TOP QUARK PRODUCTION AT THE TEVATRON

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We present the most recent results on top pairs and single top production obtained at the Fermilab Tevatron Collider by the CDF and D0 collaborations. We show the cross section measurements, the $t\bar{t}$ forward-backward asymmetry analysis results, the ratio of branching fractions R measurement, the determination of the CKM matrix element V_{tb} and search for anomalous top quark production.

1 Introduction

The Tevatron Collider provided proton–antiproton collisions at a center of mass energy $\sqrt{s} = 1.96$ TeV until september 30, 2011, when it was definitely shut down. CDF and D0 were the two multipurpose detectors taking data at the Tevatron. Since the beginning of Run II in 2001, the accelerator performances have been improving and more than 10 fb^{-1} of integrated luminosity have been delivered to each experiment. The analyses described in the following are based on up to 8.7 fb^{-1} of data (the full Run II dataset).

2 Top Quark Production

The top quark was discovered in 1995 at the Tevatron [1]. It is the most massive of the known elementary particles. A consequence of its large mass is that the top quark is the only quark that decays before hadronizing, and thus its properties are retained by its decay products. At the Tevatron center of mass energy top quarks are produced primarily in $t\bar{t}$ pairs via the strong process $q\bar{q}(gg) \to t\bar{t}$ [2]. In the Standard Model (SM) each top quark decays through charged current weak interaction almost exclusively into a real W and a b quark ($t \to Wb$). Each W subsequently decays into either a charged lepton and a neutrino or two quarks. The $t\bar{t} \to W^+bW^-\bar{b}$ events can thus be identified by means of different combinations of energetic leptons (e or μ) and jets and are labeled as *dilepton*, *single lepton plus jets* or *all–hadronic*, depending on whether a leptonic decay has occurred in both, only one, or none of the two final–state W bosons respectively.

SM predicts that top quarks can be produced also singly, through electroweak s–channel or t–channel exchange of a virtual W boson. Single top production was observed at the Tevatron in 2009 [3]. The experimental signature consists of the W decay products plus two or three jets, including one b quark jet from the decay of the top quark. In s–channel events a second b quark jet comes from the Wtb vertex. In t–channel events a second jet originates from the recoiling light–quark and a third low–E_T jet is produced at larger η through the splitting of the initial state gluon into a $b\bar{b}$ pair.

A large sample of top quarks collected by the CDF and D0 experiments allows to perform precision measurements of top production.

2.1 Top Pair Cross Section Measurement

By measuring the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ in many decay channels and comparing it to perturbative QCD calculations, one can test the SM predictions in great detail. The most precise measurements come from the single lepton plus jets signature. Figure 1–left (1–right) shows a summary of CDF (D0) $t\bar{t}$ cross section measurements in various decay channels and obtained using various techniques. All results are consistent among channels and experiments, and are in excellent agreement with NLO calculations [4].

Since a large component (about 6%) of the experimental uncertainty on the $t\bar{t}$ cross section is due to the uncertainty on the luminosity determination, CDF obtained a higher precision by measuring the ratio of $t\bar{t}$ to Z–boson cross section $\sigma_{t\bar{t}}/\sigma_Z$ and using the theoretical Z boson cross section calculation as input. With such an approach, the uncertainty on the luminosity cancels out and the most accurate determination of the $t\bar{t}$ cross section is found: $\sigma_{t\bar{t}} = 7.70 \pm 0.52$ pb [5] for a top quark mass of 172.5 GeV/c^2. The experimental uncertainty is below 7%.

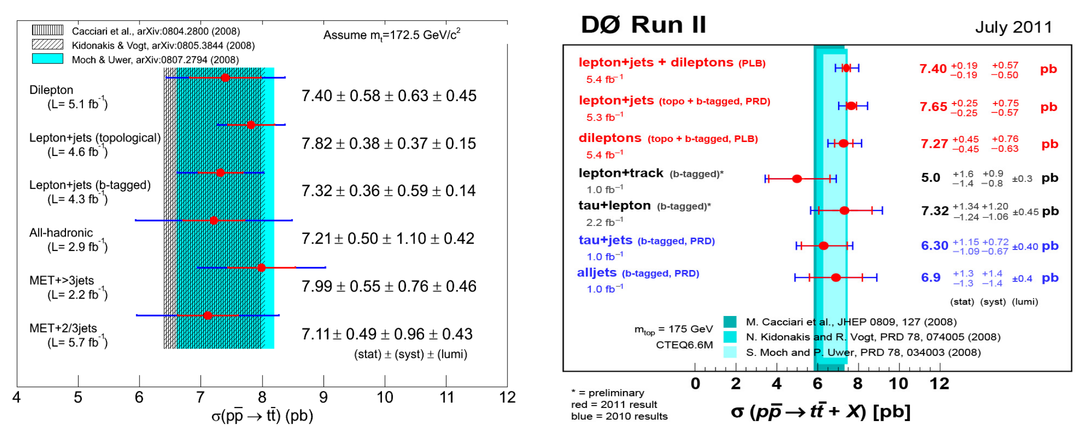

Figure 1: Summary of $t\bar{t}$ cross section measurements. Left: CDF, Right: D0.

2.2 Single Top Production

Approximate NNLO calculation predicts the single top production cross section to be $\sigma_s = 1.04 \pm 0.04$ pb and $\sigma_t = 2.26 \pm 0.12$ pb in the s and t channels respectively, for $M_{top} = 172.5$ GeV/c^2, about half than the pair production cross section, and with a much larger background [6]. On the other hand, the single top mechanism provides direct access to the V_{tb} CKM matrix element, and can be used to test the $V - A$ structure of the top charged current interaction.

D0 updated the single top observation analysis using 5.4 fb^{-1} of data and measured the combined $s+t$ channel cross section, using three different multivariate discriminants. The outputs of the individual methods have a 70% correlation, and are combined using a Bayesian Neural Network. The measured cross section is $\sigma(s+t) = 3.43^{+0.73}_{-0.74}$ pb [7] (assuming SM relative production rates for t and s channels). Potential contributions from new physics can affect differently the s and t production channels, therefore it is important to perform single top cross section measurements in the s and t channels separately. D0 made a model–independent measurement of the t–channel single top production [8]. In this analysis a two–dimensional posterior probability density is built as a function of s–channel and t–channel, with no constrains on their relative contribution. The posterior probability is integrated over the s–axis to obtain a one dimensional posterior used to extract the t–channel cross section: $\sigma(t) = 2.90 \pm 0.59$ pb, with an observed (expected) significance of 5.5 (4.6) standard deviations (see Figure 2 (left)).

CDF recently performed a combined $s+t$ single top cross section measurement based on 7.5 fb^{-1} of data and using a Neural Network discriminant [9]. The measured cross section is: $\sigma(s+t) = 3.04^{+0.57}_{-0.53}$ pb (see Figure 3 (left)).

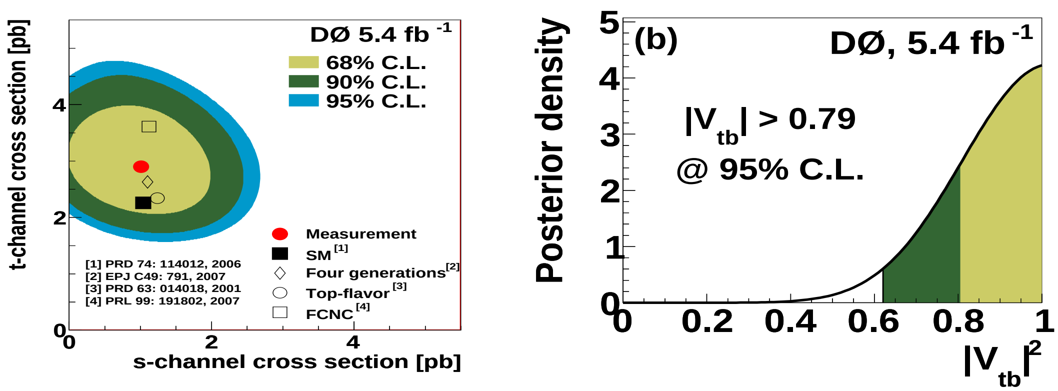

Figure 2: D0 Single top production. Left: Posterior probability density for t-channel versus s-channel cross section. The measured cross section and various theoretical predictions are also shown. Right: $|V_{tb}|$ lower limit.

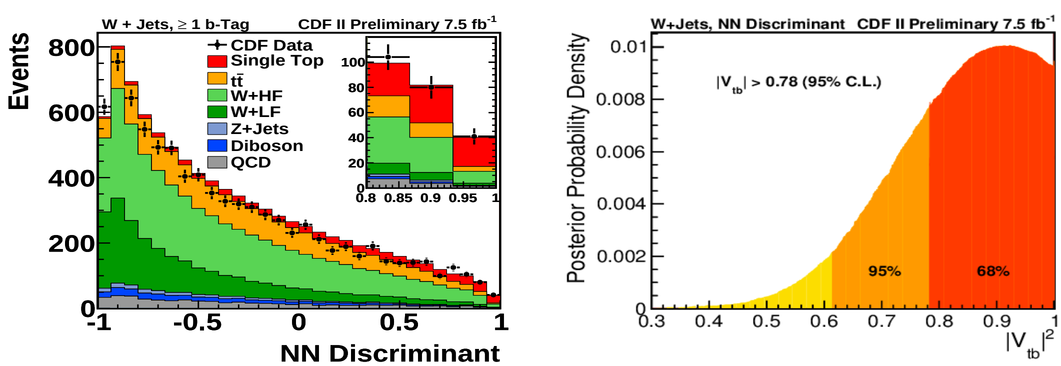

Figure 3: CDF Single top production. Left: Output of the NN discriminant. Right: $|V_{tb}|$ lower limit.

2.3 Measurement of $|V_{tb}|$ from single top cross section

Single top cross section is proportional to the $|V_{tb}|^2$ CKM matrix element, enabling to measure $|V_{tb}|$ directly without any assumption on the number of quark families or the unitarity of the CKM matrix. CDF obtains the $|V_{tb}|^2$ posterior by dividing the measured cross section by the theoretical single top cross section. CDF finds: $|V_{tb}| = 0.92^{+0.10}_{-0.08}$(stat.+syst) $\pm$ 0.05(theory) and a lower limit: $|V_{tb}| > 0.78$ at 95% C.L. assuming a flat prior in $|V_{tb}|^2$ from 0 to 1 (see Figure 3 (right)) [9]. D0 assumes that top quarks can decay exclusively into Wb and that the Wtb vertex is CP–conserving and consistent with the $V-A$ mechanism. These assumptions allow an anomalous strenght of the left–handed Wtb coupling f_1^L. Therefore D0 measures: $|V_{tb}f_1^L| = 1.02^{+0.10}_{-0.11}$. A limit $|V_{tb}| > 0.79$ at 95% C.L. is extracted if f_1^L is assumed to be one and $|V_{tb}|$ can vary from 0 to 1 (see Figure 2 (right)) [7].

3 Ratio of branching fractions R

A measurement of the $\sigma_{t\bar{t}}$ can be used to measure V_{tb} indirectly, by measuring the ratio of branching fractions R:

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

with q being a d, s or b quark. SM predicts $R = 1$ (constrained by the unitarity of the CKM matrix). $R < 1$ could indicate the presence of new physics (like the existence of additional quark families). D0 performed a simultaneous measurement of R and $\sigma_{t\bar{t}}$ using dilepton and single lepton plus jets events in 5.4 fb^{-1} of data [10]. D0 finds: $\sigma_{t\bar{t}} = 7.74^{+0.67}_{-0.57}$ pb and $R = 0.90$ $\pm$ 0.04, from which a lower limit on $|V_{tb}|$ is extracted: $|V_{tb}| > 0.88$ at 99.7% C.L.. CDF has a preliminary measurement obtained using single lepton plus jets events with either one or two identified b–jets, based on 7.5 fb^{-1} of data [11]. The CDF simultaneous measurement of $\sigma_{t\bar{t}}$ and R yields: $\sigma_{t\bar{t}} = 7.4 \pm 1.1$ pb, $R = 0.91 \pm 0.09$ and $|V_{tb}| = 0.95 \pm 0.05$.

4 Forward-Backward Asymmetry in $t\bar{t}$ Production

The measurement of the forward–backward asymmetry in $t\bar{t}$ events is a probe of the SM nature of the top quark. The strong process $q\bar{q} \to t\bar{t}$ is symmetric in production angle except for a small charge asymmetry (of the order of 7%) arising from higher order QCD [12]. In 2011 CDF and D0 published asymmetry results in the single lepton plus jets mode, based on 5.4 fb^{-1} of data [13]. CDF investigated the asymmetry as a function of the rapidity difference between top and antitop quarks Δy, and as a function of the top–antitop system invariant mass $M_{t\bar{t}}$. At high invariant mass of the system the asymmetry was consistently above the prediction. D0 also observed a larger–than–expected asymmetry. CDF presented also an independent measurement in the dilepton decay mode [14] which showed a positive deviation from SM predictions.

Recently CDF updated the asymmetry measurement in the single lepton plus jets channel, using the whole Run II dataset, (8.7 fb^{-1} of data) [15]. Parton-level results are derived with a fully general multi-bin correction procedure assuming the acceptance and resolution of the SM NLO generator Powheg [16]. Figure 5 (left) shows the parton level Δy distribution. The observed inclusive asymmetry is $A_{fb} = 0.162 \pm 0.041 \pm 0.022$. Figure 5 (right) shows the parton level A_{fb} as a function of $M_{t\bar{t}}$ with a best-fit line superimposed. The linear mass dependence slope of $(15.6 \pm 5.0) \times 10^{-4}$ can be compared to the expected NLO slope of 3.3×10^{-4}.

5 Search for new physics in top production

Several searches for new physics in the top sector were performed by both CDF and D0. Here we report the results of just a couple of the most recent analyses.

Both experiments searched for resonant production of $t\bar{t}$ in the single lepton plus jets decay channel [17]. Figure 6 shows the 95% C.L. upper limits on the cross section for resonance produc-

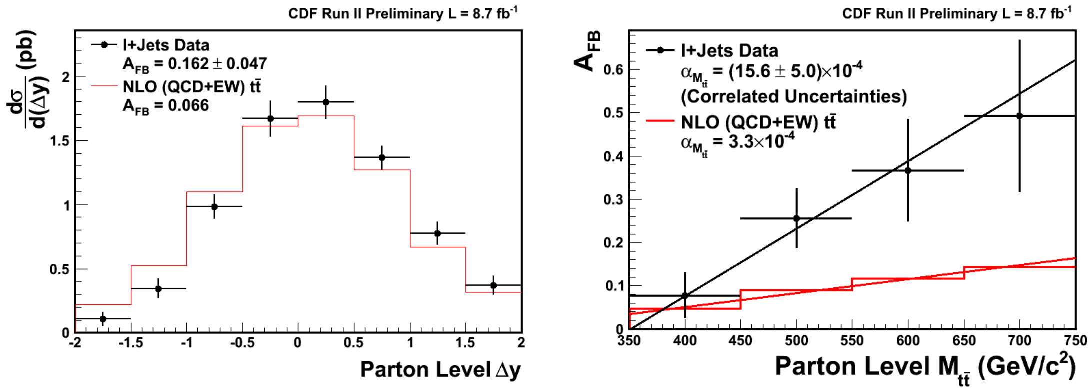

Figure 4: CDF $t\bar{t}$ Forward–Backward Asymmetry at parton level. Left: Δy distribution. Right: A_{fb} as a function of $M_{t\bar{t}}$ with best–fit line.

tion for CDF (left) and D0 (right). CDF (D0) excludes at 95% C.L. a Z' with $M_{Z'} < 900$ (835) GeV/c^2 if its width is 1.2% of its mass.

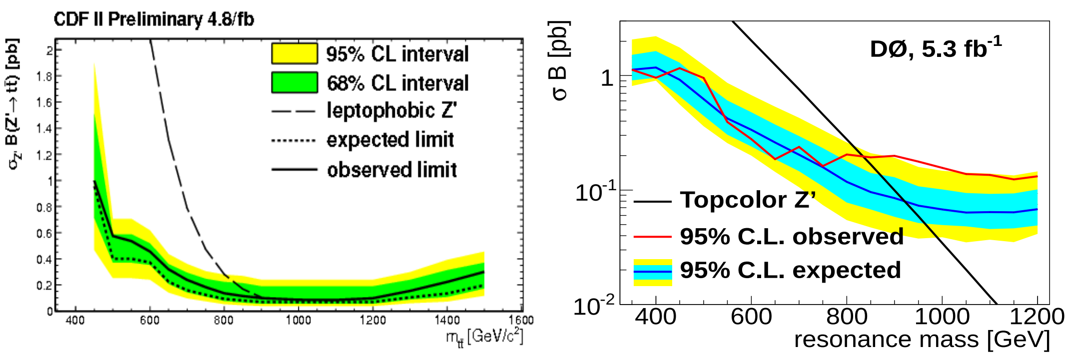

Figure 5: Search for a narrow $M_{t\bar{t}}$ resonance. Left: CDF limit. Right: D0 limit.

Recently CDF presented a search for a heavy new particle M produced in association with a top quark ($p\bar{p} \to Mt/M\bar{t}$) and decaying via $M \to \bar{t}q/tq$, leading to a resonance in the $\bar{t}/t$+jet system of $t\bar{t}$+extra jet events[18]. CDF analyzed 8.7 fb^{-1} of data, selecting events with exactly one lepton, missing transverse energy and at least five jets. Figure 7 (left) shows the reconstructed top+jet mass on a logarithmic scale. The data are consistent with SM, so upper limits from 0.61 pb to 0.02 pb for resonances ranging from 200 to 800 GeV/c^2 are set (see Figure 7 (right)).

6 Conclusions

The Tevatron experiments studied top quark properties in great details for 15 years. They keep providing precise measurements of the top pair production cross section, challenging the precision of the theoretical calculations. Electroweak single top production has been established and its new cross section measurements have a precision exceeding 20%. The study of the forward–backward asymmetry of top events keeps indicating a discrepancy with current NLO QCD prediction. On the other hand, no indication of new physics in the production process has been found. The two collaborations already produced some top results based on the whole Run II dataset and are working to update all top properties studies. Given the complementarity with the LHC, the top quark sector at the Tevatron can still offer some challenging results.

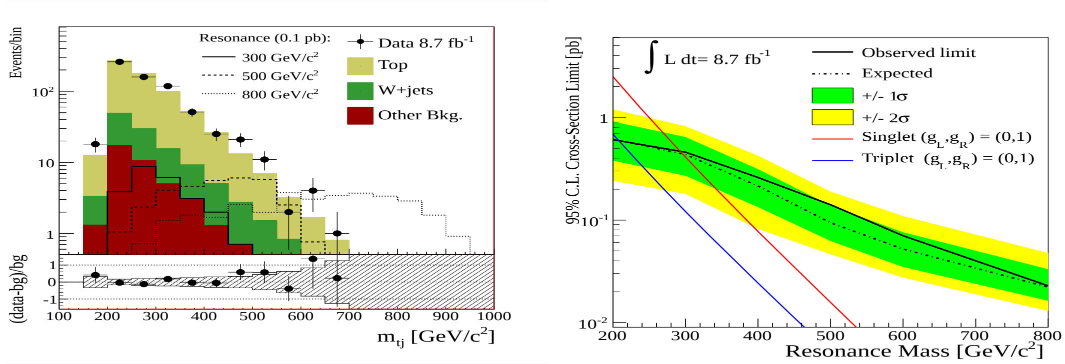

Figure 6: CDF search for a top+jet resonance. Left: $t + jet$ mass. Right: 95% C.L. cross-section upper limits.

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