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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 and the ATLAS and CMS experiments at the Large Hadron Collider (LHC) showed recent results on the production and properties of the top quark. CP violation in top decays was discussed as an example of the kind of new studies that will become possible with the very large samples of top decays that will be produced at the LHC.

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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. Top was added as a topic to the 2008 edition of Heavy Quarks and Leptons after the Tevatron had recorded a few fb^{-1} of integrated luminosity and was producing relatively precise results on fundamental top quark properties such as the production cross section and mass. In 2010, the Large Hadron Collider (LHC) at CERN began producing proton-proton collisions at 7 TeV center of mass energy. At HQL2010, in addition to impressive new results from the Tevatron, the CMS and ATLAS experiments presented the first evidence for top production at the LHC, obtained with less than $1\mathrm{pb}^{-1}$ of integrated luminosity.

At HQL2012, there were presentations of recent results on top quark production and top quark properties at the Tevatron [3], [4] and at the LHC [5], [6]. The Tevatron results are based on datasets taken at 1.96 TeV center of mass energy corresponding to integrated luminosities varying from 1 to 8 fb^{-1} depending on the analysis. The LHC results use ∼1-5 fb^{-1} of integrated luminosity taken at 7 TeV center of mass energy in 2011. Since the Tevatron concluded its long run in the fall of 2011, the future of top physics now rests with the LHC experiments, which have already recorded an additional 5 fb^{-1} of data at 8 TeV center of mass energy in 2012.

There are three aspects of studies involving the top quark: top as an elementary particle of the standard model(SM), including production properties, quantum numbers, and decay properties; top properties, including rare decays, that might 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. This session focused on the first two of these aspects.

Because they are so heavy, top quarks have very short lifetimes and must be detected via their decays. According to the standard model, and confirmed by experiment, top quarks decay almost 100% of the time into a W and b-jet. The W may decay leptonically into e, μ, or τ and the corresponding anti-neutrino; or hadronically into two jets. This gives rise to the pattern of decay modes and branching fractions for the $t-\bar{t}$ pairs shown in Fig 1. The various final states present different experimental challenges and are accompanied by different backgrounds. Measurements are made in several of these final states to cross check the results.

2. Recent Results on Top Quark Production at the Tevatron and the LHC

Production of $t\bar{t}$ pairs is the largest source of top quarks at both the Tevatron and the LHC. It proceeds via the strong interaction. Production of single top quarks via the electroweak interaction is also significant.

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

The diagrams for $t-\bar{t}$ production are shown in Fig. 2. The $q-\bar{q}$ annihilation diagram (upper left hand side) is dominant at the Tevatron, accounting for ∼90% of the total production. The other three diagrams are gluon fusion diagrams and account for 85% of the $t-\bar{t}$ production at the LHC.

Top quark pair production is studied using all three classes of $t-\bar{t}$ final states: the all-hadronic or six jet channel, $t-\bar{t} \rightarrow q_1\bar{q}_2b, q_3\bar{q}_4\bar{b}$; the dilepton final state, $t-\bar{t} \rightarrow l^+\nu b, l^-\bar{\nu}\bar{b}$; and the leptons+jets final state $t-\bar{t} \rightarrow q_1\bar{q}_2b, l\bar{\nu}\bar{b}$ (and charge conjugate) where q may be (u,d,s,c,b).

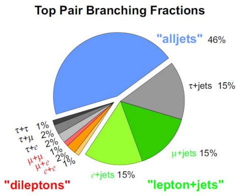

Figure 1: Classes of $t-\bar{t}$ final states

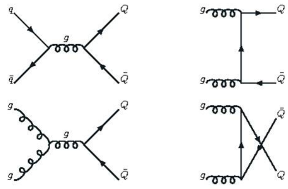

Figure 2: Mechanisms for top pair production

2.1.1 $t-\bar{t}$ production at the Tevatron

CDF and DØ have measured top pair production in many channels over the last few years. The most recent result from CDF uses the dilepton channel with 5.1 fb^{-1}. The cross section is

$$\sigma_{t-\bar{t}} = 7.40 \pm 0.58\,(\text{stat}) \pm 0.63\,(\text{syst}) \pm 0.45\,(\text{lumi})\ \text{pb [7]}$$

The events typically have two jets along with the two leptons. If at least one b-jet is required along with the dilepton, the background is greatly reduced but 40% of the signal is lost. With the b-tag requirement, the cross section is

$$\sigma_{t-\bar{t}} = 7.25 \pm 0.66\,(\text{stat}) \pm 0.47\,(\text{syst}) \pm 0.44\,(\text{lumi})\ \text{pb [7]}$$

The two results are consistent. They are also consistent with theory calculated at the Next-to-Next Leading Logarithm (NNLL) approximation, which gives at 1.96 TeV

$$\sigma_{t-\bar{t}} = 7.22^{+0.31}_{-0.34}\,(\text{total theory})^{+0.71}_{-0.55}\,(\text{PDF} + \alpha_s)\ \text{pb [8]}$$

DØ also measures the cross section in dileptons and leptons+jets. In the dilepton analysis, DØ requires at least one b-tagged jet. The combined DØ result is

$$\sigma_{t-\bar{t}} = 7.56^{+0.63}_{-0.56}\ \text{pb [9]}$$

Many additional results from CDF and DØ are given in reference [3].

2.1.2 $t-\bar{t}$ production at the LHC

CMS and ATLAS measure top pair production in all the final states noted above. The analyses and their differences are described in [5]. The combined results for each experiment [10][11] are given in Table 1, along with the result of a theoretical calculation [12]. The accuracy is dominated by systematic errors. Within the uncertainties, CMS and ATLAS agree on the cross sections and they are consistent with theory calculations.

Source	Luminosity [fb^{-1}]	Result [pb]
CMS	0.8-1.1	165.8 ± 2.2 (stat) ± 10.6 (syst) ± 7.8 (lumi)
ATLAS	0.7-1.02	177 ± 3 (stat) $^{+8}_{-7}$ (syst) ± 7 (lumi)
Theory		163 $^{+11}_{-10}$

Table 1: Results on $t-\bar{t}$ production from CMS and ATLAS at a center of mass energy of 7 TeV

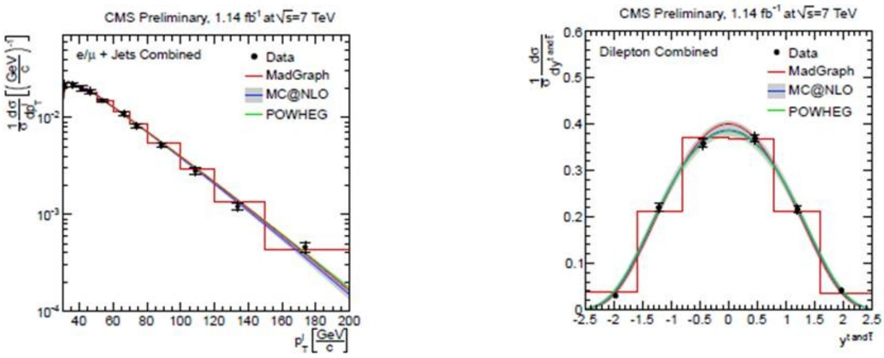

Figure 3: Inclusive top production as a function of P_T and y

The $t-\bar{t}$ production cross section is about $170pb$, more than 20 times higher at the LHC at 7 TeV than at the Tevatron at 1.96 TeV. The luminosity is also a factor of 20 higher at the LHC. The LHC is expected to eventually achieve an energy of close to 14 TeV where the cross section is calculated to be 5 times higher than at 7 TeV.

CMS has also published differential cross sections for pair-produced top quarks. Figure 3 shows the differential distributions in top transverse momentum P_T and rapidity, y, based on 1.14 fb^{-1} using dilepton and lepton+jets signatures for top pair production.

2.2 Top-antitop asymmetries

At leading order, top production is symmetric in $p-\bar{p}$ collisions. At the next-to-leading order, QCD predicts a small (few percent) asymmetry, A_{fb}, relative to the beams.

2.2.1 Top anti-top forward-backward production asymmetry at the Tevatron

CDF studied the forward-backward asymmetry in the $t-\bar{t}$ production and found that it was considerably larger than predicted. The asymmetry is a preference for the top quark to follow the direction of the incoming proton and for the antitop to follow the direction of the incoming antiproton. This may be studied by measuring the quantity

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}; \quad \text{where } \Delta y = y_t - y_{\bar{t}} \tag{2.1}$$

CDF performed the study in the lepton+jets final state with one of the members of the $t-\bar{t}$ pair decaying leptonically, which determines which is the top and which is the antitop, and the other decaying hadronically, which provides the measurement of the rapidity. DØ subsequently confirmed the CDF result. The results [13] [14] are

$$A_{fb}\,(\text{CDF}) = 0.162 \pm 0.047 \text{ with } 8.7\,\text{fb}^{-1}; \text{ and } A_{fb}\,(\text{DØ}) = 0.196 \pm 0.065 \text{ with } 5.4\,\text{fb}^{-1}.$$

These are much larger than expected and could be indicators of new physics. Several theoretical proposals have been made to explain this surprising result. This study is unique to the Tevatron.

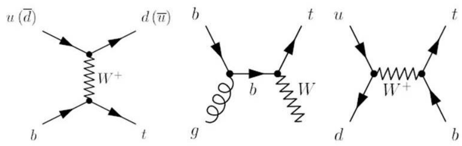

Figure 4: *t*-channel, associated production (W-t) and *s*-channel diagrams for single top quark production

2.2.2 Top anti-top rapidity difference at the LHC

At the LHC, the collisions are produced by charge symmetric beams. $t-\bar{t}$ asymmetries must be searched for in a different way. The larger momentum fraction of the valence quarks produces an excess of top quarks in the forward and backwards regions. Top antiquarks tend to be produced more centrally. The natural observable to describe this situation is $\Delta|y| = |y_t| - |y_{\bar{t}}|$. The corresponding asymmetry is defined as

$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)} \tag{2.2}$$

The result for CMS [15], using 4.7 fb^{-1}, is $A_C = 0.004 \pm 0.010(stat) \pm 0.012(syst)$. The result for ATLAS [16], using 1.0 fb^{-1}, is $A_C = -0.019 \pm 0.028(stat) \pm 0.024(syst)$. These are consistent with the very small asymmetry expected in the SM but rule out many of the new physics scenarios proposed for explaining the much larger (and somewhat different) asymmetry at the Tevatron.

2.3 Single top production by the electroweak interaction

Single top production via the electroweak interaction can occur via *s*-channel or *t*-channel processes or in association with a W boson, *W-top channel*, shown in Fig. 4. 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, 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 top pair production, which has a larger number of jets that help distinguish it from background. The single top analysis is therefore based on multivariate techniques that take advantage of many variables, each of which by itself may have only a small discrimination between signal and background but, taken together, provide the necessary discrimination power and efficiency.

2.3.1 Single top at the Tevatron

The single top cross section has been measured by CDF and DØ . The combined result is $2.76^{+0.58}_{-0.47}$ pb [17]. DØ has separated the *t*-channel and *s*-channel processes based on the number and type of jets and their kinematics. The observation of electroweak top production 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 $|V_{tb}| = 0.91 \pm 0.08$ [17].

2.3.2 Single top at the LHC

The results for t-channel and the W-top channel single top production by CMS and ATLAS are shown in Table 2 along with theory predictions. The s-channel process is predicted to have the smallest cross section and suffers the worst backgrounds. It has not been convincingly observed so far and so only the theory prediction for the cross section is given. Observation of s-channel process and measurement of its cross section should be possible with the data accumulated in the 2012 run of the LHC.

Source	Luminosity [fb^{-1}]	Result [pb]
t-channel: $t \to bl\nu, l = e\mu$		
CMS [18]	1.14-1.51	70.2±5.2 (stat) ±10.4 (syst) ±3.4 (lumi)
ATLAS [19]	1.04	83±4 (stat) $^{+20}_{-19}$ (syst)
Theory [20]		$64.6^{+2.7}_{2.0}$
W-top channel: $t \to l\nu, bl\nu, l = e\mu$		
CMS [21]	2.1	22^{+9}_{-7} (stat + syst)
ATLAS [22]	2.05	16.8 ±2.9 (stat)± 4.9 (syst)
Theory [23]		15.7 ± 1.1
s-channel: $t \to l\nu, bl\nu, l = e\mu$		
Theory [24]		4.6 ± 0.2

Table 2: Results on electroweak single top production from CMS and ATLAS at 7 TeV

From the measured t-channel cross sections, CMS [18] and ATLAS [19] determine the CKM matrix element $|V_{tb}|$:

$$|V_{tb}|(CMS) \;=\; 1.04 \pm 0.09\,(exp) \pm 0.02\,(theory); \text{ and } |V_{tb}|(ATLAS) \;=\; 1.13^{+0.14}_{-0.13}$$

These are compatible with the results from the Tevatron and with a value very close to 1.0 as predicted by the SM.

3. Top Quark Properties

3.1 Top quark properties at the Tevatron

3.1.1 Top quark mass and width

The top quark mass plays a significant role in the study of electroweak symmetry breaking. The W boson mass and the top mass can be used to constrain the Higgs mass within the context of the SM, albeit weakly. The mass can be reconstructed explicitly only in the 3-jet fully hadronic final state which suffers from poor resolution and high backgrounds from QCD multi-jet events. The top quark mass can, however, be obtained more accurately 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 more recent results use more data and more advanced analysis techniques that improve the sensitivity of the analysis. In addition, CDF has added measurements based on all-jets and missing transverse energy (MET) plus jets. Recent results, from CDF and DØ are shown in Table 3.

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Exp.	luminosity [fb^{-1}]	final state, method	result [GeV/c^2]
CDF	8.7	leptons+jets	172.85 ± 0.71(stat) $\pm$ 0.84(syst) [25]
DØ	3.6	leptons+jets	174.94 ± 0.83(stat) $\pm$ 0.78(JES) $\pm$ 0.96(syst) [26]
DØ	5.3	dilepton	174.0 ± 2.4(stat) $\pm$1.4(syst) [27]
DØ	5.4	dilepton, ME	174.0 ± 1.8(stat) $\pm$ 2.4(syst) [28]
CDF	5.3	dilepton, νwt	170.6 ± 2.2(stat) $\pm$ 3.1(syst) [29]
CDF	5.8	all jets	172.5 ± 1.4(stat) $\pm$ 1.4(syst) [30]
CDF	8.7	MET+jets	173.9 ± 1.6(stat+JES) $\pm$ 0.9(syst) [31]
Combined			173.2 ± 0.9(stat+syst) [32]

Table 3: Recent measurements of the top quark mass at the Tevatron

The uncertainty in the combined results is an astounding 0.54%! 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, consistent with an indirect determination [33] by DØ . 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 most accurately determined of all the quark masses.

The cross section for $t-\bar{t}$ production depends on the top quark mass. DØ has used this to obtain a measurement of the top mass with 5.3 fb^{-1}. The value is ~ 167 GeV/c^2 with an accuracy of $\sim$5 GeV/c^2 [34].

3.1.2 Top-antitop mass difference

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+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:

$$\Delta M_{t-\bar{t}} = -1.95 \pm 1.11(\mathrm{stat}) \pm 0.59\,(\mathrm{syst})\ \mathrm{GeV/c^2} \quad \text{for CDF with } 8.7\,\mathrm{fb}^{-1}\ [35]$$
$$\Delta M_{t-\bar{t}} = 0.8 \pm 1.8(\mathrm{stat}) \pm 0.5(\mathrm{syst})\ \mathrm{GeV/c^2} \quad \text{DØ with } 3.6\,\mathrm{fb}^{-1}\ [36]$$

3.1.3 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

$$\frac{1}{\sigma_{t\bar{t}}} \frac{d^2\sigma_{t\bar{t}}}{d\cos\theta_+ d\cos\theta_-} = \frac{1 + C\cos\theta_+\cos\theta_-}{4} \tag{3.1}$$

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 C is given by

$$C = \frac{N_{opp\ helicity} - N_{same\ helicity}}{N_{opp\ helicity} + N_{same\ helicity}} \tag{3.2}$$

Theory predicts $C = 0.777^{+0.027}_{-0.042}$. Recently, DØ improved the sensitivity of their measurement using matrix element techniques. Using the dilepton mode with 5.4fb^{-1}, they found $C = 0.57 \pm 0.31$ (stat+syst) [37]; using leptons+jets and 5.3 fb^{-1} [38], they got $C = 0.85 \pm 0.29$ (stat+syst); and the combined result $C = 0.66 \pm 0.23$(stat+syst) [38]. C is shown to be greater than 0.26 at 95% confidence level (CL) and greater than 0.041 at 99.7% CL. This is the first evidence for non-zero spin correlation and is at the 3.1 standard deviation level.

3.1.4 Helicity of W bosons from top decay

CDF and DØ have measured the W boson helicity in top decays. This is discussed below. The combined CDF and DØ results [39] are $F_0 = 0.722 \pm 0.062$(stat) ± 0.052(syst) and $F_R = -0.033 \pm 0.034$(stat) ± 0.031(syst). CDF has a new result using leptons+jets and 8.7fb^{-1}. Their result is $F_0 = 0.726 \pm$ 0.066(stat) $\pm$ 0.067(syst) and $F_R = -0.045 \pm 0.043$(stat) $\pm$ 0.058(syst) [40].

3.2 Top Quark Properties at the LHC

3.2.1 Top quark mass

CMS and ATLAS, using many of the techniques developed at the Tevatron and in some cases developing them further or adding new approaches, have rapidly produced precision measurements of the top mass. These are shown in Table 4. At present, they are approaching, but have not yet surpassed, the precision achieved by CDF and DØ. With additional work on reducing the systematic uncertainties, which in some cases will benefit from more data, it is anticipated that improvements in the top mass measurement will eventually be achieved.

Exp.	luminosity fb^{-1}	final state, method	result GeV/c^2
ATLAS	1.04	leptons+jets	174.5 ± 0.6(stat) ± 2.3 (syst) [41]
CMS	4.7	muons+jets	172.6 ± 0.6 (stat) ± 1.2 (syst) [42]
CMS	2.3	dileptons	173.3 ± 1.2 (stat) ± 2.5 (syst) [43]
ATLAS	2.04	all-jets	174.9 ± 2.1 (stat) ± 3.8 (syst) [44]
CMS Combined			172.6 ± 0.4 (stat) ± 1.2 (syst) [45]

Table 4: Recent measurements of the top quark mass at the LHC

ATLAS and CMS have also derived the top mass from $t - \bar{t}$ cross section measurements. ATLAS, using 35 pb^{-1} of data, reports a top mass of $166.4^{+7.8}_{-7.3}$ [46]; CMS, using 1.1 fb^{-1} gets $170.3^{+7.3}_{-6.7}$ [47]. These masses are pole masses derived from NNLO calculations of the cross section by Langenfeld [48]. Various theory calculations differ by a few GeV/c^2.

3.2.2 Top-antitop mass difference

CMS used lepton+jets events from 5 fb^{-1} [49] to measure the mass difference between top quarks and top antiquarks. The sign of the lepton determines whether the away side 3-jet combination is a quark or anti-quark. The mass of the hadronically decaying top is then determined and the mass of the t-quark and the $\bar{t}$ quark are histogrammed separately. The difference between the centers of the distributions provides a measurement of the mass difference. The result is $\Delta m_t = -0.44 \pm 0.46$ (stat) ± 0.27 (syst) GeV which is consistent with 0, as required by the CPT theorem.

3.2.3 Top quark charge

Both CMS and ATLAS have done studies to rule out the charge assignment of 4/3 for the top quark. The charge of the quark is determined from top decays to a lepton plus b-jet. The W charge is determined from the charge of the lepton. The b-quark charge is determined either from the presence of leptons in the b-jet or from a weighting technique on the tracks observed to form the b-jet. The ATLAS study uses 0.7 fb^{-1} and the CMS study uses 4.6 fb^{-1}. The exotic charge 4/3 hypothesis is ruled out by more than 5 σ.

3.2.4 Top quark branching fractions

The conventional wisdom that top decays almost 100% into a W boson and a b-quark (b-jet) has been tested by CMS [50]. By studying the rates of b-tags in jets from produced $t-\bar{t}$ events, they have measured $R_b \equiv \frac{BR(t\to Wb)}{BR(t\to Wq)} = 0.98 \pm 0.04$ (stat+syst) which gives a 95% confidence level lower limit of $R_b > 85\%$. The main systematic uncertainty in this analysis is knowledge of the b-tagging efficiency.

3.2.5 Search for flavor changing neutral current (FCNC) decays of the top quark

ATLAS has looked for flavor changing neutral current couplings in the production mode [51]. Such couplings could result in the production of single-top events through the processes $u+g\to t$ and $c+g\to t$. These interactions can be distinguished from normal single top production by their kinematics. These can be inverted to give limits on the FCNC decays of the top of $BR(t\to ug) < 5.7\times10^{-5}$ and $BR(t\to cg) < 2.7\times10^{-4}$ at 95% confidence level.

3.2.6 W-boson polarization in top decays

The distribution of the quantity $\cos\theta^*$, where θ^* is the angle between the lepton from the W decay in the W rest frame relative to the momentum of the W in the top rest frame. This angle is given in terms of the polarization coefficients F_0, F_L and F_R for longitudinal, left-handed and right-handed polarization respectively:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)F_0 + \frac{3}{8}(1-\cos\theta^*)^2F_L + \frac{3}{8}(1+\cos\theta^*)^2F_R \tag{3.3}$$

The results (CMS [52], ATLAS [53]) along with theory expectations are given in Table 5.

Quantity	CMS	ATLAS	Theory
F_0	0.567 ± 0.074(stat) ± 0.047(syst)	0.67 ± 0.03(stat) ± 0.06(syst)	0.685 ± 0.05
F_L	0.393 ± 0.045(stat) ± 0.029(syst)	0.32 ± 0.02(stat) ± 0.03(syst)	0.311 ± 0.05
F_R	0.04 ± 0.035(stat) ± 0.044(syst)	0.01 ± 0.01(stat) ± 0.04(syst)	0.0017 ± 0.0001

Table 5: Results on the polarization of the W boson from the top quark decay in $t-\bar{t}$ production

3.2.7 Spin correlations in top production

According to the SM the spins of the top quark and the anti-quark are correlated at production. Because of its large mass, the top quark decays before it hadronizes. As a consequence, the information on the correlation is transferred to the decay distributions. The ATLAS collaboration has studied the angular separation of the leptons in the dilepton mode [54]. They have shown that the hypothesis that there is no correlation is ruled out by 5.1 σ. The measured degree of correlation is $A_{helicity} = 0.40 \pm 0.04$ (stat) $^{+0.08}_{-0.07}$ (syst), compatible with the SM explanation of $A^{SM}_{helicity} = 0.31$.

4. Theory Perspective

The LHC will produce top at the rate of 1 Hz when it reaches its final energy and design luminosity. This enables new investigations into top quark production and decay. At HQL2012, we heard a talk on the prospects for observing CP violation either due to new physics at the top pair production vertex or in the top decay vertex [55]. Since top decays involve a chain of momentum vectors that are correlated by spin, new observables such as triple products of momentum vectors $\vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$ are sensitive to T-violation that also signifies CP-violation in a world where CPT symmetry is respected. Here the momentum vectors may be those of the leptons or jets from the top decays. CP violation may occur in the production if there are new particles with a CP phase that decay into $t - \bar{t}$ pairs. CP violation can occur at the decay vertex through anomalous couplings. The exciting part of this is that these studies become interesting at a few tens of inverse femtobarns. We are about to enter a phase of precision top quark studies in which top quarks will be examined for any indication of new physics beyond the SM.

5. Conclusion

CDF and DØ have made remarkable progress in determining the properties of the top quark, which so far, conforms to the expectations of the SM. Although the Tevatron has now ceased operations, they will continue the analysis of the data, emphasizing the topics that are most likely to have lasting value, such as the top production asymmetry, where the $p - \bar{p}$ initial state makes the Tevatron unique. ATLAS and CMS have already acquired 10 fb^{-1} at 8 TeV with the expectations of a total of 20 fb^{-1} by the end of 2012. After a two year shutdown, the LHC will operate at close to 14 TeV center of mass energy at a luminosity exceeding 10^{34}cm^{-2}s^{-1}. This provides a top pair production rate of about 1/sec. There is a bright future for precision top physics at the LHC!

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