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Top quark physics at CDF: status and prospects

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In this paper I report a selection of the most recent CDF results on top quark physics, based on Tevatron Run 2 data. The top quark is being studied in great detail by the CDF experiment. The top pair production cross section has been measured with a precision comparable to the theoretical one ($< 7\%$). A precision of 1.2 GeV/c^2 in the measurement of the top quark mass has been achieved. The single top production has been observed and the first direct measurement of the CKM V_{tb} matrix element has been performed. The top quark candidates sample is used for many detailed studies of top properties. The production mechanism, decay vertex and kinematic distributions have been investigated to test many aspects of the Standard Model. Finally, searches for new physics have been performed using the the top quark candidates sample.

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1. Introduction

CDF II is a multipurpose detector taking data at the Tevatron Collider. The Tevatron provides proton–antiproton collisions at a center of mass energy $\sqrt{s}$ = 1.96 TeV. Accelerator performances have been improving since the start of Run 2, in 2001. A peak luminosity of 4×10^{32} cm^{-2}s^{-1} was recently achieved, and almost 10 fb^{-1} of integrated luminosity have been delivered. The detector is taking data with an efficiency commonly $>$ 85%. The analyses described in the following are based on up to 5.7 fb^{-1} of data. A detailed description of the CDF II detector can be found in [1].

2. Top Quark Physics

The top quark was discovered in 1995 at the Tevatron [2]. It is the most massive of the known elementary particles. At the Tevatron center of mass energy top quarks are produced primarily in $t\bar{t}$ pairs via the strong process $p\bar{p} \rightarrow t\bar{t}$ [3]. In the Standard Model (SM) each top quark decays through charged current weak interaction almost exclusively into a real W and a b quark ($t \rightarrow Wb$). Each W subsequently decays into either a charged lepton and a neutrino or two quarks. The $t\bar{t} \rightarrow W^+bW^-\bar{b}$ 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 s–channel or t–channel exchange of a virtual W boson. Single top production was observed at the Tevatron in 2009 [4]. 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.

3. 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. 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, higher precision can be obtained 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%. The result is in excellent agreement with NLO calculations. Figure 1 (left) shows a summary of CDF $t\bar{t}$ cross section measurements in various decay channels and using various techniques.

4. Single Top Observation

The single top production cross section is predicted to be σ_s = 0.88 and σ_t = 1.98 pb in the s and t channels respectively, for M_{top} = 175 GeV/c^2, about half than the pair production cross

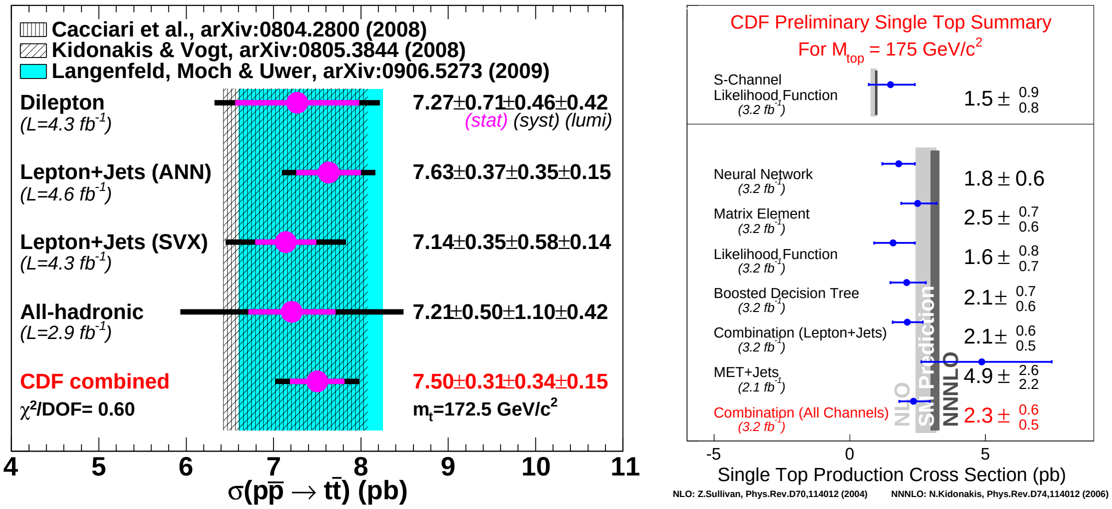

Figure 1: Left: $t\bar{t}$ cross section measurements. Right: single top cross section measurement.

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.

In CDF we select events with a W candidate decaying to either an electron or a muon and at least 2 energetic jets. At least one of the jets has to be identified as containing a B–hadron. CDF performed also an analysis selecting events with missing transverse energy and jets (MJ), while vetoing events selected by the lepton plus jets analysis. Therefore the MJ analysis accepts events in which the W decays into a τ lepton or the electron and muon fails the standard lepton identification criteria. In order to extract the single top signal from the challenging background–dominated dataset, we used several multivariate techniques: lihelihood functions (LF), matrix element (ME), neural network (NN) and boosted decision tree (BDT). Figure 1 (right) shows the CDF single top cross section measurements. The various multivariate methods give consistent results. CDF combines the LF, ME, NN and BDT using a super discriminant (SD) technique. A fit over the two exclusive channels (SD and MJ) is performed and the combined result is: $\sigma_{single} = 2.3\ ^{+0.6}_{-0.5}$ pb.

CDF interpreted the result of the lepton plus jets and missing E_T plus jets analyses in the (σ_s,σ_t) plane. The best fit corresponds to: $\sigma_s = 1.8^{+0.7}_{-0.5}$ pb and $\sigma_t = 0.8 \pm 0.4$ pb.

The CKM matrix element $|V_{tb}|^2$ is proportional to the single top cross section. We do not make assumptions about the unitarity of the 3×3 CKM matrix, and we obtain the $|V_{tb}|^2$ posterior by dividing the measured cross section by the theoretical single top cross section. We find $|V_{tb}| = 0.91 \pm 0.11$ (stat+syst) $\pm\ 0.07$ (theory) and a limit $|V_{tb}| > 0.71$ at 95% C.L., for a top mass of 175 GeV/c^2 [4].

5. Measurement of the Top Quark Mass

The top quark mass M_{top} is a fundamental parameter of the SM. Precise measurements of the top quark and W boson masses constraint the mass of the Higgs boson.

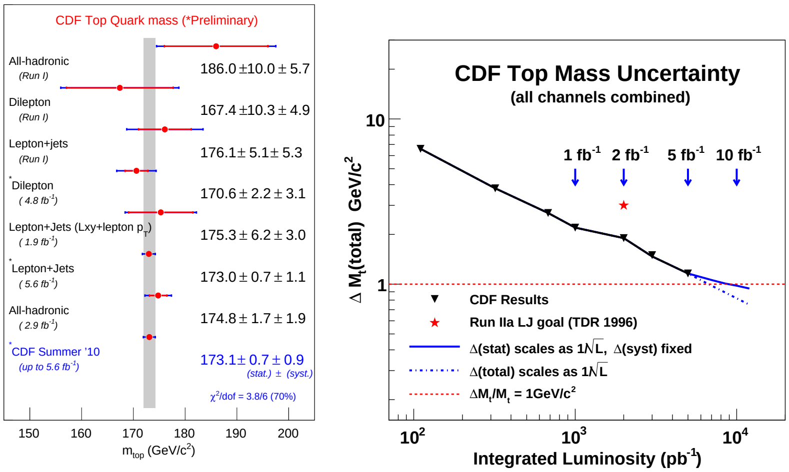

Figure 2: Left: Summary of CDF top mass measurements. Right: extrapolation of the top mass uncertainty from the current dataset result to 10 fb^{-1}.

The reconstruction of the top quark mass presents several experimental challenges. The neutrinos from W decays escape the detector. The quarks hadronize and form jets of particles whose energy must be corrected back to the parton level. The assignment of jets to partons usually has many possible permutation. Finally, there are background processes which mimic $t\overline{t}$ events.

CDF performed many determinations of M_{top} in all the top decay final states and using different techniques. In the single lepton plus jets and all hadronic channels the uncertainty from jet energy scale (JES) can be reduced by using the reconstructed invariant mass of the hadronically decaying W boson in top candidate events as an internal constraint.

At the time of this writing, CDF obtained the most precise determination of the top mass in the single lepton plus jets channel, using a matrix element integration method for the signal and a neural network discriminant to identify background events, and analyzing 5.6 fb^{-1} of data. CDF finds: M_{top} = 173.0 $\pm$ 0.7 (stat) $\pm$ 0.6 (JES) $\pm$ 0.9 (syst) GeV/c^2 = 173.0 $\pm$ 1.2 GeV/c^2. After combining with D0 results, the summer 2010 Tevatron top mass is: M_{top} = 173.1 $\pm$ 1.1(total) GeV/c^2. Figure 2 (left) summarizes the most recent CDF top mass measurements and their combination. The top quark mass is known with a precision that was thought to be unreachable at the Tevatron only a few years ago: $\Delta M_{top}/M_{top} \approx 0.6$ %. Projections indicate that before the end of Run 2 both Tevatron experiments should reach individually a $\pm$ 0.8 – 1 GeV/c^2 precision on the top quark mass. Figure 2 (right) shows the extrapolation of the top quark mass precision for 10 fb^{-1} of analyzed data.

A preliminary determination of the top and anti–top mass difference using 5.7 fb^{-1} of data gives $m_t - m_{\bar{t}} = -3.3 \pm 1.4$(stat.)$\pm$1.0(syst.) GeV/$c^2$.

6. Study of other Top Quark Properties

The experimental study of top quark physics at the Tevatron includes the determination of a variety of top properties. Since top quarks decay before hadronizing, we can directly measure many of their properties. Some of these measurements are still limited by statistics. CDF recently

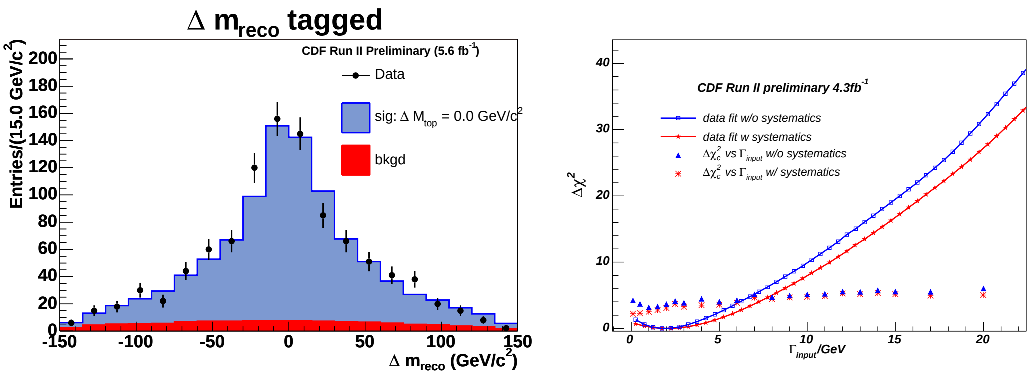

Figure 3: Left: Top–antitop mass difference. Right: top quark width measurement at 95% C.L..

determined the first preliminary direct bound on the top quark width: $\Gamma_{top} < 7.5$ GeV at 95% C. L. which corresponds to a lower limit on the top life time of $\tau_{top} > 8.7 \times 10^{-26}$ s at 95% C. L..

The top–antitop spin correlation is predicted by the SM and could be altered by new physics. CDF measures a preliminary spin correlation parameter $k = 0.48 \pm 0.48$(stat) $\pm$ 0.22(syst) in the helicity basis, in agreement with the SM prediction $k = 0.35$. Figure 4 (left) shows the helicity basis distribution of the $\cos\theta_{lep}\cos\theta_{down}$ variable in data compared to the sum of the background model, the same helicity template, and the opposite helicity template.

NLO QCD predicts a small forward–backward asymmetry in top pair production. New physics could give rise to a larger asymmetry. Studying the rapidity difference of reconstructed top–antitop candidates (see Figure 4 (right)) and after unfolding to parton level, CDF measures in the lab frame a preliminary asymmetry: $A_{fb} = 15.0 \pm 5.0$(stat) $\pm$ 2.4 (syst) %, to be compared to the prediction obtained with the MCFM NLO Monte Carlo: $A_{fb} = 3.8 \pm 0.6$ % [7].

CDF searched for a heavy top quark $t' \rightarrow Wq$ in single lepton plus jets events using 4.6 fb^{-1} of data. We exclude a SM fourth-generation t' quark with mass below 335 GeV/c^2 at 95% C.L. (see Figure 5 (left)).

CDF also searched for pair production of a heavy bottom–like fourth–generation quark b' decaying via $b' \rightarrow Wt \rightarrow WWb$ in the single lepton plus jets channel. We observe events consistent with background expectation and exclude a b' with a mass below 385 GeV/c^2 at 95% C.L. (see Figure 5 (right)).

7. Conclusions

Top quark physics is a crucial part of the Tevatron program. The measurement of the pair production cross section allows the understanding of the sample composition, fundamental to perform all the top properties measurements. It also allows precision tests of QCD. The single top production has been observed. This achievement was one of the milestones for Run 2. Moreover, it represents an important, necessary benchmark in the search for the Higgs boson at the Tevatron. The top quark mass is measured with a precision of 0.61%. So far, the study of top quark production and decay confirms the SM nature of the top quark. CDF expects to analyze $\approx$ 10 fb^{-1} of data by the end of 2011. Run 3 of the Tevatron, if approved, with at least 6 fb^{-1} additional data

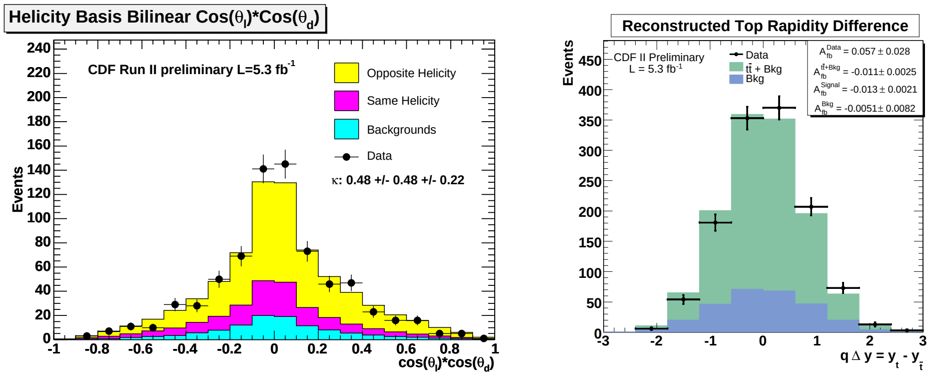

Figure 4: Left: Top–antitop spin correlation: helicity basis distribution of the $\cos\theta_{lep}\cos\theta_{down}$. Right: forward–backward asymmetry: reconstructed top–antitop rapidity difference.

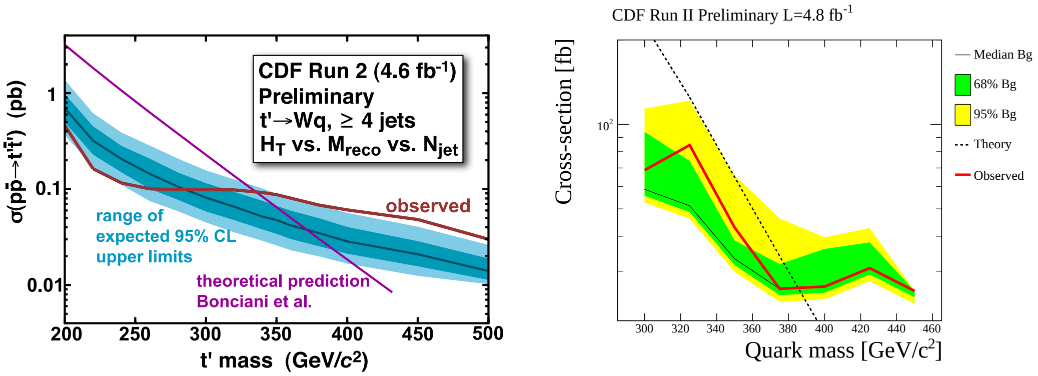

Figure 5: Left: Search for heavy $t^{'}$. Right: Search for $b^{'}$.

for experiment, would provide the opportunity to do precision top physics, being complementary to the LHC. Tevatron's top physics program and understanding of systematic effects will continue to play a significant role for years to come.

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