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Beyond the Standard Model searches with top quarks at D0

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Due to its high mass and short lifetime, the top quark plays an important role in checking the Standard Model of particle physics. In this report, we present a variety of searches for physics beyond the Standard Model, involving top quarks, at the D0 detector at the Fermilab Tevatron collider. Specifically, we present searches in top quark pair production, single top quark production and top quark decays. The search spectra discussed here involve a search for $t\bar{t}$ resonances, associated production of Higgs bosons and $t\bar{t}$, charged Higgs bosons and heavy gauge $W^{'}$ bosons. Furthermore, we measure the forward-backward charge asymmetry and a ratio of branching fractions.

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1. Introduction

The heaviest known elementary particle today is the top quark, with a mass of 173.1 ± 1.3 GeV [1]. Due to its high mass, the Yukawa coupling to the Higgs boson is expected to be large. Furthermore, the top quark decays before it hadronizes, making it a unique particle to study bare quarks.

Since the discovery of the top quark in 1995 by CDF and D0 [2, 3], several properties have been investigated with increasing precision. For example, the $t\bar{t}$ production cross section is now measured with a precision close to the theoretical uncertainty [4], and the measurement of the top quark mass exceeds 1% accuracy [1]. Due to the high precision measurements, high statistics and its particular properties the top quark sector is an interesting sector to search for deviations from the Standard Model (SM) expectation. Recently, the observation of single top quarks was reported by CDF and D0 [5, 6], opening another channel to search for physics beyond the SM.

In the following, a selection of searches beyond the SM in $t\bar{t}$ production, top quark decay and single top quark production will be presented.

2. Searches for new physics in $t\bar{t}$ production

At the Tevatron, top quark pair production occurs 85% of the time via $q\bar{q}$ annihilation and with 15% gluon-gluon fusion. Assuming SM production and decay, the measured production cross section at a top mass of 170 GeV is $\sigma_{t\bar{t}} = 8.18^{+0.98}_{-0.87}$ pb [4].

For measurements of $t\bar{t}$ cross section and top properties the $t\bar{t}$ final states are classified according to the decays of the two W bosons from the top and anti-top decay. We separate the final states into dileptonic, semileptonic and allhadronic channels according to the number of leptons in the final state. If the lepton is a hadronic decaying tau, the events are treated as separate channels (τ+lepton and τ+jets).

In the SM, no $t\bar{t}$ resonances exist, but many models like for example Topcolor assisted technicolor models predict a resonance. Using the semileptonic final state, D0 performed a search for a narrow resonance X, manifesting as a bump in the invariant $t\bar{t}$ mass spectra [7]. With 3.6 fb^{-1} of data, limits on $\sigma(p\bar{p} \to X) \times B(X \to t\bar{t})$ versus M_X have been extracted. In the reference model of Topcolor assisted technicolor a Z' can be excluded for $M_X < 820$ GeV. In Fig. 1 the invariant mass distribution is shown, together with a Z' of mass 650 GeV.

Not only invariant mass spectra, but also the forward backward charge asymmetry of $t\bar{t}$ events can give hints for deviations from the SM. In next-to-leading-order (NLO) calculations, the asymmetry is expected to be 5%. With 1 fb^{-1} of data, D0 performed a measurement of the asymmetry by looking at the number of semileptonic events with a non-vanishing rapidity difference between the top and the anti-top quark [8]. The measured asymmetry of $A_{fb} = 12 \pm 8\ (\text{stat})\ \pm 1\ (\text{syst})\%$ is consistent with the SM.

Due to its high mass, the top quark is expected to have a large coupling to the Higgs boson. An interesting search for the Higgs boson is therefore to look for associated production of $t\bar{t}$ and Higgs. By studying events with a high number of jets, and especially a high number of b-jets, D0 preformed a search for $t\bar{t}H$ with 2.1 fb^{-1} of data [9]. Compared to the SM prediction of $\sigma_{t\bar{t}H}$, we reach an upper limit of $\sigma_{t\bar{t}H}/\sigma_{SM} < 48$ at 95% C.L. assuming a Higgs mass of 105 GeV. In models beyond the SM, the $t\bar{t}H$ cross section can be enhanced, for example, if a t' is produced via a heavy color-octet vector particle $G^{'}$ [10]. Considering this scenario, we can exclude a region in the $[m_{t'}, M_H]$ parameter space, excluding for example values below a Higgs boson mass of 146 GeV at a $t^{'}$ mass of 355 GeV.

3. Searches for new physics in top quark decays

We study the possibility of the top quark decaying into any other quark but a b-quark by measuring the ratio of branching fractions, and consider the possibility of the top quark decaying into another boson than the W boson by performing a search for charged Higgs bosons.

In the SM, the top quark decays with a probability of almost 100% into a W-boson and a b-quark. If, for example, a fourth generation of quarks would exist, it could modify $B(t \rightarrow Wb)$ to a value below one. We study such a possibility, by measuring the ratio of branching fractions, defined as $R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)}$ with $q = b, s, d$. By analysing the distribution of events with 0, 1 or ≥ 2 identified b-jets, a simultaneous measurement of $\sigma_{t\bar{t}}$ and R yields $\sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84}$ (stat + syst) ± 0.5 (lumi) pb and $R = 0.97^{+0.09}_{-0.08}$ [11]. We use this result to set lower limits on $|V_{tb}|$ assuming unitarity of the 3×3 CKM matrix, yielding $|V_{tb}| > 0.89$ at 95% C.L. Without this assumption we can set an upper limit of 0.27 on $(|V_{ts}|^2 + |V_{td}|^2)/|V_{tb}|^2$ at 95% C.L. The measured values of R and $\sigma_{t\bar{t}}$ are fully consistent with the SM expectation.

Not only the quark-part of the top decay can be modified by new physics, but also the bosonic part can be different. If, for example, a charged Higgs boson exists with a mass smaller than the top quark mass, the decays $t \rightarrow Wb$ and $t \rightarrow H^+b$ can compete. Due to the different decay modes of W boson and $H^{\pm}$ boson the occurance of a charged Higgs boson leads to a different distribution of events between various final states than in the SM. By comparing the distribution of events in the lepton+jets, dilepton and τ+lepton final states, we are sensitive to $B(t \rightarrow H^+b)$ [4, 12]. We consider two decay modes of charged Higgs bosons: $H^+ \rightarrow \tau\nu$ and $H^+ \rightarrow c\bar{s}$, and the mixture of both decays. For the tauonic decaying charged Higgs, we expect a decreasing number of events (disappearance) in the lepton+jets and dilepton final state and a increasing number of events (appearance) in the τ+lepton channel for increasing $B(t \rightarrow H^+b)$. In case of hadronic decaying charged Higgs bosons, all considered channels are disappearance channels. We use two approaches to explore the distribution of events between the final states. One is using the ratio of the $t\bar{t}$ cross section measured in two exclusive final states [4]. This has the advantage that many systematic uncertainties, as for example on the luminosity, cancel. The second approach uses the full information of all final states by performing a global fit [12]. Extra sensitivity can be gained here by performing a simultaneous fit of $\sigma_{t\bar{t}}$ and $B(t \rightarrow H^+b)$ for tauonic decaying charged Higgs bosons. Using this approach, we can set upper limits on $B(t \rightarrow H^+b)$ between 0.13 for low charged Higgs masses and 0.26 for high masses at 95% C.L. In case of a the hadronic decaying charged Higgs, we set upper limits of 0.22 at 95% C.L.

Besides the distribution of events between different final states, we also study topological differences between events with tauonic decaying charged Higgs bosons and SM $t\bar{t}$ events in the lepton+jets final state [13]. Especially for high charged Higgs masses, the upper limits on $B(t \rightarrow H^+b)$ are comparable with the global fit method.

The limits we derived on $B(t \rightarrow H^+b)$ can be used to set exclusion regions in the Minimal Supersymmetric Standard Model (MSSM) parameter space $[M_{H^+}, \tan\beta]$. We consider three different

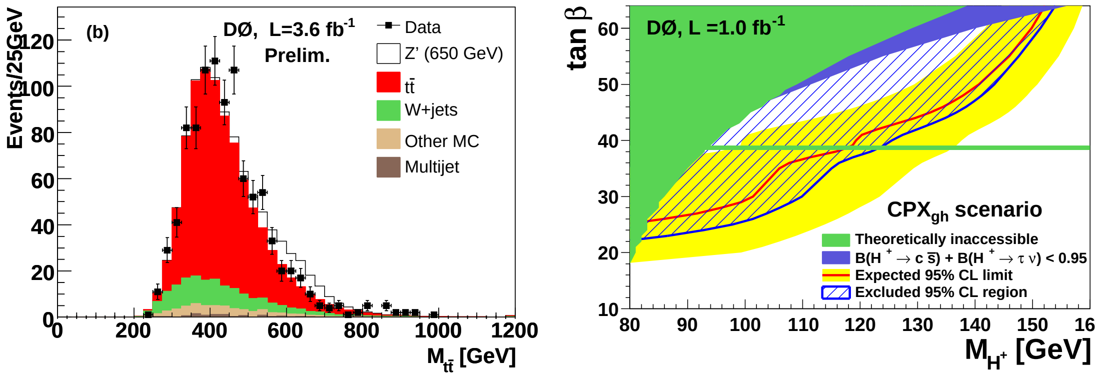

Figure 1: Left: Invariant $t\bar{t}$ mass [7]. Right: Excluded region in $\tan\beta$ and M_{H^+} in the MSSM for the strangephilic CPX model [14, 12].

benchmark models, two of them are CP-conserving and one is CP-violating. The CP-conserving models under study are the so-called MhMax and no-mixing scenarios. By setting the stop-mixing parameter to be large (MhMax) or to zero (no-mixing) a large parameter space in direction of the mass of the lightest Higgs boson of the MSSM or a relatively restricted MSSM parameter space are provided.

As a CP-violating model we consider a strangephilic CPX scenario [14], where the charged Higgs boson decay into charm and strange quarks is enhanced by introducing a hierarchy between the first two and the third generation of sfermions. In this model, we can exclude charged Higgs masses up to 154 GeV for large $\tan\beta$. Figure 1 shows the exclusion region in this model.

4. Searches for new physics in single top quark production

Besides doing searches in the $t\bar{t}$ production channel, it is also interesting to search for deviations from the SM expectation in single top production. At the Tevatron, single top quarks are produced dominantly via the electroweak interaction in s- and t-channel diagrams in the SM. Two examples of searches in the single top sector are presented here, namely the search for a heavy charged Higgs bosons and a heavy gauge boson $W^{'}$.

If a charged Higgs boson heavier than the top quark would exist, the process $p\bar{p} \rightarrow H^+ \rightarrow t\bar{b}$ could take place. Besides leading to an increased number of expected events than in the SM prediction only, such a process would lead to a bump in the invariant mass distribution of the $t\bar{b}$ final state. At D0, a search for heavy charged Higgs bosons with masses between 180 and 300 GeV has been performed using 0.9 fb^{-1} of integrated luminosity [15]. To allow for a full reconstruction of the final state, only events with exactly two jets are considered for this search. No evidence for a heavy charged Higgs boson is found. Upper limits on $\sigma(p\bar{p} \rightarrow H^+) \times B(H^+ \rightarrow t\bar{b})$ are set using three different types of two-Higgs-doublet models (2HDM). For type I 2HDM models, where only one of the doublets couples to fermions, a region in the $[M_{H^+}, \tan\beta]$ plane can be excluded.

Similar to the heavy charged Higgs boson search, the invariant mass distribution of the $t\bar{b}$ final states can also be used to search for heavy gauge bosons $W^{'}$. We performed a search for $W^{'}$ bosons with 0.9 fb^{-1} of D0 data [16]. Two different scenarios have been considered: One where the $W^{'}$

has a left-handed coupling, leading to interferences with the SM W boson, and one where the $W^{'}$ has a right-handed coupling. We can exclude $M_{W'} < 731$ GeV for $W^{'}$ with left handed couplings. In case of $W^{'}$ with right-handed couplings, we exclude $M_{W'} < 739$ GeV if the $W^{'}$ decays to leptons and quarks and $M_{W'} < 768$ GeV if the $W^{'}$ decays only into quarks.

5. Conclusion and Outlook

In this report, a representative extract of searches for physics beyond the SM using top quark events has been presented. We used up to 3.6 fb^{-1} of data collected with the D0 detector, yielding high sensitivity for various new models. Until today, more than 6 fb^{-1} of data have been collected. With improving techniques and the increasing statistics the top quark will remain an ideal particle to look for new physics.

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