CDF note 8087

Search for resonant $t\bar{t}$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

The CDF Collaboration
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This note describes a search for vector resonant production of $t\bar{t}$ pairs in 680 pb^{-1} of Run 2 data. We use the Standard Model $t\bar{t}$ matrix element information to reconstruct the $t\bar{t}$ invariant mass spectrum ($m_{t\bar{t}}$) for top candidates in the lepton+jets sample. We test the consistency of the data with SM $t\bar{t}$ production and with the production through a neutral vector resonance: $p\bar{p} \to X^o \to t\bar{t}$. For a given resonance mass we compute for the data the 95% C.L. upper limit on the cross section for such resonance production and compare it to the expectation assuming Standard Model sources alone. The 95% CL upper limits on the resonance production can be used in conjunction with theoretical models in order to exclude certain mass regions. For example, for a leptophobic Topcolor model for resonances with a width equal to 1.2% of the mass we exclude masses below 725 GeV/c^2. The corresponding CDF Run 1 limit was 480 GeV.

Preliminary Results for Winter 2006 Conferences

I. INTRODUCTION

The $t\bar{t}$ production mechanism is an interesting process in which to search for New Physics. The full compatibility of $t\bar{t}$ candidate events with the Standard Model is not known with great precision and there is room to explore for possible non-SM sources within such an event sample.

We focus on the search for a heavy resonance decaying into $t\bar{t}$ pairs. Such a particle is predicted in various topcolor models, for instance "topcolor assisted technicolor" [1]. In some models the resonance couples preferentially to third generation quarks and weakly to leptons which makes this search even more attractive.

In $p\bar{p}$ collisions such a resonance can be produced via $q\bar{q}$ annihilation.

We chose the lepton+jets channel to perform this search because it is the best compromise between statistics and purity.

This search was done in Run I also. The CDF collaboration excluded resonance masses below 480 GeV/c^2 [2] and the D0 collaboration excluded resonance masses below 560 GeV/c^2 [3]. Our results extend this limit to 725 GeV/c^2 however it should be remembered that it is a particular theoretical model that is excluded rather than a resonance mass range. The search at lower masses remains as interesting as before.

CDF is a general purpose detector and is described in detail elsewhere [4]. The components relevant to this analysis are briefly described here. Closest to the beam pipe is the charged-particle tracking system used to reconstruct particle momenta and the collision vertex, which consists of multi-layer silicon detectors and a large open-cell drift chamber covering the pseudorapidity region $|\eta| \leq 1$. The tracking system is enclosed in a superconducting solenoid. It is surrounded by a calorimeter, which is organized into electromagnetic and hadronic sections segmented in projective tower geometry and covers the region $|\eta| \leq 3.6$. The central and plug electromagnetic calorimeters utilize a lead-scintillator sampling technique, whereas the central, wall and plug hadron calorimeters use iron-scintillator technology. Outside the calorimeter there is a muon detection system, which covers the range $|\eta| < 2$.

II. DATA SAMPLE & EVENT SELECTION

The parton level final state for our decay channel is $l\nu bbqq$ and therefore we require one tight high-p_T isolated lepton, large missing E_{T} ($\not\!\!E_{\mathrm{T}}$) and at least four jets. The $\not\!\!E_{\mathrm{T}}$ is defined as the energy imbalance in the plane transverse to the beam direction and reconstructed as a vector sum of energy deposited in calorimeter towers. A jet is defined as a localized energy deposition in the calorimeter and is reconstructed using a fixed cone algorithm with a cone of radius $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ in $\eta - \phi$ space. An energy correction procedure [5] corrects jet energies and $\not\!\!E_{\mathrm{T}}$ for detector effects. A subclass of jets is defined as "tight" jets, i.e. jets with $|\eta| < 2$ and $E_{\mathrm{T}} > 15\ GeV$ after corrections. Our event selection requires at least 4 such tight jets.

The data sample for this analysis was collected using high-p_T triggers for electrons and muons.

The dominant backgrounds to the resonance are W boson production in association with one or more jets, SM $t\bar{t}$, QCD events and dibosons (WW, WZ, ZZ).

The ALPGEN generator [6] was used for the simulation of the W boson plus parton production, with Herwig [7] used to model parton showers. Pythia [8] was used to generate $t\bar{t}$ events and to model parton showers for both SM and resonant production.

III. SEARCH METHODOLOGY

Top pair resonant production could be discovered by looking at the invariant mass of the $t\bar{t}$ pair ($M_{t\bar{t}}$). SM $M_{t\bar{t}}$ drops exponentially while a resonant production would show a mass peak.

The task of reconstructing the $M_{t\bar{t}}$ is complicated by the relatively poor jet resolution and not knowing the neutrino longitudinal momentum. The transversal component of the neutrino momentum is usually identified with the $\not\!\!E_{\mathrm{T}}$ and as such it is also not so well known in fact.

Our approach is to use matrix element information and "transfer functions" to help with the $M_{t\bar{t}}$ reconstruction. Transfer functions are probability distributions describing the correlation between parton energy and jet energy for final state quarks. They are parametrized in $|\eta|$ bins and parton energy bins since they vary with these quantities but their main function is to link parton level quantities like differential cross sections to measured quantities like jet momenta. The main approximation made is that the jet direction is the same as the parton direction. These transfer functions are also different for b-quarks and are derived from Monte Carlo events.

The a priori probability density for producing a particular $t\bar{t}$ parton level final state $\{\vec{p}\}$ *relative to other final states* is simply the normalized differential cross section. Let us denote it by $P_1(\{\vec{p}\})$. We can take this one step further and say that the a priori probability density for the parton level final state $\{\vec{p}\}$ *and* the measured jet quantities $\{\vec{j}\}$ is given by the product $P_2(\{\vec{p}\},\{\vec{j}\}) = P_1(\{\vec{p}\}) \cdot T(\vec{j}_1|\vec{p}_1) \cdot T(\vec{j}_2|\vec{p}_2) \cdot T(\vec{j}_3|\vec{p}_3) \cdot T(\vec{j}_4|\vec{p}_4)$ where by $T(\vec{j}_i|\vec{p}_i)$ we denoted the transfer function, i.e. the probability that a parton of momentum $\vec{p}$ is measured as a jet of momentum $\vec{j}$. We identify the parton direction with the jet direction so the transfer functions depend essentially only on the magnitudes of the parton and jet momenta. The lepton momentum is considered to be well enough measured so it is plugged in directly in the matrix element formula while the neutrino momentum is not measured at all so it can take any value.

From $P_2(\{\vec{p}\},\{\vec{j}\})$ one can build $P(\{\vec{p}\} \mid \{\vec{j}\})$, the probability of having the parton momenta $\{\vec{p}\}$ *given* the observed quantities $\{\vec{j}\}$. Having that distribution one can derive probabilitity distributions for any new variable which is a function of the parton level quantities $\{\vec{p}\}$, in particular $M_{t\bar{t}}$, and this is what we do. In general, if $f(\{\vec{p}\})$ is a new random variable then $P_f(x \mid \{\vec{j}\}) = \int P(\{\vec{p}\} \mid \{\vec{j}\}) \cdot \delta(x - f(\{\vec{p}\}))\, d\{\vec{p}\}$. In our case f is the invariant mass of the parton level final state which is equivalent to $M_{t\bar{t}}$. Having an *event* probability distribution for $M_{t\bar{t}}$ we pick the mean as the reconstructed value for that event. However since we don't know which jet matches which parton we average on all possible permutations. If b-tagged jets are found we use only permutations which match b-tagged jets to b quark partons.

This reconstruction algorithm is run over all Monte Carlo samples and these are combined with proper weights to produce the expected SM $M_{t\bar{t}}$ spectrum. Also resonant production $t\bar{t}$ samples are reconstructed via the same algorithm and in the end the data is tested for such a contamination.

We derive the posterior probability for $\sigma(p\bar{p} \to X^0) \cdot BR(X^0 \to t\bar{t})$ given the observed $M_{t\bar{t}}$ spectrum based on

$$P(\vec{n} \mid \sigma) = \prod_i e^{-\mu_i} \frac{\mu_i^{n_i}}{n_i!}$$

which is the prior probability of observing the data $M_{t\bar{t}}$, with n_i being the number of observed events in $M_{t\bar{t}}$ mass bin i and μ_i the number of expected events in the same bin which depends on the assumed signal cross section. If one uses a flat prior distribution for the signal cross section then the Bayes theorem gives the posterior $P(\sigma|\vec{n})$ and this is equal to the distribution above up to a normalization factor. For brevity we use the term "signal cross section" but we always mean "signal cross section times branching ratio".

The posterior is used to define upper and lower limits at any given confidence level together with the most likely value. If the lower limit is zero then the data is considered consistent with the Standard Model at that level of confidence. These levels are derived such that the probability of the upper limit point is equal to the probability of the lower limit point unless the lower limit is zero. We also extract the reconstructed cross section as the most probable value of the posterior.

This entire exercise is repeated for various resonance masses from 450 GeV/c^2 to 900 GeV/c^2 and 95% confidence level (CL) upper limits are established. Together with theoretical cross-section vs mass curves these limits are used to exclude certain mass ranges.

IV. SYSTEMATIC UNCERTAINTIES

There are two types of uncertainties we are concerned about depending on whether they change the shape of the $M_{t\bar{t}}$ templates or not.

Uncertainties which do not change the shape of the template can be incorporated as "nuisance" parameters in the prior signal probability. The knowledge about these parameters is summarized by their prior densities (tipically gaussians). Bayes' theorem then specifies how the prior information about the signal cross section (and the nuisance parameters) is updated by the data measurement to yield the joint posterior density. The marginal posterior density for the cross section only is obtained by integrating out the nuisance parameters. These systematics incorporate the acceptance uncertainties on signal and backgrounds as well as the uncertainties on the backgrounds cross sections. For instance the overall uncertainty on the SM $t\bar{t}$ background contribution has been estimated at 12%.

After the jet energy corrections we are left with an uncertainty on the jet energy scale. A change in the jet energy scale modifies both the acceptances and the templates. To account for this type of uncertainties (*shape uncertainties*) we generate a set of pseudoexperiments using the shifted templates and acceptances and then we analyze them with the correct ones. This will result in a shifted reconstructed cross section with respect to the input one. The mapping of this shift versus the input cross section provides an evaluation of the impact of the 1σ jet energy scale uncertainty at any given cross section. Finally by convoluting the cross section posterior with a gaussian, whose width is given by the above mentioned mapping function, we obtain a new posterior which includes shape systematics.

Besides the jet energy scale uncertainty there are other sources of shape systematics, they are listed below. To account for all of them we first calculate the shift function for each contribution, then we combine them in quadrature into a smearing function for all the shape systematics. The result of this convolution leads to smear the cross section posterior and the upper limits are pushed to higher values.

The complete list of the shape systematics sources we considered is:

- Jet energy scale. Due to the residual uncertainty after the jet energy corrections.
- ISR and FSR. Uncertainty on the modeling of initial an final state radiation in Monte Carlo simulations.
- $W - Q^2$ scale. Uncertainty in the appropriate Q^2 scale for W+jets production.
- PDF. Uncertainty in the proton and anti-proton Parton Distribution Functions.

The last item (PDF) was investigated but in the end ignored since the change in template shape was negligible.

V. RESULTS

In the CDF data gathered between 2002-2005 at the Tevatron we found 450 events that passed our event selection. 447 of these were reconstructed successfully and the $M_{t\bar{t}}$ spectrum is shown in Figure 1.

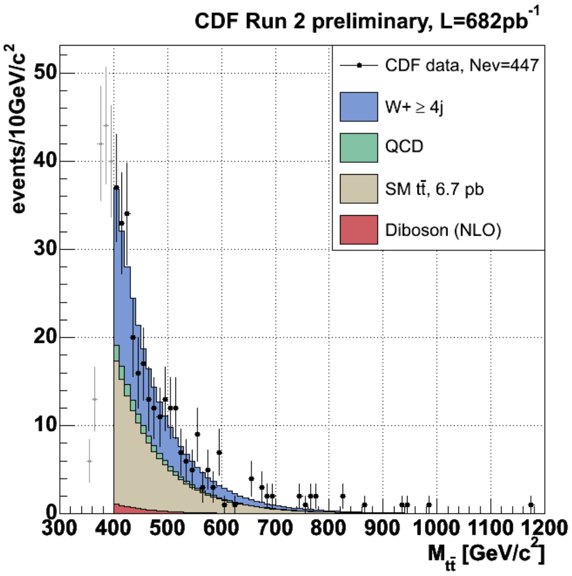

FIG. 1: Reconstructed $M_{t\bar{t}}$. SM expectation is shown in the search region above 400 GeV/c^2.

We perform our search in the region above 400 GeV/c^2 for which the SM expectation is shown.

The corresponding upper limits are shown in Figure 2 together with the expected upper limits and their uncertainties based on pseudoexperiments.

No evidence for resonant $t\bar{t}$ production is observed (the 95% lower limits for all the masses are equal to zero) and the small peak around 500 GeV/c^2 [9] observed for the first 320 pb^{-1} has been diluted.

The upper limits exclude a leptophobic topcolor resonance candidate up to masses of 725 GeV/c^2 based on the theoretical cross section predictions of the model, as shown in the same Fig 2.

The width of the resonance in this model is 1.2% of the resonance mass which matches the choice in our MC samples.

In conclusion, we performed a search for a heavy resonance decaying into $t\bar{t}$ in the lepton + jets channel using 680 pb^{-1} of CDF Run 2 data. No evidence is observed and we set upper limits on the production cross section at the 95% C.L. For one leptophobic topcolor production mechanism we exclude masses up to 725 GeV/c^2.

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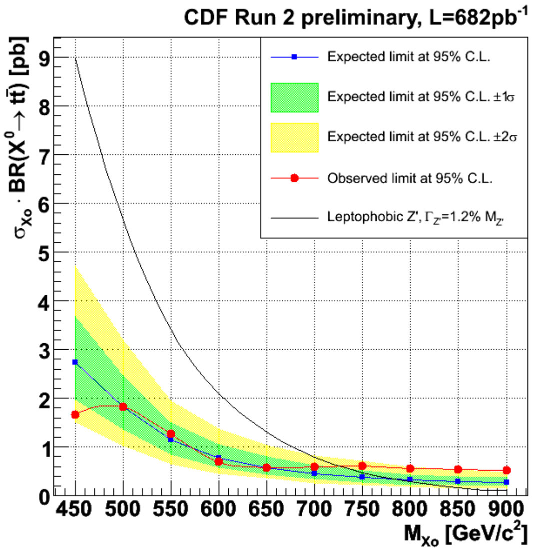

FIG. 2: Expected and actual upper limits for 680 pb^{-1} of CDF data, together with leptophobic topcolor Z' cross section prediction.

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