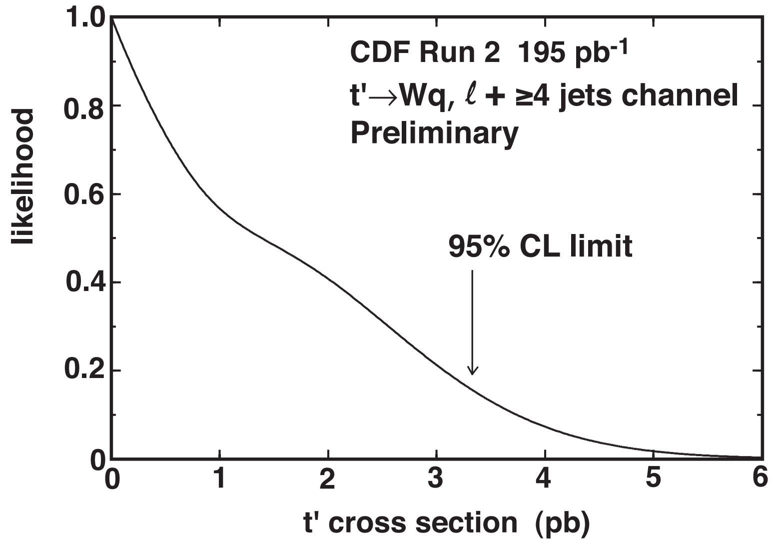

FIG. 4: Example likelihood versus t' cross section, for $m(t') = 225$ GeV.

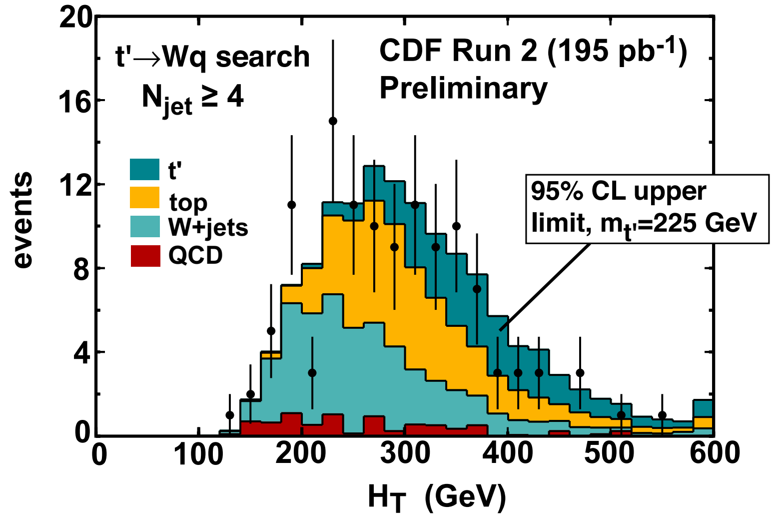

FIG. 5: Distribution of H_T, showing result of fit for t' for $m(t') = 225$ GeV. The normalizations of the various sources are those corresponding to the maximum likelihood when the cross section for t' is set to its 95% CL upper limit. (In this case the $t\bar{t}$ cross section floats down to 6.1 pb.)

	m(t)		
$m(t')$ (GeV)	170 GeV	175 GeV	180 GeV
175	6.24	6.73	7.54
200	4.90	4.95	5.38
225	3.61	3.61	3.86
250	2.17	2.11	2.26
300	0.96	0.92	0.97
350	0.51	0.50	0.51

TABLE III: Upper limit, in pb, at 95% CL, on the pair production of t' quarks where $t' \to Wq$.

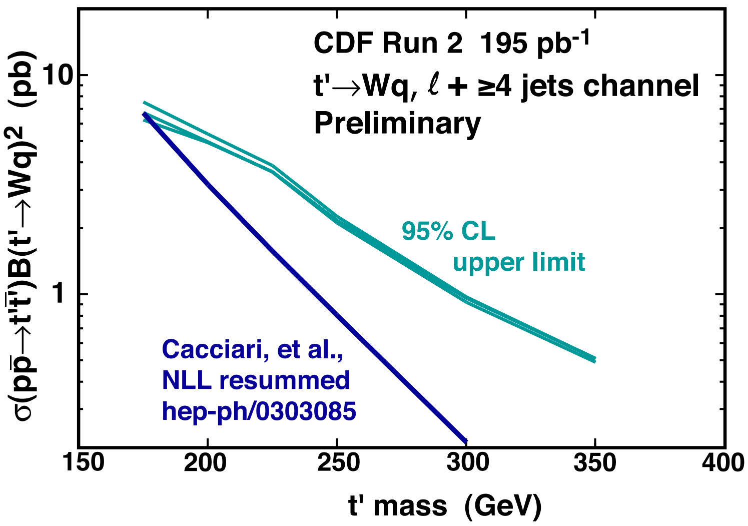

FIG. 6: Upper limit, at 95% CL, on the production rate for t' as a function of t' mass. The three upper (blue) curves correspond to top masses of 170, 175, and 180 GeV. (The lowest curve is the lowest mass.) The lowest (purple) curve is a theoretical cross section calculated from PYTHIA and scaled to agree with NNLO calculations.

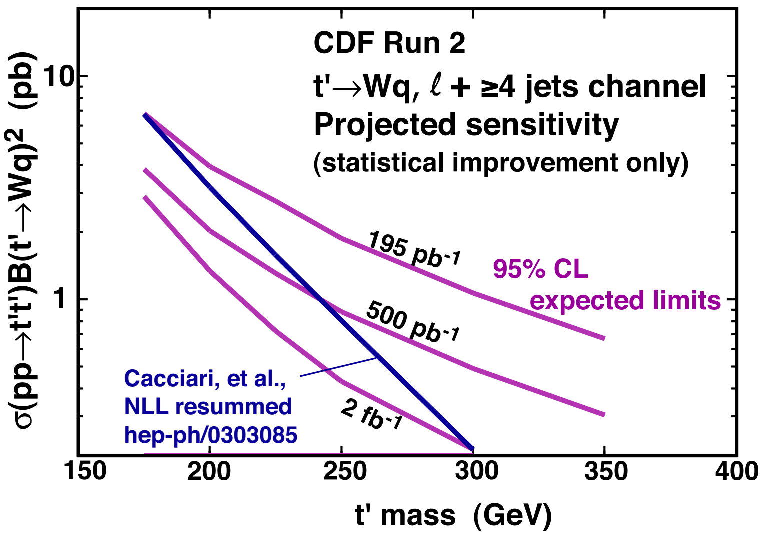

FIG. 7: Mean expected Upper limit, at 95% CL, on the production rate for t' as a function of t' mass, for several levels of integrated luminosity.

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