Experimental Top Quark Physics

Jacobo Konigsberg
University of Florida, Gainesville, FL 32611, U.S.A.
konigsberg@phys.ufl.edu

Abstract. In this article I summarize the lectures given at the XI School of Particles and Fields in Xalapa, Mexico, in August 2004. By necessity descriptions and details are kept brief. Emphasis is made on key issues relevant to the most up-to-date experimental results from Run 2 at the Tevatron, the only place so far where one can study experimentally the intriguing top quark.

1. Introduction

The goals of these lectures were a) to give the flavor of the intricacies associated to studying the top quark experimentally b) to describe the current status of the various possible measurements at the Tevatron and to point out their limitations and future direction and c) to convey the possibilities for exciting discoveries in the top quark sector.

The top quark, discovered by the CDF and D0 collaborations in 1995 [1], joined the illustrious group of elementary particles (three families of quark and leptons) which are understood to be of sizes smaller than $\sim 10^{-18}$m. These particles, together with the fundamental interactions between them, transmitted by particles known as bosons, comprise what is known as the “Standard Model” (SM). This model, described mathematically in the language of Quantum Field Theory, is the culmination of about one-hundred years of experimental and theoretical research. The agreement between the theoretical calculations and predictions with the experimental observations and measurements is nothing short of amazing. Still, many mysteries remain, among them:

- Why are there 3-generations of “elementarity”?
- Why the very different masses of the elementary particles? (quark masses span about five orders of magnitude, with the top quark as heavy as a gold atom!)
- The existence of the Higgs particle/field to explain (albeit somewhat in an ad-hoc fashion) the origin of mass.
- How is the force of gravity incorporated/unified together with the other forces?
- What are we missing to explain the dark matter and dark energy in the universe?

Many new theories/models attempt to extend the Standard Model in order to address some of these questions: Supersymmetry, Technicolor, Grand Unified Theories, Superstrings, Extra-dimensions etc. New particles are predicted but so far nothing has been detected in the current experiments. Studying the top quark with as much precision as possible may provide some clues, and maybe even some answers, to these mysteries.

Even though the top quark was discovered ten years ago, the field of experimental top physics is still in its infancy. The “discovery samples” that CDF and D0 gathered during the 1992-1996 Tevatron “Run 1” period are very small; of the order of 100 relatively clean top candidates. In the ongoing “Run 2”, which started in 2001 (with a slightly higher center-of-mass energy than Run 1: 1.96 TeV vs. 1.8 TeV), we have accumulated already maybe five times more data. It is expected that by the end of Run 2, maybe by 2009, we will accumulate about fifty times more data than in
Run 1. These samples will provide much needed experimental information about the top quark and will serve as a solid springboard for the upcoming LHC experiments that will be able to study this fundamental particle with even further precision.

I now proceed to describe the experimental status of top quark physics as it stands now, with the data samples that the CDF and D0 collaborations have collected and analyzed so far in Run 2. The aim here is to try to be pedagogical and not strive for a full compilation of measurements. The reader is invited to browse the latest particle physics conferences web sites for perhaps a more comprehensive and up-to-date account. The CDF and D0 public web sites contain the latest results on top physics [2]. For an extensive review of top quark physics please consult with [3] and the references therein.

2. Top Quark Production and Decays

2.1. Top Quark Production

In \( p\bar{p} \) collisions the production of heavy quarks can be calculated within the formalism of the parton model. In this model the cross-section for a given sub-process, \( \hat{\sigma}_{ij} \), is calculated (to a given order in perturbation theory) for two incoming constituents of the proton (partons), \( i \) and \( j \), each carrying a given fraction of the proton and anti-proton momenta, \( x_i \) and \( x_j \). This process is calculated at the center-of-mass energy \( E_{cm}^2 = \hat{s} \) where \( \hat{s} = x_i x_j s \) (\( s \) being the total available center-of-mass energy in the proton anti-proton collision). Then the probabilities for these momentum fractions (“parton distribution functions”) to occur for a given parton, \( F_i(x_i), F_j(x_j) \) are folded in with the sub-process cross-section to give the total production cross-section. For example for \( t\bar{t} \) pair-production the cross section is given by:

\[
\sigma(p\bar{p} \to t\bar{t}) = \sum_{i,j} dx_i F_i(x_i) \cdot dx_j F_j(x_j) \cdot \hat{\sigma}_{ij}(\hat{s})
\]

At the Tevatron, for large \( m_{top} \), the dominant top quark production process is of \( t\bar{t} \) pairs via \( q\bar{q} \) annihilation (about 85% of the cross-section). Gluon-gluon diagrams contribute the remaining 15% of the cross-section. Figure 1 shows the LO (leading order) Feynman diagrams for these processes.

![Figure 1](image)

Figure 1 Leading order processes for top pair-production

Effects of order \( \alpha_s^3 \) ("next-to-leading order") contribute about 25% more to the cross section. Contributions due to higher orders are estimated by “gluon resummation” techniques and contribute another 10-20%. Of course, the \( t\bar{t} \) production cross section depends on the top mass.
The dependence (can be deduced from dimensional arguments) is inversely proportional to the square of $m_{\text{top}}$ and for $m_{\text{top}} = 175$ GeV it is calculated to be 6.7 pb$^{-1}$, with a theoretical uncertainty of about 10%.

The top quark can also be produced singly at hadron colliders (“single top” production). In this case a $W$ boson is involved in the production. Figure 2 shows the LO Feynman diagrams involved. The theoretical cross section is predicted to be about 0.88 pb for the s-channel and about 1.98 pb for the t-channel.

![Figure 2](image)

**Figure 2** Leading order processes for single-top production

Detecting single-top production, as we shall see later, has not yet been possible due to the copious backgrounds.

In figure 3 we see how the production of top quarks compares to other processes at the Tevatron. Only one in every $10^9$ collisions produces top quarks! Still, the experiments are able to select samples that are enriched in top quarks in which to make their measurements.

![Figure 3](image)

**Figure 3** Top quark production at the Tevatron vs. other processes

Given the size of the production cross section, the next question to understand is how frequently top quarks are produced in hadron colliders. Clearly, the more protons and antiprotons in the colliding bunches, and the more focused these bunches are, the more likely it will be that at a given crossing an interaction will occur. The beam parameter that describes the intensity of its flux at the collision region is called [instantaneous] “luminosity” and can be described by the following formula:
\[
L = \frac{N_p \cdot N_{\bar{p}} \cdot B \cdot f}{4\pi \sigma^2}
\]

Here \( N_p, N_{\bar{p}} \) are the average number of protons and antiprotons per interacting bunch, \( B \) is the number of bunches in the accelerator (in Run 2 we have 36 proton and 36 antiproton bunches) and \( f \) is the frequency with which bunches cross each other (about 2 MHz in Run 2). The effective beam focusing is represented by an effective cross section \( \sigma \) that is of the order of 100\( \mu \)m. At the moment the record luminosity at the Tevatron is about \( 1.2 \cdot 10^{32} \text{ cm}^{-2}\text{ s}^{-1} \) and the average about \( 2 \cdot 10^{31} \text{ cm}^{-2}\text{ s}^{-1} \).

The rate of production of top pair events is then given by \( R = \sigma(pp \rightarrow t\bar{t}) \cdot L \). We therefore produce, on average, only about 10 \( t\bar{t} \) events per day! The goal is to increase this further by a factor of four or five over the next few years.

Furthermore the number of detected top pairs after a period of running is given by:

\[
N_{\text{top detected}} = \sigma(pp \rightarrow t\bar{t}) \cdot \varepsilon \cdot L \cdot dt_{\text{run}}
\]

Here \( L \cdot dt \) is the “integrated luminosity” and it is used to define the size of the analysis datasets.

The units used are “inverse picobarns” (pb\(^{-1}\)) or “inverse femtobarns” (fb\(^{-1}\)). The Run 1 datasets were of the order of 100 pb\(^{-1}\), at the end of Run 2 datasets up to 50 times larger are expected. \( \varepsilon \) is the total efficiency to record and analyse top quark events and thus depends on the trigger efficiency, the detector geometrical acceptance and the event selection used to obtain a clean sample of top events. Before discussing in more detail the detection of these events, we need to understand the features of the final [observable] state.

2.2. Top Quark Decays

The top quark, being as massive as it is, has a lifetime of only about \( 4 \cdot 10^{-24} \text{ s} \). The corresponding width is about 1.5 GeV. Given that QCD hadronization is expected to take place in a time of the order of \( 10^{-23} \text{ s} \), the top quark decays as a free quark. This means that no hadronic states with top quarks in them exist in nature and that there is no toponium spectroscopy to study. This is unique for a quark and the top quark therefore serves as a laboratory for the study of the properties of a “naked” quark.

Within the Standard Model the top quark is expected to decay very close to 100% of the time into a \( W \)-boson and a \( b \)-quark: \( t \rightarrow Wb \). The \( W \) decays almost instantaneously (lifetime\~\( 3 \cdot 10^{-25} \text{ s} \)) in one of two ways:

- Leptonically, into a lepton-neutrino pair, with branching fractions given by:

  \[
  BR(W \rightarrow e\bar{\nu}_e) = BR(W \rightarrow \mu\bar{\nu}_\mu) = BR(W \rightarrow \tau\bar{\nu}_\tau) = 1/9
  \]

- Hadronically, into two jets originated from a quark-antiquark pair (\( u\bar{d}, c\bar{s} \) with equal probabilities):

  \[
  BR(W \rightarrow q\bar{q}) = \frac{2}{3}
  \]

Therefore for top pair production, the different decay mode of the two \( W \)-bosons determines the final state. Figure 4 shows the relative fractions for the possible final states.
2.3. Top Quark Detection

It is interesting to notice that the final-state decay products of top pairs span the entire spectrum of quarks and leptons! Therefore the detectors used in studying top quark physics need to be suited to identify these objects with good efficiency, and to measure their properties with good accuracy.

Figure 4 also shows that the final state can be classified in terms of the leptonic content of each channel. A few general observations:

- The “all-jets” (also known as “all-hadronic”) is the channel with largest yield of events (44%). However it is also the channel with largest backgrounds, mostly from QCD multi-jet production.
- The channels with a single electron or a single muon are referred to as “lepton+jets”. These channels have a significantly better signal to background ratio than the all-hadronic channel while still having a decent (30%) yield. The main backgrounds are from QCD production of $W$-boson associated with jets.
- The channels with two leptons in the final state (muon and/or electron) are called “dilepton” channels. These have very good signal to background ratio but their yield is rather low (~5%). The main backgrounds come from electroweak Drell-Yan and diboson production.

This large and complex set of final state permutations has significant implications for data collection. Although a multilayered hardware and software triggering system is carefully designed to retain as many of the most interesting events as possible, and the detector is almost hermetic, some fraction of top events will be lost depending on the decay mode and distribution, as well as the priorities of the experimental program. A brief account of the major issues for particles entering the detector is in order:

- Electrons are recognized with about 90% efficiency by their short interaction length leading to a compact shower in the calorimeter and an associated track of matching momentum in the central tracking volume of the detector.
• Muons are highly penetrating particles that are distinguished by their minimum-ionizing trail all the way through being the only particles to reach the outermost detector layers, with about 90% efficiency.

• Neutrinos escape direct detection because of their tiny weak interaction. Since the beam-axis component of net event momentum varies over a wide range at a hadron collider, only the transverse component of invisible particles’ total momenta can be inferred in any given event. Simplistically, it is the negative vector sum of observed particles’ transverse momenta, called “missing transverse energy” or missing-$E_T$. The missing-$E_T$ resolution depends strongly on the content and topology of an event.

• Detection of $b$-quarks is particularly important in selection of top event candidates since most QCD events don’t contain them, so their identification reduces backgrounds considerably. A $b$ immediately hadronizes, but typically travels about half a millimeter from the primary interaction vertex before decaying into a jet containing multiple charged particles. Such a displaced decay vertex can be isolated using a good vertex detector by extrapolating the tracks associated with the jet to a common origin (“secondary vertex tagging”). Jets initiated by gluons and lighter quarks (except sometimes $c$) are rarely associated with a secondary vertex. Additionally, about 20% of the time a $b$-jet contains a lepton that typically has a lower momentum than a prompt lepton from a $W$ decay. This offers an alternative means for tagging a $b$ quark jet (“soft lepton tagging”). Overall, $b$ quarks can be identified about 60% of the time.

• Tau leptons decay leptonically 36% of the time and hadronically 64%. The leptonic decays result (in addition to two neutrinos) in an electron or a muon that are typically softer than those from $W$ decays. Apart from a very small impact parameter that is difficult to measure, $W \rightarrow \tau \bar{\nu}_\tau \rightarrow l \bar{\nu}_l l \nu_l \tau \bar{\nu}_\tau$ decays cannot really be singled out from $W \rightarrow l \bar{\nu}_l$ in top events, and are automatically accounted for in the measurements with electron and muon final states. The hadronic modes need special consideration: ~76% of these yield a single charged daughter (“1-prong”) and ~24% yield 3 (“3-prong”). Good pattern-recognition algorithms can exploit the low charge multiplicity and characteristic features of the associated narrow shower in the calorimeter to separate hadronic tau decays from the copious QCD background. The associated neutrino carries away a significant fraction of the tau momentum, making its estimation dependent on the distribution of other objects in the event. Overall, the identification efficiency of hadronic tau decays is about 50%.

• Jets initiated by gluons and lighter quarks have nearly full detection efficiency, although establishing their partonic identity on an event-by-event basis is not possible as they hadronize into overlapping states. Subtle differences in profiles of gluon and quark jets may be discernible on a statistical basis. If so, it would be very useful to top quark studies since all jets from top decays are quark initiated (discounting final-state radiation), while jets in the QCD background are predominantly gluon-initiated. This possibility requires further studies in the context of hadron colliders. Jets arising from gluons and lighter quarks will be misidentified as a $b$ (tau) at a rate of only about 1/200. They fake an electron or muon even more rarely, at about the 1/2000 level.

Because the top quark is so heavy, its decay products are rather energetic (~10-100 GeV) and populate the most “central” part of the detectors (regions of ~$|\eta|<2.5$). The selection criteria for datasets enriched in top candidates thus take advantage of these properties and require final state objects that satisfy these conditions. Background events have typically less energetic objects and cover larger regions of pseudorapidity. Usually, to reduce background further, the minimum threshold used for lepton and jet selection is 15 to 20 GeV (in transverse energy).

Depending on $b$-tagging requirements, one can get signal-to-background ratios from about 2:1 to 10:1 in the dilepton sample, from about 1:4 to 4:1 in the lepton+jets sample and from about 1:10 to 1:2 in the all-hadronic sample. Detection efficiencies for all channels are typically in the range of 10-20% for all channels, depending on the desired measurement.
In figures 5 and 6 we show schematically the CDF and D0 detectors. These detectors have exactly the right components that allow for good detection and reconstruction of all the $t\bar{t}$ decay products. Close to the beam-pipe they have silicon vertex detectors, used in the identification of long-lived $b$-quarks. Surrounding the silicon they have large-volume tracking detectors embedded in a solenoidal magnetic field, used to reconstruct the trajectories and to measure the momenta of charged particles. Surrounding the tracker systems, calorimeters are used to measure the energy of electrons, photons and jets. And, finally, a layer of tracking chambers, surrounding the other components, is used to detect muons that traverse all other systems loosing almost no energy.

In figure 7 we show and actual $t\bar{t}$ lepton+jets candidate event, as detected by CDF during Run 1. The calorimeter view shows an electron and four jets, and the tracking view shows how two of these jets have tracks with displaced vertices, a “$b$-tag”.

Figure 5 CDF

Figure 6 D0 detector
3. Top Quark Physics

Figure 8 shows the possible measurements in top physics. In the rest of this review I discuss the salient features of these measurements and their current status.
3.1. Experimental measurements

3.1.1. Pair production cross section

The first thing to measure, in any top quark physics program, is the production cross section. This measurement helps establish a sample from which other measurements can be made. This sample needs to be well characterized in terms of its various components and its selection criteria is usually optimized to enhance the significance of a signal excess and thus to minimize the expected uncertainty in the cross section measurement. Further variations in the selection criteria can then be made to optimize for other measurements.

The $t\overline{t}$ production cross section has been measured in many different ways by CDF and D0 both in Run 1 (at 1.8 TeV center-of-mass energy) and Run 2 (at 1.96 TeV). The cross section varies with the top mass and the consistency between mass and cross section was a very important element in establishing that the newly discovered events were indeed produced by a heavy particle consistent with the properties of the top quark. Furthermore, consistency in the cross section measurements across the different final states also help establish that the top is Standard Model-like with the correct branching ratios. Sources of new physics in the top quark sector can disrupt the consistency between these measurement! It is therefore very important to measure the cross section in as many different ways as possible and with the best possible precision.

To first order, the cross section measurement is given by:

$$\sigma(t\bar{t}) = \frac{N_{\text{obs}} - N_{\text{signal}}}{(\varepsilon \times A) \cdot L \cdot dt}$$
Here $N_{obs}$ and $N_{bgnd}$ are the number of observed events and the number of predicted background events in the selected sample. The detector acceptance and event selection efficiencies are represented by $A$ and $\varepsilon$ respectively.

Figures 9 and 10 show the CDF and D0 Run 2 cross section measurements. The newest CDF measurements, with more than 300 pb$^{-1}$ datasets, have now an uncertainty of about 15%. It is expected that with more data, and by combining the measurements in the different channels, the uncertainties will be reduced below the 10% theoretical uncertainty level. At this point, and with a good mass measurement we can test with a lot more accuracy the SM predictions and be more sensitive to the presence of new physics.

**Figure 9** Top-pair production cross section measurements by CDF in Run 2
These systematic uncertainties in the cross section measurements are dominated by the understanding of the acceptance and detection efficiency of the various objects in the final state. Jet energy scale particle-id and b-tagging efficiencies can contribute significantly to the uncertainty. The modeling of $t\bar{t}$ production by the "Monte Carlo" generators is also an important factor. As the datasets increase some of these systematic uncertainties can be reduced due to the larger statistics in the studies that determine them.

3.1.2. Single Top Search

Even though the production cross section for single top is expected to be about half of that of top pair production, the backgrounds are much more copious. The reason is that there are less objects in the final state and the production of QCD processes decreases by about one fifth ($\sim \alpha_s$) for any extra jet in the event. Furthermore $t\bar{t}$ events in which jets are missing or outside the selection criteria will also be a background to single top production!

So far the searches have concentrated in the lepton+2-jets channel, in which one jet is required to be b-tagged. The analysis takes advantage of certain kinematical distributions that help separate single top from $t\bar{t}$ and from $Wb\bar{b}$ production. Examples are the so-called "$H_T$" distribution, which is the scalar sum of the $E_T$ of the various objects in the event, and the product $Q \cdot \eta$ of the lepton charge and the rapidity distribution of the non-tagged jet. The analyses can also uses the fact that the top mass is known and it constrains the invariant mass of the final state objects to be consistent with it. Depending on how much kinematical information is used a better sensitivity can be achieved. Using a neural net-based analysis and a $230 \text{ pb}^{-1}$ dataset, D0 has been able to rule out single top production as follows:

- $\sigma(p\bar{p} \rightarrow t + X) < 6.4 \text{ pb} @ 95\%$ c.l. (s-channel)
- $\sigma(p\bar{p} \rightarrow t + X) < 5.0 \text{ pb} @ 95\%$ c.l. (t-channel)
These results are rapidly approaching the level in which single-top is expected in the Standard Model. A “discovery” may be possible with datasets 10 times larger. Very likely, within the reach of Run 2.

Studying single top is important for several reasons besides further corroboration of the SM. It is the place where a direct measurement of $|V_{tb}|$ is possible and where new physics can come in, in the form of new charged bosons or anomalous couplings.

3.2. Measurements of Top Quark Decays and Properties

3.2.1. Top Quark Decays

It is very important to test if the top quark decays are consistent with those predicted by the couplings in the Standard Model. The consistency of the cross sections in the different final states already shows, at some level, that the SM is indeed at work in top decays. More explicit tests of the top decays are being made. Here we summarize some of them:

- **Is the rate of taus consistent with that of the SM?**

  New physics could bring an excess of tau leptons and therefore testing if
  \[ r_\tau = \frac{BR(t \to b\tau\nu)}{BR_{SM}(t \to b\tau\nu)} = 1 \]
  is important. CDF concluded, using 193 pb$^{-1}$, of Run 2 dilepton data, through direct identification of hadronic tau decays, that $r_\tau < 5.0$ @ 95% c.l.

- **Is the rate $t \to Wb = 1$ as expected from SM?**

  This value is dictated by the unitarity of the CKM matrix and the very small measured values of $|V_{ub}|$ and $|V_{cb}|$. We therefore expect that $R_b = |V_{tb}|^2 / (|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2) = 0.998$. In the top samples we can examine the fraction of untagged, single-tagged and double-tagged events to measure $R_b = \frac{BR(t \to bW)}{BR(t \to bq)}$ with $q$ being any quark. By combining dilepton and lepton+jets final states a better sensitivity is reached. CDF and D0 have so far measured (with $\sim$160 pb$^{-1}$):

  \[ CDF: \ R_b = 1.11^{+0.21}_{-0.16} (stat) \oplus 0.17 (syst) \quad \text{and} \quad R_b > 0.61 @ 95\% \text{ c.l.} \quad \text{and} \quad |V_{tb}| > 0.79 @ 95\% \text{ c.l.} \]

  \[ D0: \ R_b = 0.70^{+0.27}_{-0.24} (stat) \oplus 0.11 (syst) \]

- **Search for rare top decays**

  In the SM the FCNC decays of the top quark such as $t \to Zq$ and $t \to \gamma q$ ($q = u, c$) are expected to be incredibly small, with branching fractions in the range $10^{-8}$ to $10^{-12}$. Testing for values significantly larger than these will uncover anomalous top couplings to new physics. So far only Run 1 results (from CDF) have been published, although Run 2 searches are under way.

  \[ BR(t \to c\gamma) + BR(t \to u\gamma) < 3.2\% (95\% \text{ c.l.}) \quad \text{and} \quad BR(t \to Zc) + BR(t \to Zu) < 33\% (95\% \text{ c.l.}) \]
3.2.2. W-helicity in Top Decays

Measuring the helicity of the W-boson in the $t\bar{t}Wb$ vertex provides a stringent test of the SM and examines if a new interaction might be present. The $(V-A)$ nature of the weak interaction precludes right-handed helicity states ($F^+ = 0$) and predicts 70% of the times a left-handed $W$ with the rest having a longitudinal polarization ($F^- = 0.7$ and $F^0 = 0.3$). Several distributions of the decay products show discrimination power between these three states. Examples are: the angle between the $W$-boson direction and the lepton direction in the $W$ rest frame (shown in figure 11) and the transverse momentum of the lepton in the lab frame. Both CDF and D0 have Run 1 and Run 2 results. The best ones are:

$$F^+ < 0.18 \text{ @ } 95\% \text{ c.l. (CDF)}$$
$$0.25 < F^0 < 0.88 \text{ @ } 95\% \text{ c.l. (CDF)} \text{ and } F^0 = 0.56 \pm 0.31 \text{ (D0)}$$

![Figure 11](image_url)

Figure 11 Angle between the $W$-boson direction and the lepton direction in the $W$ rest frame for different $W$-helicity states.

3.2.3. Top Quark Mass

The measurement of the top quark mass is not only a very important one but also a very complicated one. Its importance is of course, in part, due to the fact that the top, the $W$-boson and the SM Higgs masses are intimately linked. Good precision in the top mass measurement constraints the Higgs mass significantly. A change of 1 (-1) GeV in the value of the top mass changes the expected Higgs mass by 5 (-5) GeV.

The top mass has been measured in all three decay channels: dilepton, lepton+jets and all-hadronic. Each channel has its own set of problems. In the most copious all-hadronic channel, all of the $t\bar{t}$ final state particles are reconstructed in the detector (no neutrinos) and one would therefore expect the best mass measurement to come from this channel. However, this is not yet the case. The reconstruction problem gets complicated due to the large backgrounds and due to the multiple possibilities of assigning 6-jets to two quarks (“combinatorics”). The lepton+jets channel is the channel that has achieved so far the best precision in the top mass measurement. The yield is not as large as the all-hadronic channel but the signal to background ratio (especially when a b-tagged jet is required) is very good. Even though there is one neutrino in the final state, the kinematical reconstruction is over-constrained and thus solvable. The dilepton channel is missing two neutrinos, and tricks are used in order to “guess” the most-likely kinematical configuration (comparing to Monte Carlo expectations). This channel also suffers from low statistics samples but has the advantage of very high purity of top quark events. This could make this channel contribute significantly to the mass measurement when large datasets are available towards the end of Run 2. Measuring the top mass in all channels is not only desirable in order to reduce the uncertainty as much as possible by combining the results but also in order to make sure that the processes we are dealing with indeed originate from the same particle. Significant inconsistencies between these channels could unveil the presence of unexpected new physics.
All three channels suffer from similar systematic uncertainties, dominated by the knowledge of the “jet energy scale”. Briefly, this term is used to combine all the effects that help us determine the energy of the original final-state partons from the measured energy of the jets. This is a highly non-trivial feat and requires a very good understanding of the calorimeters and of the detector simulation.

The top mass measurements can roughly be divided in two categories: those that only use kinematical information and compare the reconstructed event mass distributions to those expected from different top masses in the simulation, picking the most likely one and those that in addition use “dynamical” information such as the full LO differential matrix element in order to find the most likely mass for a set of events.

Figure 12 shows the current status of the top mass measurements. The most recent CDF result in the lepton+jets channel, with ~320 pb$^{-1}$ run 2 data, has a precision of 4 GeV, already better than the combined CDF/D0 Run 1 mass measurement! (4.3 GeV). The goal of reaching an uncertainty better than 3 GeV in Run 2 seems possible.

![Figure 12 Top Mass measurements](image)

**Figure 12** Top Mass measurements

### 3.2.4. Top Quark Spin and Charge

The agreement, within uncertainties, between the predicted and measured production cross sections imply that indeed the spin of the top quark is consistent with $1/2$. Additionally, because of the short lifetime of the top quark, the spin of the top gets conserved and transferred to its decay products. The SM predicts certain correlations between the spin polarizations of the top and the anti-top ($\kappa = 0.88$). So far only a limit for this correlation has been obtained experimentally, by D0: $\kappa > -0.25$ @ 68% c.l. It is expected that a sensitivity of about 0.60 can be reached with ~2fb$^{-1}$ Run 2 data. It is possible that when all top measurements are done a “most-likely” intrinsic spin value for the top quark can be deduced.

The electric charge of the top quark has not been yet measured directly. The consistency of the data with the $t \to Wb$ decays of course suggests that the SM $2/3e$ value is correct. A way to measure the charge is to measure the cross section for the emission of hard-photons in $tt$ events. A top quark with charge $4/3e$ will radiate four-times more than the SM top. If this extra radiation is discernible among the SM backgrounds one could either measure or rule out the $4/3e$ value. Studies are under way to measure this at the Tevatron.
3.3. Search for New Physics in Top Quark Samples

Top quarks samples provide a unique opportunity to search for new physics. Many models predict the possibility that the top quark can couple to new particles, and be sensitive to interactions, beyond those in the Standard Model [3]. Regardless of these models, it is of utmost importance that experimentally we look for any possible deviation from SM predictions within the top quark sector. Many different searches have been under way since Run 1 and with the largest datasets these are starting to become a lot more sensitive and thus a lot more interesting. Here we briefly describe some of them.

3.3.1. Search for Resonant Production of Top Pairs

No known Standard Model particle decays to $t\bar{t}$ therefore the observation of resonant production would be a discovery of new physics. Certain models, such as top-color assisted-technicolor predict such resonances in the form of a high-mass neutral $Z$-like particle that couples strongly to the SM third generation (but not to leptons, “lepto-phobic”). Studying the invariant mass distribution of $t\bar{t}$ pairs and looking for “bumps” in a hot topic for the Run 2 top physics program. Figure 13 shows tantalizing possibilities in the Run 1 CDF data. Both CDF and D0 published limits excluding resonances in certain mass ranges (~450 to 650 GeV) for certain models. Stay tuned for what ought to be very interesting Run 2 results.

![Figure 13 Invariant $t\bar{t}$ mass distribution from CDF’s Run 1 data](image)

3.3.2. Search for a 4th generation $t'$

If a 4th-generation $t'$ top-like quark decays just like the SM top $t' \rightarrow Wb$ then a trace of these processes could be found in the kinematical distributions of the top samples. An example of such case is the “$H_t$” distribution the scalar sum of the transverse energies of the lepton, jets, and missing-$E_T$. Figure 14 shows this distribution for CDF’s Run 2 data together with that of a 225 GeV $t'$ quark. No evidence for $t'$ production is found...yet.
3.3.3. Anomalous kinematics

Another way in which new physics can be searched for in top quark samples is by establishing the consistency of the event kinematics with that of the Standard Model. The Run 1 data had interesting hints of possible discrepancies. With the new Run 2 data these analyses can be performed with more sensitivity.

The CDF Run 1 dilepton sample showed some events with seemingly unusually large missing-
E_T and a possible excess of electron-muon pairs. Blind analyses in Run 2 have tested a sample of dileptons, about twice as large as that of Run 1, and have found agreement with the SM at the level of a few percent (the lepton PT distribution being the most anomalous one). Clearly, only a much larger sample of events will eventually be able to shed more light in this matter.

The CDF Run 1 lepton+jets sample exhibited a small excess of events in the 2 and 3-jet bins that had the same jet tagged both by a displaced vertex and by a soft-lepton. The kinematical distributions of these events showed discrepancies with SM expectations. Once again, very large Run 2 datasets should be tested for possible further evidence.

3.3.4. Search for Top Decays to Charged Higgs

In beyond-the-SM models with two Higgs doublets, such as MSSM, there are five Higgs fields when the electroweak symmetry is broken. Three of these particles are neutral (h^+, A^+, H^0) and two are charged (H^+, H^-). For a given charged Higgs mass (provided that M_{top} ≥ M_{H^+} + M_b), the value of the ratio of the vacuum expectation values for the two Higgs doublets, tan(β), determines the probabilities with which t → H^+b and also the branching fractions for the charged Higgs decays. Figure 16 shows these for a charged Higgs mass of 150 GeV.
Both CDF and D0 have searched for the charged Higgs in Run 1 either looking directly for an excess of taus from the charged Higgs decays or by measuring the ratio of the dilepton and single lepton cross sections in the top samples. A recent Run 2 search by CDF combines the two approaches and looks holistically at the complete set of top cross section measurements with leptons in the final state, allowing for possible "contamination" of charged Higgs processes with a given value of the Higgs mass and tan(β). Improved limits are obtained, shown in figure 17 are the exclusion regions for MSSM models that satisfy the parameter values specified at the bottom of the picture. Depending on these assumptions different regions are excluded.

Figure 17 Charged Higgs limits from CDF’s Run 2 data

3.4. Conclusions and Prospects

The area of experimental top quark physics in only now starting to take off. The CDF and D0 experiments have shown their first set of results with about three times the data from Run 1. The
final Run 2 datasets should be at least 10 times larger than the present ones! We know from experience that when datasets increase by an order of magnitude surprises can indeed happen. We look forward to that in the remaining years of the Tevatron program.

Eventually at the LHC top quarks will be produced at rates many tens of times faster than at the Tevatron, a true "top quark factory" and top production may reveal more interesting features. It will also be the background for many expected new physics processes, such is life when progress is made…

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