



Search for single production of heavy quarks

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We present a search for single production of quarks heavier than the top quark that decay to a W boson and a Standard Model quark. The search is carried out in a data sample corresponding to 5.7 fb^{-1} of integrated luminosity in a channel with a high- p_T electron or muon, two jets, and large missing transverse energy. A fit to the invariant mass of the system comprised of the lepton, \cancel{E}_T , and higher- E_T jet is used to set limits on the production cross section of the heavy quarks.

Preliminary Results for Summer 2010 Conferences

I. INTRODUCTION

New quarks heavier than the top quark are a feature of many extensions to the Standard Model (SM). Constraints from precision electroweak measurements do not exclude heavy quarks, particularly if the new quarks have vector-like couplings with the W boson. We use the framework of Ref. [1], which lays out a general description of the interaction of new heavy quarks with the Standard Model. In particular, we focus on a model with two new heavy quarks, the D and the U , that couple only to the first generation of SM quarks. They can be produced singly via charged current or neutral current interactions, or in pairs via the strong interaction. Due to the limited phase space available for pair production of the heavy quarks, we focus on their single production via charged current interactions.

We assume that the branching ratio of the new heavy quarks decay to a W and a first generation SM quark is 100%. The production cross section can be factorized as

$$\sigma(p\bar{p} \rightarrow qQ) = \tilde{\kappa}_{qQ}^2 \sigma_{SM}^{CC}, \quad (1)$$

where σ_{SM}^{CC} is the SM calculation of the electroweak single production cross section of a first generation quark with the coupling scaled by a factor of v/m_Q where $v = 174$ GeV and m_Q is the mass of the new heavy quark. $\tilde{\kappa}_{qQ}^2$ is the model-dependent coupling between the new heavy quark and the SM quark.

The leading-order production and decay diagrams for the D quark are shown in Figure 1. The spectator quark in the final state will occur at fairly high η . The decay of a the heavy quark will lead to a boosted quark and a boosted W boson. The decay of the boosted W boson, in turn, will give a fairly high- p_T lepton and neutrino, produced with a relatively small angle to each other.

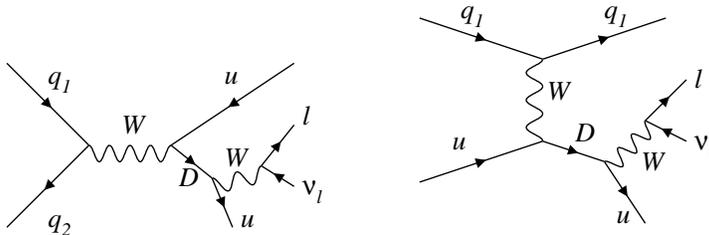


FIG. 1: Leading-order production diagrams of heavy quarks via a charged current interaction. The branching ratio of the heavy quarks to a W and a first-generation SM quark is assumed to be 100%.

We generate signal Monte Carlo events using MADEVENT [2] with the new model provided to us by the authors of Ref. [1]. We focus on a search for heavy quarks with masses between 300 GeV/ c^2 (close to the limit on the t-prime mass placed by the pair production search in Ref. [3]) and 600 GeV/ c^2 . The production cross sections (σ_{SM} from Eqn. 1, or σ_{qQ} under the assumption that is $\tilde{\kappa}_{qQ}^2 = 1.0$) are listed in Tab. I. PYTHIA [4] is used to simulate the parton shower for the signal process, and the events are run through the CDF detector simulation [5] to estimate their kinematics at the detector level.

Mass [GeV/ c^2]	D quark prod. cross section [pb]	U quark prod. cross section [pb]
300	7.0	1.7
400	1.5	0.28
500	0.36	0.053
600	0.093	0.011

TABLE I: Production cross sections for heavy quarks (assuming $\tilde{\kappa}_{qQ}^2 = 1.0$).

II. DATA SAMPLE AND BASELINE EVENT SELECTION

We carry out the search using 5.7 fb $^{-1}$ of integrated luminosity collected by the CDF II detector. The CDF detector is described in detail in [7].

Candidate events for this analysis are selected by requiring a $W + 2$ jet event topology where the W decays leptonically, $W \rightarrow e\nu_e$ or $W \rightarrow \mu\nu_\mu$. Muon events are triggered by the high- p_T central muon triggers (which have thresholds of 18 GeV/ c^2) as well as a trigger that requires large missing transverse energy and two jets. Electron events are triggered by a high- E_T central electron trigger ($E_T > 18$ GeV).

In the offline selection, events are required to have:

- Exactly one isolated electron or muon with offline E_T or $p_T > 20$ GeV.
- $\cancel{E}_T > 20$ GeV in events containing a muon and $\cancel{E}_T > 25$ GeV in events containing an electron. The \cancel{E}_T is corrected for identified muons and for jet energy corrections.
- Exactly two jets, clustered with a cone size of $\Delta R < 0.4$, and with $|\eta_{detector}| < 2.0$. One jet must have $E_T > 25$ GeV and the other $E_T > 20$ GeV after jet corrections have been applied [6].

The following event vetos are applied:

- Events with a third jet with $E_T > 20$ GeV are rejected.
- Events with a second lepton are rejected.
- A Z boson veto is implemented: we search for a second very loosely identified lepton (e.g. an isolated track) with the opposite charge of the hard lepton. If the invariant mass of the two leptons is consistent with the Z mass, i.e. $76 < M_{ll} < 106$ GeV/ c^2 , the event is rejected.
- Conversion veto: events where an opposite-charge track is found close to the lepton track are rejected.
- Cosmic ray veto (in data only).
- QCD veto: events with a muon are required to have $M_T(W) > 10$ GeV and events with an electron are required to have $M_T(W) > 20$ GeV, where $M_T(W)$ is the transverse mass of the \cancel{E}_T -lepton system. Additional cuts are placed on the \cancel{E}_T -significance and the angles between the \cancel{E}_T and the second jet as in Ref. [9].

III. BACKGROUNDS

Following the baseline event selection, we expect events from several SM processes in our data sample:

- W +jets
- Z +jets, where one lepton from the Z decay is not identified
- QCD multijet production (or non- W): events with only jets and no W or Z , which will pass our event selection criteria if a jet fakes a lepton and there is significant mismeasurement of the \cancel{E}_T .
- Dibosons: WW , WZ , and ZZ events
- $t\bar{t}$: dileptonic or semileptonic decays of top pair events can pass our selection if a lepton or several jets are not identified.
- single top.

All of these backgrounds except for the non- W background are modeled with Monte Carlo events simulated using the CDF detector simulation [5]. ALPGEN [8] with a PYTHIA parton shower is used for W and Z plus jets; PYTHIA is used for dibosons and $t\bar{t}$, and MADEVENT plus PYTHIA is used for the single top background. Data events based on loosened lepton selections are used to model the non- W background.

The contribution of each background except for non- W and W +jets is estimated with the formula $N = \sigma L \epsilon$, where σ is the production cross section, L is the integrated luminosity, and ϵ is the efficiency of detection (including detector acceptance, trigger efficiency, and selection efficiency) for an event from a particular process. ϵ is estimated based on the Monte Carlo simulation. The cross sections used in this estimate are based on NLO calculations for all processes except Z +jets, for which the cross section is taken from the CDF inclusive measurement [10].

Once the contributions of all other processes have been determined, a fit to the \cancel{E}_T spectrum in data is carried out to find the contribution from W +jets and non- W events. The fit is performed separately in each lepton category. It is performed in events passing the baseline event selection, but with the \cancel{E}_T cut removed.

Based on the procedure described above, 86% of the sample is expected to come from W +jets production; 5% from non- W processes; 4% from Z +jets; 3% from diboson processes; 1% from top pair production, and 1% from single top production.

IV. ANALYSIS METHOD

After the baseline selection and based on the models described above, we consider the kinematics of signal and background processes and select a region where we expected enhanced signal contributions. We introduce three extra cuts:

- $E_T(\text{leading jet}) > 60$ GeV
- $\Delta\phi(\cancel{E}_T, \text{lepton}) < 2.2$
- $\cancel{E}_T > 30$ GeV.

The expected yield of background events is shown together with the number of events observed in data in Tab. II. The expected contribution of signal events is shown in Tab. III.

Process	Expected number of events
W +jets	10648 ± 319
$WW + WZ + ZZ$	599 ± 60
non- W	581 ± 232
Z +jets	497 ± 75
tt	355 ± 43
Total	12829 ± 409
Number of events in data	13243

TABLE II: Expected contributions of SM processes in the signal region and number of events observed in data.

Heavy quark mass [GeV/ c^2]	Expected number of events (D)	Expected number of events (U)
300	1275 ± 115	302 ± 27
400	293 ± 26	54 ± 5
500	81 ± 7	12 ± 1
600	20 ± 2	2 ± 0.2

TABLE III: Expected signal contributions in the signal region, assuming $\tilde{\kappa}_{uD}^2 = 1$ and $\tilde{\kappa}_{aU}^2 = 1$.

We reverse the first two cuts to create control regions: the low- E_T control region ($E_T(\text{leading jet}) < 60$ GeV) and the high- $\Delta\phi$ control region ($\Delta\phi(\cancel{E}_T, \text{lepton}) > 2.2$ and $E_T(\text{leading jet}) < 60$ GeV). In addition, we use events that pass all of the event selection and signal region cuts but only have one jet (no second jet with $E_T > 20$ GeV) as the 1-jet control region. The modeling in the control regions is explored, and we check that mismodeling is covered by systematic uncertainties. In a few cases (for the p_T of the W boson in the 1-jet bin, and for the ΔR between the two jets in all control regions), we find that there is mismodeling not covered by systematics, and we impose additional systematic uncertainties to account for the mismodeling. The systematic uncertainties are more fully described in Sec. V.

We search for the signal by fitting the invariant mass of the lepton, neutrino, and jet ($M_{l\nu j}$) in the signal region to templates of signal and background processes formed from our models. The p_x and p_y of the neutrino are taken from the \cancel{E}_T measurement, while the p_z is determined by requiring that the invariant mass of the lepton and the neutrino is the mass of the W boson. This gives a quadratic equation with two possible solutions for $p_z(\nu)$. If both solutions are imaginary, we take the real part; if they are real, we use the one with the smaller absolute value.

A maximum likelihood fit is used for the signal extraction. The fitting procedure is based on the one used in the single top observation [9], with the same method of incorporating systematic uncertainties into the likelihood. In the absence of signal, we integrate the posterior probability density to find a 95% confidence level limit on the cross section of heavy quark production.

V. SYSTEMATIC UNCERTAINTIES

Several sources of systematic uncertainty are taken into account. We include both uncertainties on the shape of the signal or background templates and on the expected yields of signal and background.

A. Jet energy scale

The effect of the jet energy scale (JES) uncertainty on this analysis is determined by repeating the analysis with two sets of shifted MC samples: one where every jet in signal and background has been shifted up by 1σ and one where every jet has been shifted down by 1σ , where σ is determined by [6]. The procedure to determine the expected background contributions is repeated, and the templates are rederived. We use the JES as a shape uncertainty for both the signal and the W +jets background. We also impose a 2% rate uncertainty on the signal associated with the JES uncertainty due to the change in acceptance. The rate uncertainty and the signal and background shape uncertainties are correlated in the fit.

B. Q^2 scale in Alpgen

The choice of factorization and renormalization scale (Q^2 scale) in Alpgen can affect the W +jets modeling. The default scale used in generating the central MC models is doubled and halved to create two new MC samples for this background. We rederive the W +jets $M_{l\nu j}$ template with the different MC samples, and use the varied templates as shape uncertainties on the central W +jets template.

C. $p_T(W)$ mismodeling

The $p_T(W)$ is mismodeled in the 1-jet control region. While it is not poorly modeled in other control regions, it is reasonable to include a shape uncertainty associated with the mismodeling. The W +jets Monte Carlo is reweighted to agree with the data in the 1-jet control region. The weights as a function of the $p_T(W)$ are then applied to W +jets events in the signal region, and the $M_{l\nu j}$ template is rederived. The mismodeling uncertainty is imposed as a one-sided, truncated 1σ uncertainty.

D. Dijet mismodeling

We observe mismodeling of the ΔR between the two jets in all control regions, with the largest discrepancy observed in the low- E_T control region. The W +jets MC is reweighted to agree with the data in this control regions, and the weights as a function of ΔR_{jj} are applied to the W +jets model in the signal region to rederive the $M_{l\nu j}$ template. As with the $p_T(W)$ uncertainty, this mismodeling uncertainty is imposed as a one-sided, truncated 1σ uncertainty.

E. Background normalization uncertainties

The backgrounds are assigned uncertainties associated with the uncertainties in their cross sections and the acceptance for a given background process. The non- W model is assigned a conservative 40% rate uncertainty as mentioned above. The uncertainty on the W +jets normalization is taken to be 20%, but the data constrains its normalization more strongly in the final fit to the data. The rate uncertainties on the WW , WZ , and ZZ processes are taken to be 10%, and are correlated in the fit. The rate uncertainty on the single top and $t\bar{t}$ backgrounds are 12%, and are correlated in the fit. The uncertainty on the Z +jets rate is taken to be 15%.

F. Signal rate uncertainties

We impose three rate uncertainties on the signal: one associated with the uncertainty due to NLO production, one associated with the uncertainty on ISR and FSR, and the third associated with the uncertainty in PDFs.

The uncertainty due to NLO contributions is taken to be 5%, based on the k -factor cited in Ref. [1] and confirmed in private communication with the authors.

The uncertainty due to ISR/FSR is evaluated by regenerating the signal sample for a 300 GeV D -type quark with initial- and final-state radiation tuned higher and lower, according to the standard prescription. The change in the rate of the signal was -2% for both the higher- and lower-tuned samples.

The uncertainty due to PDFs was evaluated using the standard Joint Physics procedure, and was found to be $\pm 2\%$.

G. Integrated luminosity

A 6% uncertainty due to the integrated luminosity is applied to the normalization of all processes except those whose normalization is derived from data, so all signal and background processes except non- W and W +jets.

H. Trigger and lepton ID efficiency

There is a 2% uncertainty in the efficiencies of the triggers and lepton ID. We apply this uncertainty as a rate uncertainty on all processes except non- W and W +jets.

VI. RESULTS

The distribution of $M_{l\nu j}$ observed in the signal region in data compared to the prediction is shown in Fig. 2. No significant excess associated with our signal is found in the data. As a result, we set limits on the production cross section of new heavy quarks, shown in Fig. 3, and translate them into limits on the couplings between heavy quarks and SM quarks, shown in Fig. 4. The limits themselves are given in Table IV.

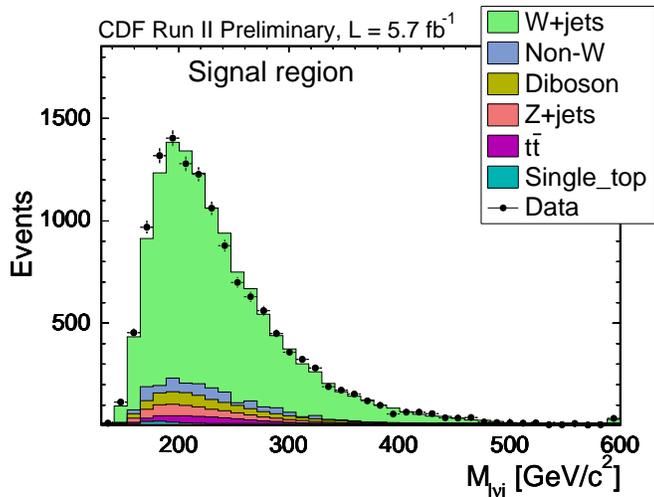


FIG. 2: $M_{l\nu j}$ observed in data in signal region compared to prediction.

M_Q [GeV/ c^2]	Limit on $\sigma(p\bar{p} \rightarrow qQ)$ [pb]	Limit on $\tilde{\kappa}_{uD}^2$	Limit on $\tilde{\kappa}_{dU}^2$
300	2.4	0.34	1.5
400	0.67	0.45	2.4
500	0.27	0.74	5.4
600	0.18	1.9	15

TABLE IV: Limits on production cross section of heavy quark and coupling between heavy quark and SM quark.

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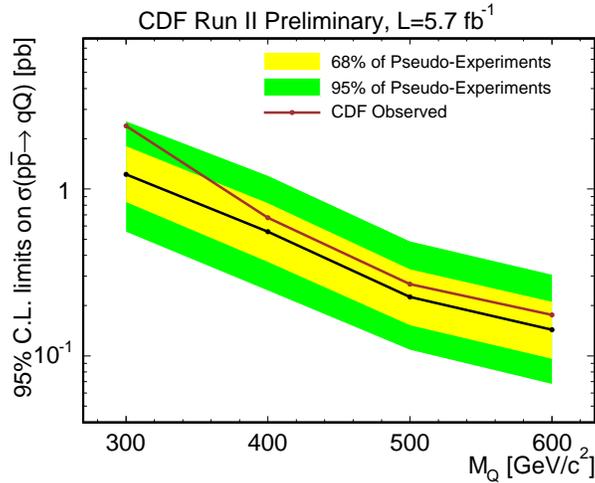


FIG. 3: 95% C.L. limit on production cross section of new heavy quarks as a function of their mass.

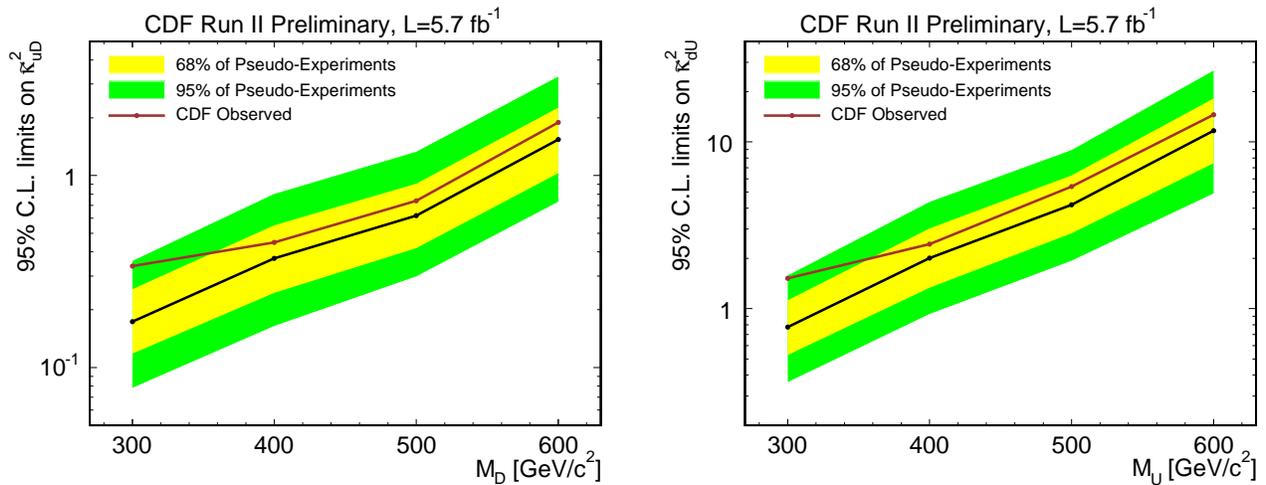


FIG. 4: 95% C.L. limit on couplings between SM quarks and new heavy quarks as a function of heavy quark mass.

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