TOP AND b PHYSICS AT THE TEVATRON*

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A review of recent top and b physics results from the CDF and DØ Collaborations is presented.

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1. Introduction

After undergoing considerable upgrades, the Tevatron $p\bar{p}$ collider at Fermilab has been running at $\sqrt{s} = 1.96$ TeV since 2001 and has now produced approximately 500 pb^{-1} of integrated luminosity. Located at the Tevatron storage ring are two multi-purpose detectors, CDF and DØ, which have been upgraded [1–3] in parallel with the accelerator.

Both collaborations pursue a large and varied top and b physics program and only a selection of the recent results can be presented here. For a full overview of the respective physics programs, please refer to the web pages of the experiments [4, 5]. All results quoted in this article are preliminary, unless a journal reference is given.

2. Top results

Discovered in 1995 at the Tevatron, then running at $\sqrt{s} = 1.8$ TeV, studying the top quark is one of the main goals of the current Tevatron physics program. Under investigation are the top production cross-section, mass, W-helicity, spin correlations, branching ratios, anomalous kinematics, resonance production and anomalous couplings.

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2.1. Top cross-section measurements

The dominant production mechanism of top quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$ is strong $t\bar{t}$ pair production via $q\bar{q}$ annihilation (85%) and gluon fusion (15%). Single top production via electroweak interactions is also possible, but has not yet been observed. Current upper limits for single top production cross-section at 95% confidence level for the s and t channels combined are 17.8 pb (CDF) and 23 pb (DØ).

In the Standard Model the top quark decays almost 100% of the time to a W boson and a b quark. Top quark analyses are grouped in channels determined by the W decay. The dilepton channels, where both W's decay into a lepton and a neutrino, provide a clean signal, but have a low branching ratio ($\approx$ 11%). More common ($\approx$ 44%) are decays to the lepton plus jets channel where one of the W's decays hadronically. Due to the difficulty of identifying taus, most analyses in this channel are restricted to the use of muons and electrons. Neutrinos are identified by a large missing transverse energy in the event. In about 44% of the decays, both W's decay hadronically. These decays are generally difficult to reconstruct, with analyses typically requiring the reconstruction of six or more jets in the event.

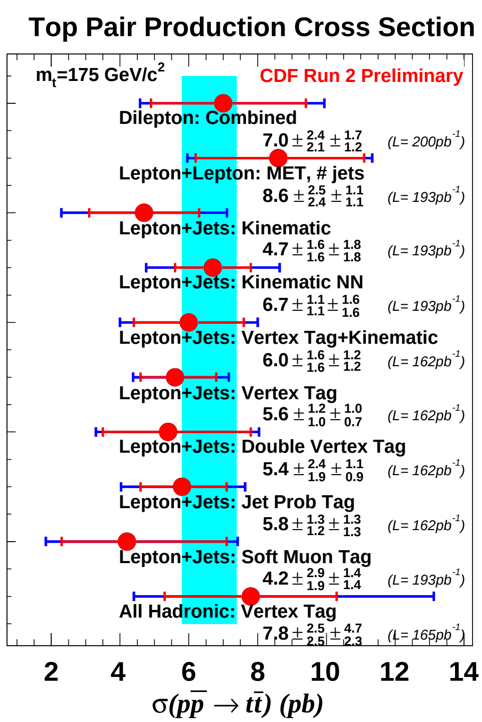

Fig. 1. Overview of recent CDF top cross-section measurements at $\sqrt{s} = 1.96\,\mathrm{TeV}$. Further details for some of the analyses can be found in [6, 7].

The background in analyses using jets can be reduced by requiring one or more jets to contain a b quark. To tag these jets, either displaced vertices or soft lepton tags from semileptonic b decays are used.

An overview of cross-section measurements at $\sqrt{s} = 1.96\,\mathrm{TeV}$ for CDF and DØ is shown in Figs. 1 and 2.

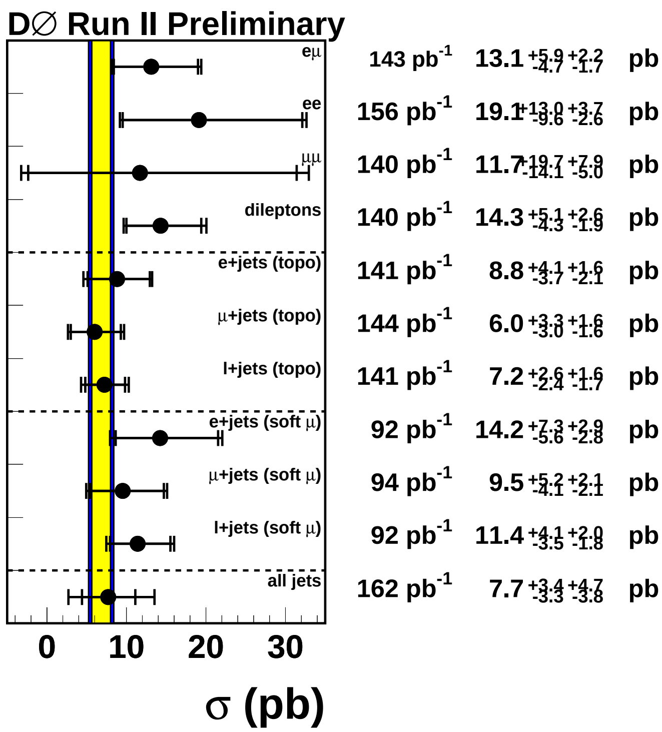

Fig. 2. Overview of recent DØ top cross-section measurements at $\sqrt{s} = 1.96\,\mathrm{TeV}$.

2.2. Top mass measurements

The mass of the top quark had been measured after its discovery to be $(174 \pm 5.1)\,\mathrm{GeV}/c^2$. DØ recently re-evaluated the original data set taken at $\sqrt{s} = 1.8\,\mathrm{TeV}$ using an improved analysis technique [8] and measured the top mass to be $(180 \pm 3.6\,(\mathrm{stat})\, \pm 3.9\,(\mathrm{syst}))\,\mathrm{GeV}/c^2$. Including this measurement in the world average top mass increases it to $(178 \pm 4.3)\,\mathrm{GeV}/c^2$.

CDF has measured the top quark mass on data taken at $\sqrt{s} = 1.96\,\mathrm{TeV}$. An overview of these results is shown in Fig. 3.

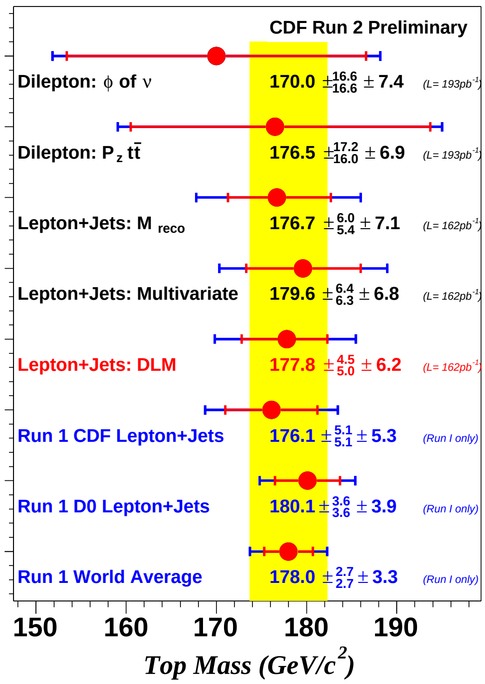

Fig. 3. Overview of recent CDF top mass measurements at $\sqrt{s} = 1.96$ TeV.

3. *b* physics results

The Tevatron collider with its large b quark production cross-section, $\sigma(p\bar{p} \to b\bar{b}) \approx 150\ \mu b$ at $\sqrt{s} = 1.96$ TeV, provides an excellent environment for studying b quarks. Unlike the e^+e^- factories that operate at the $\Upsilon(4S)$ resonance, all the possible b hadrons ($B^0_d, B^0_s, B_c, B^\pm, \Lambda_b$) are produced, albeit with a much larger background compared to the relatively clean environment of the e^+e^- colliders.

3.1. *Mixing*

One of the main goals of the b-physics program at the Tevatron is to measure B^0_s mixing. As a first step, both experiments have measured Δm_d. Given a current world average of Δm_d of (0.502 ± 0.007) ps^{-1}, CDF has measured $\Delta m_d = (0.55 \pm 0.10 \pm 0.01)$ ps^{-1} in the exclusive decay channels $B^0 \to J/\psi K^{*0}$ and $B^0 \to D^-\pi^+$. For semileptonic decays using same side tagging, CDF finds $\Delta m_d = (0.443 \pm 0.052\ \text{(stat)} \pm 0.030\ \text{(sample composition)} \pm 0.012\ \text{(syst)})$ ps^{-1}.

DØ uses semileptonic decays with opposite side muon tagging and finds $\Delta m_d = (0.506 \pm 0.055\ \text{(stat)} \pm 0.049\ \text{(syst)})$ ps^{-1}.

3.2. Lifetime measurements

The measurement of the lifetime ratios between different b hadrons can be used to evaluate deviations from the naive spectator quark model. HQET/OPE [9] predicts $\tau(B^+)/\tau(B^0) = (1.053 \pm 0.016 \pm 0.017)$ ps.

CDF has measured $\tau(B^+)/\tau(B^0) = (1.080 \pm 0.042)$ ps and $\tau(B_s^0)/\tau(B^0) = (0.890 \pm 0.072)$ ps using exclusive decay modes.

DØ finds $\tau(B^+)/\tau(B^0) = (1.093 \pm 0.021\,(\text{stat}) \pm 0.022\,(\text{syst}))$ ps using inclusive semileptonic decays modes in an innovative analysis technique comparing the relative B^+ and B^0 rate as a function of visible proper decay length. All measurements agree within errors with the theoretical predictions.

Mixing in the B_s^0 system results in two distinct mass eigenstates with two different lifetimes. Unlike the B_d^0 system, CP violation in the decay $B_s^0 \to J/\psi\phi$ is negligible in the Standard Model and the mass and CP eigenstates are (almost) identical. Theory [10] predicts that an angular analysis of the decay products can be used to separate the even and odd CP eigenstates to allow the separate lifetime measurement of each state. Using the definitions

$$\Gamma = \tfrac{1}{2}\left(\Gamma_{\mathrm{L}} + \Gamma_{\mathrm{H}}\right) \equiv \frac{1}{\tau}\,, \qquad \Delta\Gamma = \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}}\,,$$

and the constraint $\Gamma_s = \Gamma_d$, CDF finds $\tau_{\mathrm{L}} = (1.13^{+0.13}_{-0.09} \pm 0.02)$ ps and $\tau_{\mathrm{H}} = (2.38^{+0.56}_{-0.43} \pm 0.03)$ ps. The width difference is measured to be $\Delta\Gamma/\Gamma_s = 0.71^{+0.24}_{-0.28} \pm 0.01$ for the constrained fit and $\Delta\Gamma/\Gamma_s = 0.65^{+0.25}_{-0.33} \pm 0.01$ for the unconstrained fit. Theoretical predictions [11] indicate a lower width difference of $\Delta\Gamma/\Gamma_s = 0.12 \pm 0.06$.

3.3. The $X(3872)$ particle

The $X(3872)$ particle was discovered by Belle [12] in 2003 in the channel $X(3872) \to J/\psi\pi^+\pi^-$. Both CDF and DØ confirm this discovery. The results of these measurements are listed in Table I. At the present time

TABLE I

Mass and significance for the $X(3872)$ particle.

Experiment	Mass	Significance
Belle	3872.0 ± 0.6 (stat) ± 0.5 (syst) MeV/c^2	$> 10\sigma$
CDF	3871.3 ± 0.7 (stat) ± 0.3 (syst) MeV/c^2	$\approx 12\sigma$
DØ	3871.8 ± 3.1 (stat) ± 3.0 (syst) MeV/c^2	$\approx 5\sigma$

it is unclear whether the $X(3872)$ is a $c\bar{c}$ state or a more complex object such as a meson molecule. DØ has investigated the production and decay characteristics [13] of the $X(3872)$ and found them to be similar to those of the $\psi(2S)$ state (see Fig. 4).

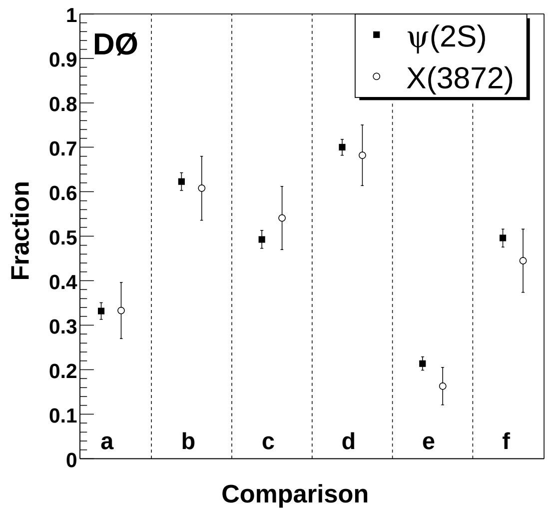

Fig. 4. Comparison of event-yield fractions for $X(3872)$ and $\psi(2S)$. Plotted are the fractions of $X(3872)$ or $\psi(2S)$ with (a) $p_{\mathrm{T}}(J/\psi\pi^+\pi^-) > 15\,\mathrm{GeV}$; (b) $|y(J/\psi\pi^+\pi^-)| < 1$; (c) $\cos(\theta_\pi) < 0.4$, where $\cos(\theta_\pi)$ is the angle between the $X(3872)/\psi(2S)$ and one of the pions in the dipion restframe; (d) effective proper decay length $< 0.01\,\mathrm{cm}$, (e) $X(3872)$ or $\psi(2S)$ is isolated; (f) $\cos(\theta_\mu) < 0.4, \cos(\theta_\mu)$ is defined analogous to $\cos(\theta_\pi)$.

3.4. Charmless B decays

CDF sees 12 events over an expected background of 1.95 events for the decay $B_s^0 \to \phi\phi$, corresponding to 4.7σ. Derived from this measurement the branching ratio is

$$\mathrm{BR}(B_s^0 \to \phi\phi) = (1.4 \pm 0.6\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst}) \pm 0.5\,(\mathrm{BRs})) \times 10^{-5}\,.$$

3.5. Rare decays

The Standard Model predicts [14] the branching ratio for $B_s^0 \to \mu^+\mu^-$ to be $(3.4 \pm 0.5) \times 10^{-9}$. The decay $B_d^0 \to \mu^+\mu^-$ is further suppressed by $|V_{td}/V_{ts}|$ and its branching ratio calculated to be $(1.00 \pm 0.14) \times 10^{-10}$.

Table II lists the measured limits for both decays.

TABLE II

Measured limits for rare decays.

BR($B_s^0 \to \mu^+\mu^-$)	CDF	$< 5.8 \times 10^{-7}$ at 90% CL
	DØ	$< 3.8 \times 10^{-7}$ at 90% CL
	DØ	$< 4.7 \times 10^{-7}$ at 95% CL
BR($B_d^0 \to \mu^+\mu^-$)	CDF	$< 1.5 \times 10^{-7}$ at 90% CL

3.6. Pentaquark searches

CDF has performed a search in the following channels:

$$\begin{aligned} \theta^+(uudd\bar{s}) &\to p\ K_s^0 \ \to p\pi^+\pi^- \,, \\ \theta_c(uudd\bar{c}) &\to p\ D^{*-} \to D^0 p\pi^- \,, \\ \Xi^0_{3/2}(ssdu\bar{d}) &\to \Xi^-\pi^+ \to \Lambda\pi^+\pi^- \,, \\ \Xi^{--}_{3/2}(ssdd\bar{u}) &\to \Xi^-\pi^- \to \Lambda\pi^-\pi^- \,. \end{aligned}$$

So far no signal has been observed.

4. Conclusions

Both the DØ and CDF experiments have re-established, and in many cases improved, the b and top signals seen in the current run period at $\sqrt{s} = 1.96$ TeV using their upgraded detectors.

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