Discovery of Top Quark

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2008

Motivation

By mid-seventies, the theory of fundamental interactions could explain a vast range of experimental data by postulating four quarks, grouped into two weak isodoublets: (up,down) and (charm,strange). A new quark — bottom — was discovered in 1977 at Fermilab during the study of Upsilon resonances in an experiment led by Leon Lederman. This immediately suggested the existence of its flavor partner, top quark. This, coupled with an authentically pleasing symmetry that 6 quarks would have with the three-generation structure of the leptons, encouraged searches for the new particle. It turns out that the mass of the top is nearly two hundred times that of a proton (or 35 times that of the bottom quark), so the energy required to produce such heavy particles in collider experiments was only reached in early nineties. Indeed, in the words of one Fermilab physicist, "*Because of the great mass and short lifetime, it is popular to say that top quarks were produced in great numbers in the fiery cauldron of the Big Bang, that they disintegrated in the merest fraction of a second, and then vanished from the scene until physicists learned to create them in the Tevatron*".[1]

Due to its extremely short lifetime ($\sim 10^{-25}$ s), top quark is the only quark that decays before the process of hadronization, offering a unique window into bare quarks. The decay is described by pure (V-A) weak interactions, giving an excellent opportunity to study the electroweak sector. The value of the top mass puts constraints (through radiative corrections) on the masses of the Higgs boson and supersymmetric particles, while its proximity to the electroweak symmetry breaking scale (a few hundred GeV) makes it a sensitive probe of new physics. Top physics thus remains very important both in the present and future collider experiments.

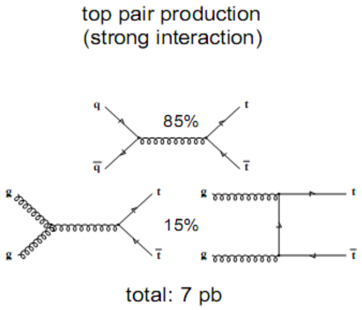
In this paper we review discovery of the top quark by the CDF collaboration, and then consider some exciting possibilities that LHC will bring to top physics.

Note: it is important to to note that CDF is currently in the Run II phase with new hardware upgrades, higher luminosity, and improved analysis techniques. With a lot more data compared to 1995, CDF has since produced (and will produce prior to full LHC commissioning) many high-quality top-related physics analyses, which are not discussed in this note.

Note 2: paper and literature sources are only mentioned once, when they are used for the first time.

Production and Decay

Top quarks are produced in hadron colliders via two mechanisms: pair production via strong force, and single-top production via exchange of a W boson. While single-top production is a very interesting topic in itself, we will focus on the ttbar process, whose signatures were used to identify top quark in the 1995 papers by CDF and D0 collaborations. The leading-order Feynman diagrams for ttbar production are[2]:



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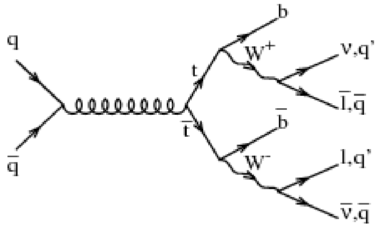
[1] «Discovery of the Top Quark», Chris Quigg

[2] «TOP QUARK PRODUCTION AND PROPERTIES AT THE TEVATRON», Frank Fiedler, 2005

In Standard Model, the top quark is expected to decay to a W boson and down-type quark. However, the branching fractions for ($t \rightarrow Wd$) and ($t \rightarrow Ws$) decays are strongly suppressed by the square of the corresponding CKM amplitudes (V_{td} and V_{ts}), making $B(t \rightarrow Wb) \approx 99.8\%$ the only channel with enough statistics for a thorough analysis.[3]

The W boson can decay either into lepton+neutrino or quark+antiquark (see the figure below), resulting in the following event topologies for the ($t \rightarrow Wb$) decay:



- **All-hadronic** (44%), where each W hadronizes into two jets. These events, characterized by 6 energetic jets in the final state, are very challenging to trigger and analyze due to large QCD backgrounds.
- ***τ*** (21%), where at least one W decays into a tau+neutrino. These events are also hard to identify because *τ*'s can decay into leptons or hadrons, making them indistinguishable from other final states, thus contaminating other samples.
- **Dileptonic** (5%), where both W's decay into an electron or a muon. These events are characterized by 2 energetic, isolated leptons of opposite charges, two b jets, and missing transverse energy from neutrinos. Although it suffers from a low branching ratio and presence of two missing E_T vectors, this channel provides a clean signature and is easy to trigger, making it important for the top discovery.
- **Semileptonic** (30%) channel offers a compromise between all-hadronic and dileptonic channels, with one isolated lepton, two b-jets, and two light-quark jets from the W. This channel was also instrumental in the discovery of the top and measurement of its mass.

CDF detector[4]

At Tevatron, beams of protons and antiprotons are accelerated to an energy of 980 GeV and collided at two general purpose detectors – CDF and D0. CDF consists of several detection layers arranged coaxially around the beamline.

The innermost layer is a tracking system enclosed by a solenoid that generates a 1.4-T magnetic field. It consists of silicon detectors and a drift chamber, providing high-resolution measurement of charged particle momenta. The silicon detectors are located near the beam extending radially to 22 cm, and are discussed in the next section. The drift chamber consists of a set of axial and small-angle stereo sense wires, providing tracking in the r-z plane to an outer radius of 132 cm.

The solenoid and tracking volume are surrounded by calorimeters extending to an η of 4.2. Electromagnetic calorimeter is composed of alternating layers of scintillator and aluminum-covered lead, and measures energy deposited by electrons and photons. Beyond it, hadronic calorimeter samples energies of hadronic jets in a series of scintillators and steel absorbers. The calorimetry output is

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[3] The Top Quark, T.M. Liss and A. Quadt, 2006

[4] Based on the overview from «Initial State Gluon Radiation in Drell-Yan Dilepton Production», A. Rahlin et al, 2005

summed into towers of (Δη=0.2)x(Δφ=15°) and used for triggering and analysis.

Muons normally pass through calorimeters without depositing much energy due to their large mass, and are detected in the muon drift chambers extending to an η of 1.0. Most muons with P_T in excess of 1.4 GeV reach the muon detector and can be matched with the tracks from the inner drift chamber.

Finally, the events are selected and saved on tape by a three-level trigger system. Each level is a logical-OR of a number of triggers that select events based on the presence of certain objects (such as electrons or muons) or values of global quantities, such as missing E_T. First two levels use dedicated hardware processors, while Level 3 employs a farm of commodity computers.

Triggering and object selection

Since the exact cuts are available in the original discovery paper, we will here limit to a discussion of the general ideas behind object candidate selection.

At LVL1, electron trigger requires a single trigger tower in the EM calorimeter at LVL1 with E_t>6 GeV (for central part of the detector). At LVL2, the event must have an EM cluster with E_t>9 GeV AND a track with similar P_t as measured by the tracking chambers. At LVL3, the E_t cuts are tightened, and spatial association between calorimetry and tracking is performed. At the time of top discovery, the electron trigger was 92-93% efficient for high-P_t electrons.

Electrons that come from photon conversions can be removed with an 88% efficiency by noting the absence of hits in the silicon detectors at a location extrapolated from cluster position. To discriminate against hadrons, a variety of offline cuts are applied, such as ratio of hadronic to EM cluster energy, ratio of cluster energy to track momentum, cuts on shower profile, and isolation requirements both in calorimetry and tracking subsystems.

Muon trigger requires a single calorimeter tower at LVL1, and a spatial match between central tracking system and track segment in the muon chambers for LVL2. LVL3 performs reconstruction and tightens the cuts, and also required suppressed activity in the hadronic calorimeter. When all subsystems were operational, muon trigger was measured to be 87% efficient for high-E_t muons.

Offline selection cuts for muon candidates include cuts on energy deposition in hadronic and EM calorimeters consistent with the passage of a minimum-ionizing particle, impact parameter, distance between extrapolated track from the central tracking system and muon chambers, and isolation criteria.

Jets are reconstructed from calorimeter towers using cones of radius 0.4 in the η-φ space. However, their energies can be mismeasured due to a variety of effects, such as non-linearities in calorimeter and B-field, reduced response at module boundaries, dead cells, out-of-cone losses, and contamination from the underlying event.

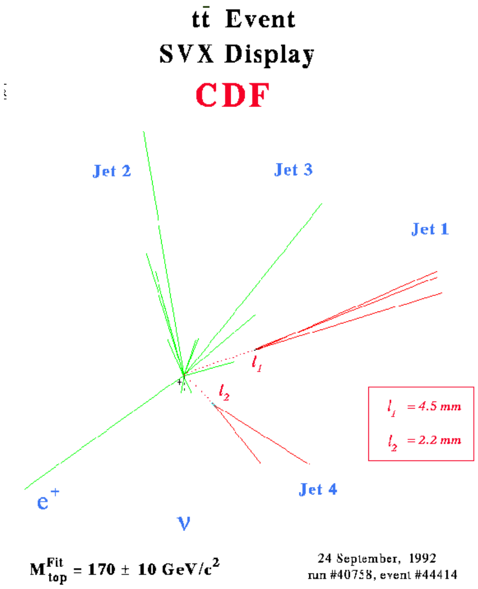
Hadronic jet energy must be corrected to account for these effects. Correction functions are determined in-situ from the events with back-to-back jets and photons (or π^0's decaying via $\pi^0 \rightarrow \gamma\gamma$). Since the EM calorimeter energy scale is well-understood (thanks to narrow and clean lepton jets), transverse momentum balance can be used to study hadronic calorimeter performance.

Typically, these corrections are on the order of 30%, with the residual jet energy uncertainty ranging from 5% (for 20 GeV jets) to 3% (for 300 GeV jets). However, due to the presence of undetected soft gluon radiation, CDF uses a conservative 10% as its jet energy uncertainty, making it the dominant systematic in the ttbar analysis.

The detection efficiencies for muons and electrons were computed from MC and cross-checked against well-understood Z decays ($Z \rightarrow ee$) and ($Z \rightarrow \mu\mu$). Similarly, jet background predictions were compared with the data in the Z+jets sample and were found to be in perfect agreement.

B-tagging

B hadrons originating from b-quarks have a lifetime of around ~1.5 ps – long enough to displace the decay vertex away from the interaction point. This allows to "tag" some jets as b-jets by matching displaced vertices in the silicon detectors with hits in the tracking chamber. This, in turn, provides a stronger discriminative power for the semileptonic channel against generic QCD backgrounds. For example, the following reconstructed ttbar event has two tagged b-jets that are displaced by 2.2 and 4.5 mm in the transverse plane[5]:



Displaced vertices are detected in the microstrip vertex detector (SVX)[6] that covers the region from the beam pipe up to a radius of 7.9 cm (for the outer layer). SVX impact parameter resolution at high momentum was measured to be ~17 microns. The efficiency for tagging at least one b-quark in a ttbar event with ≥3 jets is found from MC simulation (and cross-checked in inclusive electron and muon samples enriched in b decays) to be around 42%. However, due to radiation damage to the silicon, SVX detector performance decreased over time.

Another b-tagging technique is soft lepton tagging (SLT), which searches for an additional lepton from semileptonic b decays ($b \to l\upsilon X$). Electrons and muons are found by matching tracks from the central tracking chamber with EM calorimeter clusters or muon chamber track segments. However, backgrounds from hadrons misidentified as leptons, and electrons from unidentified photon conversions make it hard to see the ttbar signal on top of expected background (as of 1995)[7].

Dileptonic channel

In addition to standard lepton and jet selection cuts, *ee* and $\mu\mu$ events with dilepton invariant mass between 75 and 105 GeV are rejected to reduce backgrounds from Z decay. In order to reduce the Drell-Yan *ee* and $\mu\mu$ backgrounds, a missing E_T cut of 25 GeV is imposed. Additional cuts on the direction of missing E_T with respect to nearest jet and lepton are used to discriminate against Drell-Yan

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[5] «B tagging at CDF», Daniel Jeans for the CDF collaboration

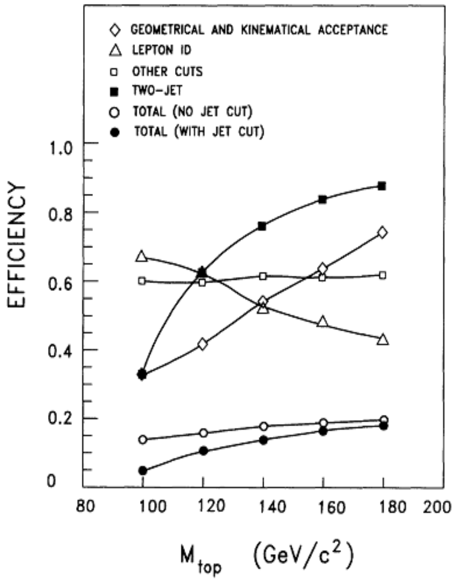
[6] This note covers the original SVX subsystem, as described in PRD Vol. 50, Number 5, 2966-3026

[7] «Observation of Top Quark Production...», PRL Vol. 74, Number 14, p. 2626-2630

continuum and ($Z \rightarrow \tau\tau$) with both τ's decaying leptonically, which can also suppressed by requiring jet activity in the event.

The most significant background in addition to those already mentioned is the WW production, which was studied with the ISAJET MC program. Over 85% of WW background is suppressed by requiring two energetic jets in the event. Finally, QCD+jets or W+jets with a misidentified lepton or undetected photon conversion are kept under control thanks to missing E_T and isolation cuts.

The geometric (e.g., η cuts) and kinematic (e.g, P_T cuts) efficiencies are evaluated with ISAJET and CDF simulation software for different masses of top quark. These efficiencies tend to increase for larger top masses, which result in more large-momentum activity in the central region. Lepton identification and isolation efficiencies are also evaluated from MC simulations and cross-checked against dileptonic Z decays. These efficiencies tend to decrease for larger top masses because of harder fragmentation products. Trigger efficiencies were calculated directly from the data collected by independent triggers.



The fractional uncertainty on the total efficiency ranges from 38% to 9% for M_{top} between 100 and 180 GeV, including the effects of initial-state gluon radiation.

Semileptonic channel

The major challenge in the leptons+jets channel is W+multijet background. Requiring presence of a secondary vertex from b-quark decays strongly suppresses this background.

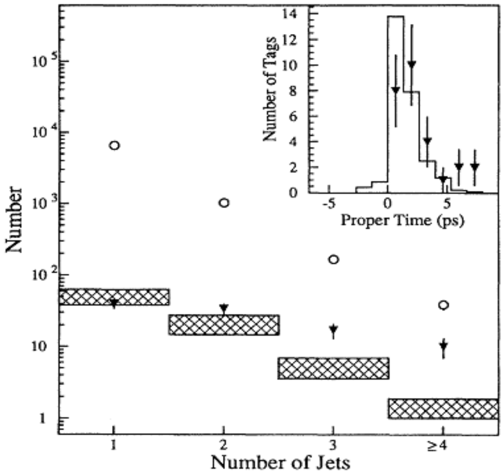
In order to measure the ttbar production cross-section, it is important to understand the b-tagging efficiency. This is done with an inclusive electron sample enriched in b-bbar, where an electron from the b decay recoils against the other b-jet. Then, the efficiency is $\frac{N_{tagged\ e}}{(N_e * F_b)}$, where $N_{tagged\ e}$ is the number of tagged jets that contain an electron, N_e is the number of electron candidates, and F_b is the fraction of electrons that come from semileptonic b-hadron decay. Subsequently, a Monte-Carlo simulation is used to extrapolate this efficiency to generic b decays in ttbar events (which basically differs from single semileptonic b efficienct by a scale factor).

In order to claim top quark discovery, it is also important to study sources of background tags, such as W production in association with b or c-quark pairs or mistags due to track mismeasurements. The mistag rate is evaluated by first measuring the tag rate in inclusive jet data (which contains contributions both from heavy-flavor tags and mistags), and then applying it to W+multijet events to produce a background estimate. Wbb and Wcc rates are explicitly computed from HERWIG MC simulation.

Results[8]

The observed and predicted number of SVX tags in 67 pb^{-1} of data is shown below as a function of the number of jets passing all selection cuts in an event. In the plot on the right, circles represent number of events before tagging, triangles are the observed number of SVX-tagged events, and shaded rectangles show the expected number of tagged events in the absence of top signal.

N_{jet}	Observed events	Observed SVX tags	Background tags expected
1	6578	40	50 ± 12
2	1026	34	21.2 ± 6.5
3	164	17	5.2 ± 1.7
≥4	39	10	1.5 ± 0.4



When N_{jets} is 1 or 2, observed results are consistent with the background prediction (with a small contribution from the top signal in the N_{jets}=2 case). When N_{jets} is 3 and above, there is a clear excess of observed events over the background. Since we expect 4 jets in the semileptonic final state (one from each top and two from one of the W's), data strongly suggests the existence of top decays.

The summary of 3-jet + 4-jet cases above, plus the SLT-tagged case and dileptonic case are presented below:

Channel	SVX	SLT	Dilepton
Observed	27 tags	23 tags	6 events
Expected background	6.7 ± 2.1	15.4 ± 2.0	1.3 ± 0.3
Background probability	2×10^{-5}	6×10^{-2}	3×10^{-3}

The last line shows the probability of corresponding backgrounds fluctuating up to give the observed number of events. Together, they would require a 4.8-sigma deviation from a Gaussian, establishing the existence of the top quark.

Finally, taking SVX and SLT-tagged events with ≥4 jets, one can reconstruct the invariant mass of the ttbar pair (by taking the lepton, neutrino / missing E_T, and 4 hardest jets as ttbar daughters). A chi-square fit is performed to resolve ambiguity in assigning different jets to different W bosons in the event. The dilepton case is excluded from this procedure due to inability to split the missing E_T vector between two neutrinos.

Values of reconstructed top masses can be histogrammed and fitted to a sum of expected backgrounds + signal distribution (signal being parametrized by the top mass value):

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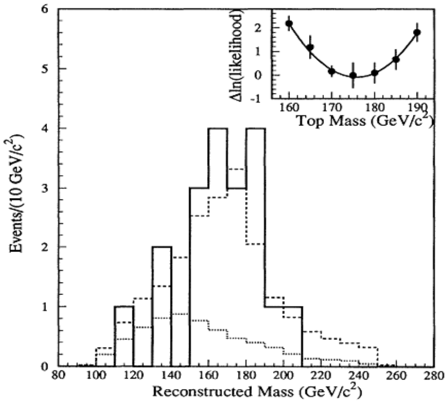
[8] Shamelessly stolen from the «Observation of Top Quark...» PRL



The most likely top mass is 176 ± 8 (stat) ± 10 (syst) GeV. Using integrated luminosity of the sample, acceptance, and actual number of observed events, one also finds the ttbar cross-section to be $6.8^{+3.6}_{-2.4}$ pb.

Future at the LHC

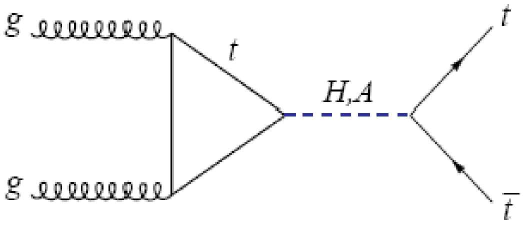
LHC will collide beams with a CM energy of 14 TeV at a design luminosity of 10^{34} cm^{-2} s^{-1}. After one year of operation, corresponding to 100 fb^{-1} of data, it will produce roughly 80 million ttbar pairs[9]. Looking for deviations from SM predictions among the selected ttbar sample opens exciting possibilities in the search for new physics.

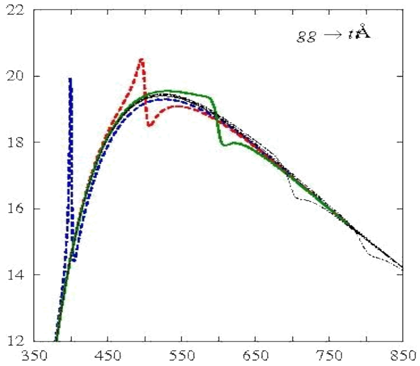
New heavy particles decaying into top

One way to extend the SU(3) x SU(2) x U(1) structure of the Standard Model is to include the second U(1) group with an associated spin-1 gauge boson Z'. If the new gauge coupling is large, the U(1) symmetry must be spontaneously broken at a scale larger than electroweak scale, giving Z' a mass of several hundred GeV[10]. Z' are kinematically allowed to decay into two on-shell top quarks, and their presence will result in a peak in the invariant mass distribution of the top pair. With 30 fb^{-1} of data, such resonance can be discovered for Z' masses up to 500 GeV / 1 TeV / 2 TeV if its cross section x BR (*Z'→ttbar*) = 2560 / 830 / 160 fb.[11]

MSSM Higgs and ttbar invariant mass

Neutral MSSM Higgs (H^0, A^0) decaying to ttbar will interfere with the Standard Model top production diagrams, resulting in new structure in the M_{tt} production spectrum. The effect can reach 6-7%, as can be seen in the figure below showing cross-section (in arbitrary units) versus ttbar invariant mass. Black curve represents pure SM production; blue / red / green include Higgs-mediated contribution for Higgs masses of 400 / 500 / 600 GeV, respectively.[12]





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[9] «TOP PHYSICS AT LHC WITH ttbar EVENTS», F. Hubaut, on behalf of ATLAS and CMS collaborations, 2006

[10] «Z' Gauge Bosons at the Tevatron», M. Carena, A. Daleo etc, 2004

[11] «Top Physics During First LHC runs», Ivo Van Vulpen, 2006

[12] «Top Physics: from LHC to ILC», talk by M. Cobal at Firenze, 2007

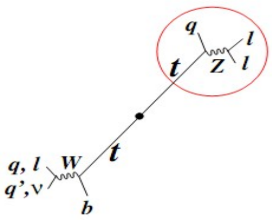
SUSY mimicking top signal

If supersymmetric particles exist at around a TeV, squarks will be abundant at the LHC. During their decay, they can produce energetic jets and leptons, as well as a pair of lightest SUSY particles that escape detection. These events have topology similar to that of standard ttbar production. Studies by the ATLAS SUSY working group suggest that detection is possible after 1 year of ATLAS data. For example, $M_{eff}=E_T^{miss}+\sum_{jets} P_T^{jets}$ is sensitive to the scale of the hard interaction and can reveal differences between data and SM predictions.

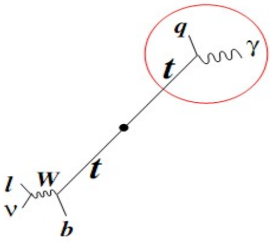
Top quark FCNC decays

FCNC decays are severely suppressed in the Standard Model (and are completely non-existent at the tree level). For example, branching ratios of the following top decays are both on the order of 10^{-13}:

$t \rightarrow qZ$

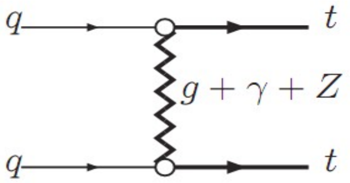


$t \rightarrow q\gamma$



However, presence of new physics can enhance these branching ratios to 10^{-6} / 10^{-7} in case of 2-Higgs model, 10^{-4} / 10^{-5} in some versions of SUSY, and 10^{-2} / 10^{-5} if there are exotic quarks – making the analysis plausible with LHC's abundant production of top quarks.[13] The ($t \rightarrow qZ$) case with W decaying leptonically looks particularly interesting from the point of view of background suppression, thanks to three (!) energetic leptons in the final state, a b-tagged jet, and a single (and thus fully reconstructible) missing E_t vector.

Another manifestation of FCNC in the top sector is same-sign top production through the following diagram:



This process has a clean dileptonic signature, because one would require two same-sign isolated leptons and two hard jets. Requiring at least one jet b-tagged allows to search over a large range of FCNC anomalous couplings with 100 fb^{-1} of data[14].

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[13] «ATLAS sensitivity to top decays beyond the SM», talk by Nuno Castro, 2005

[14] «Top Quark Physics», ATLAS note, hep-ph/003033v1, 2000