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Summary of the Session on the Top Quark

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The CDF and DØ experiments at the Fermilab Tevatron showed recent results on the production and properties of the top quark. The CMS and ATLAS experiments presented first observations of top events at the LHC. Prospects for the top physics at the LHC over the next few years were discussed.

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1. Introduction

The top quark was discovered more than 15 years ago by the CDF [1] and DØ [2] collaborations in proton-antiproton collisions at the Fermilab Tevatron. Until recently, only the Tevatron had enough energy to produce top, whose mass is ∼170 GeV/c^2. In the ensuing years, CDF and DØ have established the main properties of top and have shown that they are in good agreement with the expectations of the Standard Model (SM) for a third generation charge 2/3 quark. In particular, all investigations of top quarks rely on the decay modes predicted by the SM, namely that top decays nearly 100% of the time into a W boson and a b-jet. The W may decay leptonically, with corresponding Missing Transverse Energy (MET) due to the escaping neutrino, or hadronically, so the topologies (with their relative frequencies) that appear in $t-\bar{t}$ production are: 2 leptons plus 2 b-jets and large MET- 5%; 1 lepton plus 4 jets (of which at least two are b-jets) + MET - 30%; and 6 jets (of which at least two are b-jets) and no MET - 44%, with the remaining 21% having at least one W decaying to a τ that decays hadronically.

In the top quark session of HQL 2010, CDF and DØ presented their latest results based on several fb^{-1} of proton-antiproton data at 1.96 TeV. ATLAS and CMS presented first evidence for the top quark production at the LHC based on data sets of only a few hundred nb^{-1}. An integrated luminosity of ∼40 pb^{-1} is expected by the end of the commissioning run of the LHC.

Now that the LHC has begun operation with proton-proton collisions with 7 TeV in the center of mass, a new era of precision top measurements will begin. The cross section for the production of $t-\bar{t}$ pairs at 7 TeV (14 TeV) is expected to be 20 (120) times larger than at the Tevatron. Ultimately, 10^7 top quark pairs will be produced per year.

2. Recent Results fron CDF and DØ

CDF and DØ have investigated three aspects of top physics: top as an elementary particle of the SM, including production properties, quantum numbers, and decay properties; top properties, including rare decays, that differ from the expectations of the SM and could be indicative of new physics beyond the SM; and top as a final state particle in the decays of heavier objects that would be new physics. Each experiment has recorded an integrated luminonsity of ∼8 fb^{-1}. The results presented here are typically based on 4-6 fb^{-1}.

2.1 $t-\bar{t}$ pair production via the strong interaction

CDF and DØ presented new measurements of the top pair production cross sections. CDF used three signatures: leptons+jets, dileptons, and MET + b-jets. DØ used a topological identification of jets, dilepton signatures, and b-tags. DØ also gave a measurement of $\frac{d\sigma}{dP_T}$. In general, the results cluster around 7.0-8.5 pb with uncertainties of around 6%.

2.2 Single top production by the electroweak interaction

Single top production via the electroweak interaction can occur via *s*-channel or *t*-channel processes shown in Fig. 1. The cross section for the *t*-channel process is expected to be about twice as large as the *s*-channel process at the Tevatron. The expected cross section at the Tevatron is a few picobarns, which is smaller than top pair production but not that much smaller. However,

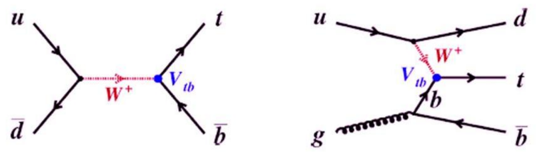

Figure 1: *s*-channel and *t*-channel diagrams for single top quark production

the event topology is W ($\rightarrow lepton$) plus one or two b-jets. The background to the "lepton plus small number of jets" from W+jets is quite large, making single top much harder to observe than pair production, which has a larger number of jets. The single top analysis is therefore based on multivariate techniques that take advantage of many variables, each of which by itself has only a small discrimination between signal and background.

The single top cross section has been measured by CDF and DØ . The combined result is $2.76^{+0.58}_{-0.47}\ pb$ [3].

DØ has separated the *t*-channel and *s*-channel processes based on the number and type of jets and their kinematics.

Once single top is observed, the cross section can be compared with theoretical expectations, which have small uncertainties. This permits the extraction of the CKM matrix element $|V_{tb}|$, a fundamental parameter of the Standard Model. It is expected to be almost exactly 1. The combined value measured at the Tevatron, which is consistent with the SM, is

$$|V_{tb}| \ = \ 0.91 \pm 0.08 \tag{2.1}$$

2.3 Top quark mass and width

The top quark mass is obtained from either the leptons+jets or dilepton samples using a variety of techniques to constrain the kinematics to make up for the missing information due to the escape of the neutrino from the W decay. The combined result across all channels and all methods from CDF and DØ from July of 2010 [4] is:

$$\begin{aligned} M_{top} \ &= \ 173.3 \pm 1.1(\text{total})\, GeV/c^2 \qquad (2.2)\\ \sigma(M_{top})/M_{top} \ &\sim \ 0.61\% \end{aligned}$$

The measurement of the top mass to well under a percent is a triumph of the Tevatron program. The Standard Model prediction for the width of the top quark, based on its decay to W+ b-jet and $|V_{tb}| = 1$ is around 1.3 GeV/c^2. This means that the top decays before it hadronizes and thus one is measuring unambiguously the mass of a quark. The top quark's mass, which appears in many calculations involving loops or box diagrams, is now by far the best known of all the quark masses. This is very important for example in providing, together with precision measurement of the W boson mass, a constraint on the SM Higgs mass since the top quark appears as a radiative (loop) correction to both the W and the Higgs.

CDF attempts to measure the width by direct reconstruction of the top mass event-by-event from the lepton plus jets sample. The width is extracted by fitting the data to templates that contain a finite width. Their result, based on 4.3 fb^{-1} is a limit:

$$\begin{aligned} \Gamma_{top} &< \;\; 7.5\, GeV \;\; 95\% \text{C.L.} \qquad (2.3)\\ 0.3 < \Gamma_{top} &< 4.4\, GeV \;\; 68\% \text{C.L.} \end{aligned}$$

DØ uses their measurement of the single top cross section $\sigma(t-channel)Br(t \rightarrow Wb) = 3.14^{+0.94}_{-0.80}$ to determine the total width of the top via

$$\Gamma_t = \frac{\sigma(t-channel)\Gamma(t \rightarrow Wb)_{SM}}{Br(t \rightarrow Wb)\sigma(t-channel)_{SM}} \qquad (2.4)$$

The branching fraction is determined from previous DØ studies of $t-\bar{t}$ events with different b multiplicities: $Br(t \rightarrow Wb) = 0.962^{+0.068}_{-0.066}(\text{stat})^{+0.064}_{-0.052}(\text{sys})$. The resulting width is

$$\Gamma_t = 1.99^{+0.69}_{-0.55}\; GeV \qquad (2.5)$$

The mass of the top quark and anti-quark are required by the CPT theorem to be equal. CDF and DØ have tested this by analyzing the lepton plus jets channel. The sign of the lepton from the W decay determines whether the parent was a top or an anti-top. The results are:

$$\Delta M_{t-\bar{t}} = 3.3 \pm 1.4\,(\text{stat}) \pm 1.0\,(\text{sys})\ \text{GeV/c}^2 \ \ \text{CDF} \qquad (2.6)$$

$$\Delta M_{t-\bar{t}} = 3.8 \pm 3.7\ \text{GeV/c}^2 \ \ \text{DØ} \qquad (2.7)$$

2.4 Correlations and asymmetries

2.4.1 Top anti-top forward-backward production asymmetry

At leading order, top production is symmetric in proton-antiproton collisions. At the next-to-leading order, QCD predicts a small (few percent) asymmetry, A_{fb}. The results are

$$A_{fb}\ (\text{CDF}) = 15 \pm 5\ (\text{stat})\ \pm 2.4(\text{sys})\ \% \qquad (2.8)$$

$$A_{fb}\ (\text{DØ}) = 8 \pm 4\ (\text{stat})\ \pm 1(\text{sys})\ \% \qquad (2.9)$$

There are indications that this might be larger than expected.

2.4.2 Top anti-Top spin correlations

When a $q-\bar{q}$ pair is produced, correlations exist between the spins of the quarks. For light quarks, these are scrambled by the hadronization process. For the top quark, the decay occurs before there is time to hadronize so the spin correlation at production is preserved and can be observed as an angular correlation between the decay products of the top and anti-top. These correlations reflect both the spin-1/2 property of the top quark and the production mechanism. At the Tevatron, the dominant production mechanism is quark-antiquark annihilation through a single gluon. This favors opposite helicity for the top and anti-top. The correlation is expected to be different at the LHC, where gluon-gluon fusion is the dominant production mechanism. It is also possible for new physics to change the spin correlations. The quantity that is measured is

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta^+ d\cos\theta^-} = \frac{1\ +\ \kappa\cos\theta^+\cos\theta^-}{4} \qquad (2.10)$$

where the angle θ is the angle of the lepton or the spectator b-jet in the top(+) or anti-top(-) rest frame relative to the beam axis or the helicity axis. The quantity κ is

$$\kappa = \frac{N_{opp\ helicty} - N_{same\ helicity}}{N_{opp\ helicity} + N_{same\ helicity}} \tag{2.11}$$

The results, using the beam basis are

$$CDF\ (5.3 fb^{-1})\ \kappa = 0.72 \pm 0.64\ (\text{stat})\ \pm 0.26\ (\text{sys}) \tag{2.12}$$

$$D\O\ (4 fb^{-1})\ \kappa = -0.2^{+0.6}_{-0.5} \tag{2.13}$$

Theory predicts $\kappa = 0.77$.

2.5 Search for new particles: heavy top, t' and heavy botton, b'

Both CDF and DØ have looked for a heavier version of the top quark decaying into a W boson and a light down-type quark using the reconstructed mass in lepton + jet events. CDF excludes this kind of t' below 335 GeV/c^2 at 95% C.L; DØ rules out a t' below 296 GeV/c^2 at 95% C.L. CDF looks for a very heavy b' decaying into a top quark and a W boson, leading to a WWb final states. These would be very energetic events, with many jets. The main background is $t - \bar{t}$ + jets. In 4.8 fb^{-1}, CDF excludes a b' for masses less than 385 GeV/c^2 at 95% C.L.

3. First observation of top events at the LHC

At the time of this conference, the LHC had delivered only a few inverse picobarns to CMS and ATLAS. CMS has analyzed at this point 0.84 pb^{-1} of data and ATLAS 0.295 pb^{-1}. Because the $t - \bar{t}$ cross section at the LHC is expected to be about a factor of 20 higher than at the Tevatron, both experiments are able to present solid evidence that they are observing top quark production. Since CMS and ATLAS are new experiments in their first substantial data run, they both emphasize that top studies exercise key elements of their analysis toolkits, including lepton reconstruction and isolation, jet reconstuction and jet energy scale, b-jet tagging, MET, and transverse mass reconstruction.

3.1 CMS results

CMS relies on single lepton triggers to select top events. Analysis is carried out for both the single lepton plus jets channel and the dilepton plus jets channel. For muons, P_T must be greater than 20 GeV/c and $|\eta| < 2.1$. For electrons, P_T must be greater than 30 GeV/c and $|\eta| < 2.4$. Isolation requirements are imposed based on information from the calorimeters and tracking detectors. Jets are reconstructed using using the anti-Kt algorithm (R=0.5). For jets, P_T must be greater than 30 GeV/c and $|\eta| < 2.4$

MET and b-tagging are not used in the initial selection but are used in the study of the surviving event samples. In particular, QCD backgrounds can be estimated from the data by studying MET and isolation distributions.When b-tagging is imposed on the lepton plus jets sample, a clear excess is seen for N(jets) ≥ 3 as expected for $t - \bar{t}$ production. This is shown in Fig. 2.

The dilepton analysis requires two oppositely charged isolated leptons (ee,$\mu\mu$, eμ) with $P_T >$ 20 GeV/c. A Z-boson veto is applied in the case of ee and $\mu\mu$. MET is required to be >30 GeV

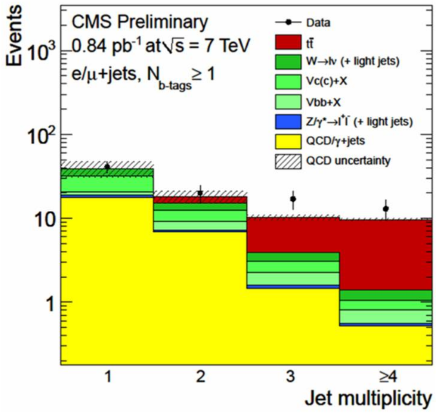

Figure 2: B-tagged lepton plus jets distribution from CMS

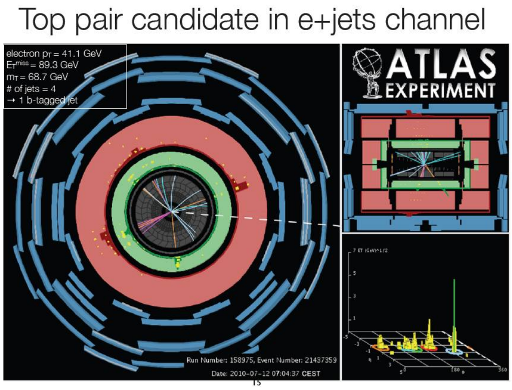

Figure 3: A candidate for top event with a lepton plus 4 jets in ATLAS

for ee and $\mu\mu$ and is lowered to 20 GeV/c in the case of eμ. The jet definition is the same as for the single lepton plus jets case. Backgrounds from QCD and Drell-Yan lepton pair production are estimated from the data. A few event excess is observed as expected.

3.2 ATLAS results

ATLAS' analysis is very similar to CMS'. In addition to the basic isolated electron identification, they also define a tighter identification using "high-threshold" hits in their Transition Radiation Tracker (TRT). Electron conversions in the material of the detector are suppressed by requiring a hit in the first layer (B-layer) of the pixel detector. Muon identification employs information from both the muon spectrometer and the inner detector. Jet reconstruction is based on the Anti-Kt algorithm with R=0.4-0.6. Much attention is given to establishing the jet energy resolution and jet energy scale so that MET can be used reliably in the event selection. b-jet tagging is based on the signed decay length significance, $\frac{L}{\sigma_L}$ of a reconstructed secondary vertex. With this analysis, a small excess in leptons plus jets is observed. A typical example of an event with a lepton and 4 jets is shown in Fig. 3.

3.3 Prospects for top Physics at the LHC in the near, meduium, and long term

It is expected that the LHC will deliver a few fb^{-1} in the next year or two. Due to the large cross section for $t-\bar{t}$ production, CMS and ATLAS may be expected to carry out a program of top studies that is competitive with the Tevatron.

Single top will be an important early goal for the LHC. The production mecahnisms tends to favor At the LHC, *t*-channel production will be even more favored relative to *s*-channel production than at the Tevatron. At 7 TeV center of mass energy, the *t*-channel cross section is calculated to be 65 pb and 4 pb for *s*-channel. In addition, the process $g + b-$quark $\rightarrow t + W$, which proceeds via an exchange of top in the *t*-channel and results in 2 W bosons and a top, will have an expected cross section of 11 pb and should be observable. The single top signal is measured by studying the angle, $\cos\theta_{lj}$ between the lepton from the W decay and the b-jet from the top decay. A 5σ signal for single top should take a luminosity of about 1-2 fb^{-1}. $|V_{tb}|$ can be determined with an uncertainty of 10%.

Because of the high energy of the LHC , the production of high mass states is favored relative to the Tevatron. There is great hope that new massive particles, expected in models of physics beyond the SM, decaying into top quarks will be observed. One novel aspect of the search for particles with masses of a few TeV/c^2 is that they can produce top quarks that are boosted so that their decay products can overlap resulting in merged or "fat jets"'. These "boosted tops" require special techniques that identify them via their substrucutre and give rise to a new set of analysis tools for "tagging" boosted tops.

4. Conclusion

CDF and DØ have made remarkable progress in detemerining the properties of the top quark, which so far, conforms to the expectations of the SM. The sophisticated methods they have developed form the basis of the exploration that is now starting at the LHC. New methods, such as the use of boosted top quark signatures, will be necessary to realize fully the potential of the LHC for finding new high mass particles decaying to top and for searching for deviations from the SM. Prospects for the future of top quark physics are very bright!

References

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PoS(HQL 2010)089