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Top and Higgs at the Tevatron: Measurements, Searches, Prospects

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TOP AND HIGGS AT THE TEVATRON:
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In this paper we summarize the status of Top Quark Physics and of searches for the Standard Model Higgs at the Tevatron. Results from both the CDF and D0 experiments are discussed and the prospects for the upcoming Run 2, in the year 2000, are outlined. Much work has been performed on these topics and due to the nature of these proceedings only a brief explanation can be offered here. For more details the reader should turn to the excellent sources listed in the reference section.

1 Top Quark Physics

1.1 Introduction

The announcement of the discovery of the top quark was made in March 1995[1,2]. Since then the two Tevatron experiments, CDF and D0, have analyzed all their data taken during the 1992-1996 "Run 1" period and have been upgrading their detectors to match the high-luminosity running conditions that the Tevatron collider will provide during "Run 2". The results presented here come from datasets corresponding to a total integrated luminosity of about 110 pb^{-1} for CDF and about 125 pb^{-1} for D0.

At the Tevatron top quarks are produced mainly in pairs, via $q\bar{q}$ anihilation[3], with a cross section of about 5 pb. Therefore only about 600 $t\bar{t}$ pairs, per experiment, were created during the entire Run 1. When geometrical acceptances and detection efficiencies are folded in, the datasets available for studies are rather small. Nonetheless, as it will be shown here, significant information has been extracted about the identity and behaviour of this newest quark.

During Run 2 the luminosity is expected to increase by about a factor of twenty, to 2 fb^{-1}, and the Tevatron center-of-mass energy is expected to reach 2 TeV. We expect to collect datasets that are about thirty times larger than those in Run 1 which will help improve significantly our knowledge about the top quark [4].

In the Standard Model (SM) the top quark decays effectively 100% of the time to a W boson and a b quark. The top decay width is approx. 1.5 Gev (at $\mathrm{M_{top}} \sim 175$ GeV) and the corresponding lifetime is 4×10^{-25} sec. In this short time there is no hadronization and the top quark decays as a free quark. No hadronic states with top can be formed and there is no toponium spectroscopy to be studied. The signatures for $t\bar{t}$ pair production depend exclusively on the decays of the two W bosons from each of the $t \rightarrow W, b$ decays. The channels are classified according to the number of leptons appearing in the final state. Excluding final states with tau leptons, which are more difficult to detect, the "dilepton" channel ($t\bar{t} \rightarrow \ell\bar{\nu}b\ell\nu\bar{b}$) has a branching fraction of 5%, the "lepton+jets" channel ($t\bar{t} \rightarrow q\bar{q}b\ell\nu\bar{b}$) of 30% and the "all-jets" channel ($t\bar{t} \rightarrow q\bar{q}bq'\bar{q}'\bar{b}$) of 40%. Significant excess of events has been observed in all these channels and the results reported below come from the analyses of these channels.

1.2 Measurements

Event selection

The large mass of the top quark allows for an event selection biased towards high transverse energy, or momentum, objects. This helps reduce backgrounds significantly [5,6,7,8]. For leptons, jets, and missing transverse energy ($\not{E}_t$) the requirement is $E_T(P_T) > 20$ GeV approx. These objects are also required to be isolated from other objects in the event and in the central region of the detector with pseudorapidity $|\eta| < 2$ approx. Also due to the large $\mathrm{M_{top}}$, global event kinematical variables are useful in separating signal from backgrounds. The aplanarity and sphericity of the event and the sum of transverse energies of all objects have been used for this purpose. Neural nets are also useful in separating further the top signal from backgrounds.

A key feature of $t\bar{t}$ events is the production of two b quarks and the ability to tag these objects has proven essential in top quark physics. The tagging of long-lived heavy flavor quarks can be performed by means of secondary vertex detectors which can be $\sim 50\%$ efficient in finding at least one tag in a $t\bar{t}$ event (CDF) and by finding the softer leptons in semi-leptonic b decays with $\sim 20\%$ efficiency (D0 and CDF). The secondary vertex method works best because of the relatively low fake rate.

In the dilepton channel (including taus), after the selection cuts CDF (D0) finds 13 (9) events, with a signal purity of $\sim 66\%$ ($\sim 90\%$). The dominant backgrounds come from Drell-Yan, $Z \rightarrow \tau\tau$, WW and fake lepton processes [9,10]. In the lepton+jets channels CDF (D0) finds 74 (30) events with a purity of

$\sim 57\%$ ($\sim 63\%$). The dominant backgrounds are W+*jets* production and QCD multi-jet processes [11,12]. The all-jets channel is dominated by QCD multi-jet productions and b-tagging is essential, CDF (D0) finds 344 (41) events with a purity of about $\sim 24\%$ ($\sim 39\%$) [13]. It is with these relatively small samples of events that the measurements described below are performed. In the lepton+jets channel the experiments have been able to reconstruct the invariant mass of the hadronic W decay and the Jacobian peak for the leptonic W decay. Additionally the kinematical distributions for all examined variables, including the invariant mass of the $t\bar{t}$ system (which could reveal a resonant production) match very well those expected from SM $t\bar{t}$ production.

Production cross section

The $t\bar{t}$ production cross section has been measured separately in the channels described above and all channels yield consistent results. A final result is obtained by combining the individual channel cross sections. CDF measures $7.6^{+1.8}_{1.5}$ pb^{-1} and D0 5.9 ± 1.7 pb^{-1} [14,7]. The uncertainty is of the order of 25%. The theoretical predictions range between 4.7 and 5.5 pb^{-1} depending on assumptions about gluon resumation. In Run 2 the experimental uncertainty is expected to go down to less than 10%.

From the ratios of observed number of events in the different channels CDF has extracted a measurement of the branching fractions for top to decay leptonically: $BR(t \rightarrow eX, ort \rightarrow \mu X) = 0.094 \pm 0.024$

Top Quark mass

In the lepton+jets channel, events with four or more jets are selected and all objects are measured precisely [15,5]. The jet energies are corrected to what, on average, parton energies would have been. A 2C kinematic fit is performed for each combinatorial assignment of objects to the $t\bar{t}$ system. The b-tagging helps reduced the combinatorics. For each event, the solution with the best χ^2 is chosen and the reconstructed mass distribution is compared to a Monte-Carlo mix of $t\bar{t}$ events at a given top mass and background. The top mass that results in the best fit is chosen as the central value and the statistical uncertainty is taken as the range in which the χ^2 changes by ± 0.5 (see Fig. 1.2). The systematics are dominated by the understanding of the jet energy scale in the detectors and of initial and final state radiation. The CDF and Do results are: $175.9 \pm 4.8(\mathit{stat.}) \pm 5.3(\mathit{syst.})$ and $173.3 \pm 5.6(\mathit{stat.}) \pm 5.5(\mathit{syst.})$, respectively.

In the all-jets channel the kinematics are also over-constrained and a 3C-fit is performed using the same technique as in the lepton+jets channel [13]. CDF measures $186.0 \pm 10.0(\mathit{stat.}) \pm 5.7(\mathit{syst})$. For the dilepton events, the

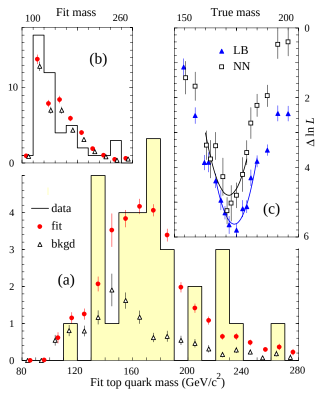

Figure 1: D0's top mass in the lepton+jets channel.

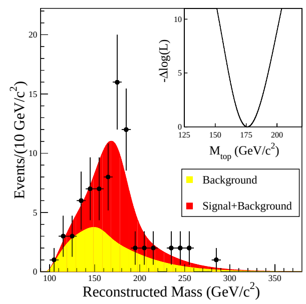

Figure 2: CDF's top mass in the lepton+jets channel.

kinematical fit is under-constrained and the event reconstruction is performed hypothesizing a given $\mathrm{M_{top}}$ and performing a scan over $\mathrm{M_{top}}$. For each value of $\mathrm{M_{top}}$ the likelihood that the reconstructed kinematics compare well with those expected from $t\bar{t}$ production is measured and the reconstructed $\mathrm{M_{top}}^{\mathrm{best}}$ for the maximum likelihood is chosen. The distribution of $\mathrm{M_{top}}^{\mathrm{best}}$ is then compared with Monte-Carlo to find the best value of $\mathrm{M_{top}}$ [15,10]. CDF gets $168.4 \pm 12.3(\textit{stat.}) \pm 3.6(\textit{syst.})$ and D0 $167.4 \pm 10.3(\textit{stat.}) \pm 4.8(\textit{syst.})$. For the all-jets and the dilepton channels the systematics are also dominated by the jet energy scale and knowledge of initial and final state radiation.

The lepton+jets channel yields the measurement with the smallest statistical uncertainty while the systematic uncertainties are comparable in all channels. The CDF and D0 combined result is: $\mathrm{M_{top}} = 174.3 \pm 3.2(\mathrm{stat.}) \pm 4.0(\mathrm{syst.})\ \mathrm{GeV/c^2}$. In Run 2 the systematics will be controlled better through higher statistics control samples and it is estimated that $\mathrm{M_{top}}$ can be measured with a total uncertainty of about 2 GeV [4].

Measurement of $|V_{tb}|$

CDF uses the taggable fraction of top decays, $R_b \equiv \frac{BR(t\to Wb)}{BR(t\to Wq)}$ as a way to measure $|V_{tb}|$. R_b is obtained from measuring the ratio of events with 0,1, or 2 b-taggs. In a 3-generation Standard Model $R_b = \frac{|V_{tb}|^2}{|V_{tb}|^2+|V_{ts}|^2+|V_{td}|^2}$. The result: $|V_{tb}| = 0.99 \pm 0.15 (> 0.76\ \textit{at}\ 95\%\ \textit{c.l.})$ [16].

Measurement of the W helicity in top decays

The helicity of the W boson in top decays carries information on the $W-t-b$ coupling. In the Standard Model a large fraction of top decays are expected to produce a W with helicity=0. CDF uses the lepton P_T distributions in the lab frame to measure the W-helicity distribution in the top rest frame. The P_T of left-handed W bosons is expected to be softer than that of zero-helicity $W's$. The fit of these two distributions to the data results in $F_o = 0.97 \pm 0.37(stat.) \pm 0.12(syst.)$, consistent with the theoretical expectation of $F_o = (70.6 \pm 1.6)\%$.

1.3 Searches

Single top production

The production of single top at the Tevatron is expected to occur via Wg-fusion and via W^* with cross sections of about 1.7 and 0.7 pb, respectively. these processes suffer from copious backgrounds from $W + 2 - jet$ QCD production. CDF has used the secondary vertex tagger to reduce the backgrounds and has performed fits to kinematical distributions that reconstruct the single top mass and include the rapidity distribution of jets in order to set limits to the single top production cross section. The obtained limits are: $\sigma(Wg) <$ 15.4 pb at 95% c.l. and $\sigma(W^*) <$ 15.8 pb at 95% c.l.. These limits are still a factor of 10-20 above the theoretical expectations and will improve considerably in Run 2, perhaps to the point of actually observing this process.

Rare top decays

CDF has looked for the rare FCNC decays $t \to \gamma q$ and $t \to Zq$, with $q = u, c$. Only one event is observed in each channel, consistent with the expected backgrounds. The corresponding 95% c.l. limits on the branching fractions are [17]: $BR(t \to \gamma q) < 3.2\%$ and $BR(t \to Zq) < 33\%$.

2 Higgs searches

2.1 Introduction

At the Tevatron energies the processes with the highest cross section for Standard Model Higgs production are [18]: $gg \to H$ and $q\bar{q} \to WH, ZH$. The first process, which has the largest cross section, is very difficult to detect because of copious backgrounds, so searches have focused on the later processes (associated production") with high P_T leptons to help reduce the background. For

$M_H \sim 120$ GeV the cross sections are about 0.1 and 0.2 pb for WH and ZH, respectively. These are about 25 smaller than the $t\bar{t}$ cross section!

For $M_H \sim 100$ GeV the decay $H \rightarrow b\bar{b}$ dominates ($\sim 90\%$); for $M_H \geq\sim 130$ GeV $H \rightarrow WW$ starts to contribute significantly and dominates after $M_H \geq\sim 160$ GeV. Excellent b-tagging is therefore crucial for Higgs searches.

2.2 Results

Both CDF and D0 have performed searches in the $WH \rightarrow \ell\nu b\bar{b}$, $ZH \rightarrow \ell^+\ell^- b\bar{b}$ and $ZH \rightarrow \nu\bar{\nu}b\bar{b}$ channels [18]. CDF uses b-tagging with secondary vertices and soft leptons and D0 uses the soft lepton taggs with a more relaxed kinematical selection. Both experiments find the data consistent with well known backgrounds and set limits for the production cross section times the branching fraction ($\sigma \cdot BR$) in the range $\sim 90 < M_H <\sim 140$ GeV. The enhanced b-tagging capability of CDF allows for better limits and also enables the search in the $VH \rightarrow q\bar{q}b\bar{b}$ channels [18]. The limits on $\sigma \cdot BR$ are still more than one order of magnitude higher than the Standard Model prediction but show that these searches are possible and limited only by luminosity, provided the experiments have excellent b-tagging and b-jet energy resolution. Both CDF and D0 have improved their detectors with precisely these capabilities in mind. Figure2.2 show the CDF limits and the expected sensitivity for Higgs searches as a function of integrated luminosity in Run 2 and beyond when CDF and D0 are combined' For 10 fb^{-1} the Higgs can be observed at the 3σ level up to $M_H \sim 130$ GeV and excluded up to 190 GeV at the 95% c.l. This is definitely a goal the Tevatron should aim for.

3 Conclusions

The Tevatron at Fermilab, for the next several years, remains the frontier of high energy physics. In Run 2, and beyond, with the upgraded CDF and D0 detectors and the improved accelerator complex, it has the capability of producing very important and exciting physics. The top quark will be studied with much more precision and a window of opportunity exists, before the LHC takes over the energy frontier, where the the Higgs boson could be found if enough luminosity is gathered.

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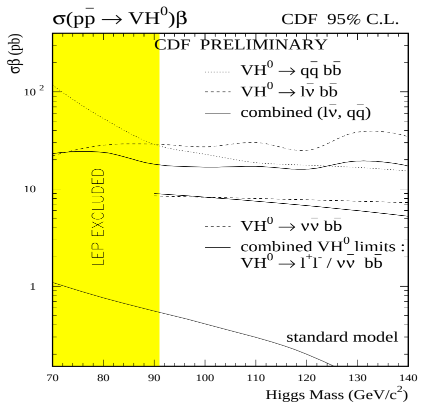

Figure 3: CDF SM Higgs limits.

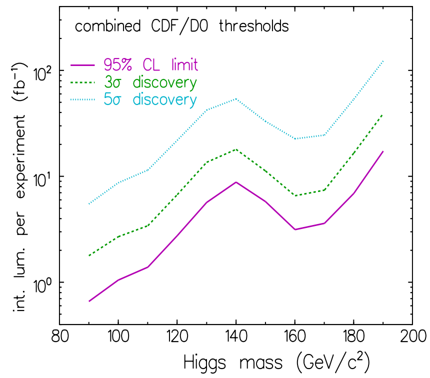

Figure 4: Tevatron sensitivity to SM Higgs.

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References

1. F. Abe *et al.*, Phys. Rev. Lett. **74**, 2626 (1995)
2. A. Abachi *et al.*, Phys. Rev. Lett. **74**, 2632 (1995)
3. Laenen, E.J. *et al.*, 1994, Phys. Lett. **B321**, 254; Berger, E.L. *et al.*, 1996, Phys. Rev. D **54**, 3085; Catani, S. *et al.*, 1996, Phys. Lett. **B378**, 329.
4. "Thinkshop" at FNAL, Top Quark Physics for Run 2: http://lutece.fnal.gov/thinkshop/.
5. F. Abe *et al.*, Phys. Rev. Lett. **80**, 1197 (1998)
6. F. Abe *et al.*, Phys. Rev. Lett. **79**, 3585 (1997)
7. S. Abachi *et al.*, Phys. Rev. Lett. **79**, 1203 (1997)
8. B. Abbott *et al.*, submitted to Phys. Rev. D, Fermilab-Pub-98/130-E (hep-ex/9808034).
9. F. Abe *et al.*, Phys. Rev. Lett. **80**, 2779 (1998); Phys. Rev. Lett. 79, 3585 (1997)
10. B. Abbott *et al.*, Phys. Rev. Lett. **80**, 2063 (1998)
11. F. Abe *et al.*, Phys. Rev. Lett. **80**, 2767 (1998);
12. S. Abachi *et al.*, Phys. Rev. Lett. **79**, 1197 (1997); B. Abbott *et al.*, Phys. Rev. D **58**, 52001 (1998)

13. F. Abe *et al.*, Phys. Rev. Lett. **79**, 1992 (1997);
14. F. Abe *et al.* Phys. Rev. Lett. 80, 2773 (1998).
15. F. Abe *et al.*, Phys. Rev. Lett. 82, 271 (1999)
16. F. Tartarelli, Proceedings of "International Europhysics Conference on High Energy Physics", Jerusalem, Israel, August 19-26, 1997.
17. F. Abe *et al.*, Phys. Rev. Lett. 80, 2525 (1998).
18. Higgs and SUSY workshop: http://fnth37.fnal.gov/susy.html