Top quark production at hadron colliders
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Chapter 6

Experimental setup

6.1 The Tevatron collider

The Tevatron collider is a proton-antiproton collider situated at Fermilab, near Chicago. The protons and antiprotons are produced and accelerated in a chain of accelerators before being injected into the Tevatron, which is depicted in Figure 6.1. The first step in the chain is the Cockcroft-Walton accelerator, where negatively charged hydrogen ions are accelerated to 750 keV. Bunches of these hydrogen ions are accelerated up to 400 MeV by a linear accelerator (the LINAC). The hydrogen ions are now stripped of their electrons by going through a carbon foil, and are then accelerated up to an energy of 8 GeV by the booster, a circular accelerator. At this energy the protons are put into the Main Injector, which accelerates them either to 150 GeV for injection into the Tevatron, or up to 120 GeV for the production of antiprotons. In the later case, the 120 GeV protons are collided with a nickel target, producing many secondary particles. About one in every $10^5$ protons produces an antiproton among the secondary particles. These antiprotons are collected and stored in the accumulator or antiproton source. When enough antiprotons have been collected, bunches of protons (at 150 GeV) are injected into the Tevatron by the Main Injector, followed by bunches of antiprotons from the accumulator, which are also accelerated up to 150 GeV by the Main Injector. The Tevatron finally accelerates the bunches of protons and antiprotons up to 980 GeV. The beams are made to collide at two interaction points along the Tevatron, where the CDF and DØ experiments are located, resulting in $pp$ collisions at a center of mass energy of 1.96 TeV.

Luminosity

An important collider parameter is the luminosity. The instantaneous luminosity is related to the number of particles that cross the collision region per unit of (transverse)
area per second. The event rate $\frac{dN}{dt}$ of a certain physical process is proportional to the instantaneous luminosity $L$:

$$\frac{dN}{dt} = L \cdot \sigma_{\text{proc}}.$$  \hspace{1cm} (6.1)

This proportionality constant $\sigma_{\text{proc}}$ is called the cross section for that process. This can obviously be measured in an experiment, and for certain well defined processes, the cross section can also be calculated from theory. This makes the cross section a very interesting property of processes, because it can be used to compare theory and experiment. Integrating the previous equation, we see that the total number of events available is determined by the integrated luminosity:

$$\int_{\Delta t} L \, dt = \frac{N}{\sigma_{\text{proc}}}. \hspace{1cm} (6.2)$$

The typical cross sections for processes that we are interested in are expressed in picobarn (pb, 1 barn $\equiv 10^{-28} \text{ m}^2$), so the integrated luminosity is often quoted in units
of inverse cross section, such as pb⁻¹.

6.2 The DØ detector

The DØ detector is a general purpose detector which is optimized for the measurement of electron and jet energies. It consists of several subdetectors, which are positioned more or less symmetrically around the interaction point. Starting at the interaction point, moving outward, the DØ subdetectors are:

- Silicon Microstrip Tracker (SMT);
- Central Fiber Tracker (CFT);
- Central and Forward Preshower (CPS and FPS);
- Calorimeter;
- Muon system.

In addition to these subdetectors that cover more or less all directions, there are the Luminosity Monitors which cover only a small region. A cross section view of the detector is given in Figure 6.2.

The following convention for coordinates is used: The direction of the protons is the positive z direction. The positive x direction points away from the center of the Tevatron ring and thus the positive y direction points up. In hadron colliders, pseudorapidity is normally used instead of the polar angle. The pseudorapidity $\eta$ is defined as $\eta = -\log\tan(\theta/2)$, where $\theta$ is the polar angle (the angle with respect to the proton beam).

6.2.1 Inner tracker

Together, the SMT and the CFT form the inner tracker. They are placed in a 2.0 Tesla solenoidal magnet of about 1.2 meter diameter, which makes it possible to measure the transverse momentum and the charge-sign of charged particles. A cross section view of the inner tracker is given in Figure 6.3.

The SMT is composed of silicon strip detectors arranged in disks and cylinders centered on the beam. Most silicon modules used are double sided, so that all three coordinates of the hit position are measured. The number of hits on a typical track (at low $\eta$) is 4.

The CFT is made of 830 $\mu$m diameter scintillating fibers. They are arranged in 8 layers between radii 20 and 60 cm, each layer containing a sublayer of axial fibers and a sublayer of stereo fibers mounted under a 3 degree angle. Due to the high efficiency
Figure 6.2: Cross sectional view of the DØ detector.
of the light collection, the typical number of measurements on a track should equal its maximum value of 16 (8 points).

### 6.2.2 Calorimeter

The DØ calorimeter is a liquid argon calorimeter. It consists of three parts: the central calorimeter (CC) and two endcap calorimeters (EC). The CC covers the area up to $|\eta|$ of 1.2, and the EC extends the coverage in $|\eta|$ to above 4.0.

Each calorimeter is built up out of the inner electromagnetic (EM) layers, followed by the fine hadronic (FH) layers, and the coarse hadronic (CH) layer furthest from the interaction point. The electromagnetic and fine hadronic layers use uranium absorber plates, while both copper and stainless steel is used in the coarse hadronic. Each layer is split into cells, which have a size of about $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$, except for the third EM layer which has double the granularity. This is the layer in the calorimeter where
electrons are expected to deposit most of their energy. The improved segmentation here gives a better position measurement of the electrons. Beyond $|\eta|$ of 3.2 the overall cell size is increased to $\Delta \eta \times \Delta \phi = 0.2 \times 0.2$, so that the physical size of these cells is still reasonable. The cells are arranged in towers. The arrangement of towers is projective, i.e. the towers point toward the interaction point, but the cells themselves are not. This can clearly be seen in Figure 6.4.

![Figure 6.4: Side view of a quarter of the calorimeter. The lines with numbers at the end are lines of constant $\eta$. This is a picture of the Run I detector, so the depiction of the area inside and between the calorimeters is not correct for Run II.](image)

In between the cryostats of the forward and central calorimeters scintillating material has been placed (covering $1.1 < |\eta| < 1.4$) to improve the energy measurement for particles traversing this area. This subdetector is called the intercryostat detector (ICD).

### 6.2.3 Preshowers

The central and forward preshower detectors are placed before the CC and EC calorimeters. They consist of lead radiators combined with scintillating material. These are
intended to be used for particle identification. As these were not well understood at the time of this analysis, they were not used.

6.2.4 Muon system

The DO muon system consists of several layers of drift chambers and scintillators, combined with a toroidal field solid-iron magnet. A detailed description can be found in [109]. Here it will suffice to say that the system can both identify and measure the momenta of muons out to $|\eta|$ of 2.0.

6.2.5 Luminosity Monitor

The delivered luminosity (which is an important quantity, as we have seen) at DO is measured by looking at the total event rate for $pp$ inelastic interactions. This rate is measured by hodoscopes of scintillation counters mounted close to the beam on the inner surfaces of the endcap calorimeters. As the acceptance of the hodoscopes and the total cross section of $pp$ inelastic interactions (measured by CDF, E710 and E811) are known, the instantaneous luminosity can be calculated (Eq. 6.1).

6.3 Trigger

6.3.1 Trigger system

For the analysis described in this thesis three different parts of the detector system are used for triggering purposes: the calorimeter, the muon system and the luminosity monitors.

Overview

The D0 Run II trigger system is designed to operate in a high rate environment, taking an input rate of 7 MHz (132 ns bunch crossing time, at present the bunch crossing time is 396 ns) and filtering out interesting physics events at the rate of 50 Hz, without incurring more than 5% deadtime. The trigger system is organized in three major levels, the hardware based Level 1 (L1) and Level 2 (L2) and the software based Level 3 (L3). We will describe the state of the trigger as it was used to collect the data used in this analysis.

The hardware L1 trigger takes input from the calorimeter, the muon system and the Luminosity Monitor, and produces as output a list of trigger terms. The L1 Framework (L1FW), employing a series of Field Programmable Gate Arrays (FPGA's), examines these trigger terms and issues a L1 accept when certain criteria are met.
The L2 trigger is comprised of two stages, a preprocessor stage and a global processor stage. In the preprocessor stage, each individual subdetector forms physics objects. In the global processor stage, physics objects from the different preprocessors can be combined to make the final L2 trigger decision.

Once a L2 accept has occurred, digitized data is loaded onto the single board computers (SBC) that sit in the front-end crates. Data from the SBCs are then transferred to the L3 farms where sophisticated filter codes are run to identify interesting events. At this level close-to-offline reconstruction of physics objects like electrons, muons, jets, missing $E_T$ is performed. Events satisfying L3 filter requirements are then transferred to tape for offline reconstruction.

Calorimeter

At L1, calorimeter triggering is based on towers. The size of these trigger towers is $0.2 \times 0.2$ in $\eta \times \phi$ space. Both the energy deposited in the EM layers of the tower and the total energy deposited in the tower (excluding the coarse hadronic layers) is available. Triggers can be set to require a number of both EM and total towers above certain thresholds in $E_T$. An example is $\text{CEM}(1,10)\text{CJT}(2,5)^1$. This requires an EM tower with $E_T \geq 10$ GeV, and two total (jet) towers above 5 GeV. It should be noted that the EM and total towers are not exclusive, so the EM tower above 10 GeV will also count as one of the total towers.

At L2, trigger decisions are also based on towers. L2 receives from L1 all trigger towers, both the EM $E_T$ and total $E_T$. L1 also sends two seed masks (one for EM and one for total), which have bits for every trigger tower. The EM bit in the seed mask is set to 1 if the trigger tower has at least 1 GeV of EM $E_T$. The total bit is set to 1 if the trigger tower has at least 2 GeV total $E_T$. The L2 calorimeter algorithms will only attempt to find jets or electrons around trigger towers for which the seed bit is set. Electromagnetic (EM) and jet objects are handled in different ways.

For every EM seed tower, the neighbor with the largest EM $E_T$ deposit is found, out of the 4 neighboring towers. The seed tower and its largest neighbor form the L2 electron. The total $E_T$ of the electron is the sum of the energy deposited in the EM layers of the two towers. The EM fraction of the L2 electron is the sum of the EM $E_T$'s of the two trigger towers divided by the sum of the total $E_T$'s of the two trigger towers. Trigger requirements can be placed on both the $E_T$ and the EM fraction of the L2 electrons.

For total (jet) seed towers all energy deposited in the $3 \times 3$ or $5 \times 5$ tower region\(^2\) around the seed tower is added, and this is defined as a L2 jet. The $E_T$ of the L2 jet is the sum of the total transverse energy deposited in these 9 or 25 towers. Trigger

\(^1\)The C in CEM and CJT indicates that this is a calorimeter trigger term.

\(^2\)The algorithm was changed during the period that the data used in this analysis was taken.
requirements are set on the number and $E_T$ of the L2 jets. Because of the algorithm used, all L2 electrons that pass a certain $E_T$ requirement will also pass as a L2 jet of the same $E_T$.

Both L1 and L2 use a readout of the calorimeter based on towers ("trigger readout") which is separate from the cell based readout ("precision readout") which is used for L3 and offline reconstruction.

At L3, the full cell information of the calorimeter is available. Again, L3 electrons and jets are treated differently. L3 electrons start out using a narrow cone (0.4) jet algorithm (based on towers). This defines the electron cluster. In the next step, only cells within a $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$ of 0.25 around the axis of this cluster are used to define the electron object. Trigger requirements can be placed on the $E_T$ (which is the sum over all layers), EM fraction and width of the energy deposit in each of the EM layers. The width in EM layer $i$ is defined as

$$W_i = \frac{\sum_i E_i \sqrt{\Delta \phi_i^2 + \Delta \eta_i^2}}{\sum_i E_i},$$

(6.3)

with $i$ running over cells of the cluster in the $i^{th}$ EM layer, and $\Delta \phi$ and $\Delta \eta$ the distance (in $\phi$ and $\eta$) between the cell and the cluster axis.

L3 jets are found by using a cone algorithm (based on towers) with a cone size of 0.7. No splitting and merging of jets is performed. Again, because of the algorithms used, every electron above a certain $E_T$ threshold will also show up as a jet above that same threshold.

Muon

At L1, the trigger looks for hit coincidences between different layers of the muon scintillators and drift chambers. A coincidence with hits consistent with a $p\bar{p}$ interaction in the Luminosity Monitor can also be required. At L2, the drift chamber information is combined with the scintillator hits to do a full reconstruction of the muon. The same thing is basically done in the L3 trigger, only with higher precision.

For this analysis, muon based triggers were only used to define samples (for trigger studies) that are unbiased with respect to calorimeter triggers.

6.3.2 Signal trigger

The $t\bar{t}$ events that we are interested in for this analysis have the following event signature (see Section 8.1): one isolated electron and four or more jets. The signal trigger used to select these events relies solely on calorimeter information at all three levels of the trigger system. In designing this trigger, we have noted two important points: the single electron trigger rate is very high and runs the risk of being prescaled at high
luminosity running, and we want to maximize efficiency by avoiding an overly stringent selection on the electron. We also note that, since there are several jets in signal events, it is efficient to require at least one jet. Therefore, at all three trigger levels, we select one moderate $p_T$ electron and one jet.

The used trigger is called EM15.2JT15, and the requirements at each level of the trigger are:

- **L1:**
  - one L1 electron with $E_T \geq 10 \text{ GeV}$ (CEM(1,10))
  - one L1 jet with $E_T \geq 5 \text{ GeV}$ (CJT(1,5));

- **L2:**
  - one L2 electron with $E_T \geq 10 \text{ GeV}$, EM fraction $\geq 0.85$ (L2EM(0.85,10))
  - one L2 jet with $E_T \geq 10 \text{ GeV}$;

- **L3:**
  - one L3 electron with $E_T \geq 15 \text{ GeV}$, EM fraction $\geq 0.90$ and shower shape cuts of $W_1 < 0.09$, $W_2 < 0.08$ and $W_3 < 0.05$ (L3Ele(SH,15))
  - one L3 jet with $E_T \geq 15 \text{ GeV}$.

### 6.3.3 Single object trigger efficiencies

Trigger efficiencies are measured from data. To obtain an event efficiency in this situation for signal events, we measure the per-electron and per-jet efficiencies and fold them into the signal simulation to measure a probability that an individual event would fire the trigger.

We measure efficiencies for single objects with respect to $p_T$ and $\eta$ for each trigger term. An independent control sample, unbiased with respect to the trigger under test ("test trigger"), is defined. In such an unbiased sample, offline objects are identified, yielding the unbiased reference sample with a certain $p_T$- or $\eta$-spectrum. The fraction of these events, for which the test trigger has fired, is a measure of the trigger efficiency with respect to the offline object $p_T$ or $\eta$. The resulting dependence of the efficiency versus $p_T$ is also termed 'turn-on curve'.

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3It has been noted that at all levels of the trigger, electrons above a certain $p_T$ threshold also show up as a jet above that same threshold. We will not list those objects here. When one jet is required, we mean one jet in addition to the electron.
EM objects

The electron trigger efficiencies are measured on events which were triggered by the muon system and which have an offline reconstructed electron. All offline electron energies are corrected with the EM energy corrections.

The L1 turn-on curve for CEM(1,10) is shown in Figure 6.5(a). The trigger efficiency is not 50% at 10 GeV, indicating that the gain of the L1 energy readout is low. The trigger reaches saturation at approximately twice the threshold. Figure 6.5(b) shows the efficiency as a function of detector\(^d\) \(\eta\) for electrons that have \(p_T > 20\) GeV. There is low statistics around \(|\eta_D| = 1.3\) because hardly any offline electrons are reconstructed in this region. The EM layers don’t have complete coverage in this ICD region, resulting in very low efficiency for electrons to pass the offline EM fraction requirement.

![Figure 6.5](image)

Figure 6.5: Efficiency for an electron to fire the CEM(1,10) trigger term, as a function of offline electron \(p_T\) (a) and detector \(\eta\) (b).

The Level 2 electron efficiency for L2EM(0.85,10) is 100 % for electrons with an offline \(p_T > 10\) GeV that have already passed L1 CEM(1,10).

\(^d\)Detector \(\eta\) (\(\eta_D\)) is the \(\eta\) calculated from the electron cluster position (see Chapter 7) and (0,0,0). Detector \(\eta\) is thus directly correlated with the position of the cluster in the calorimeter. This is different from the usual \(\eta\) (also called physics \(\eta\)), which is taken from the direction of the track that has been associated with the electron.
The Level 3 electron efficiency for L3Ele(SH,15) is measured on the Mark&Pass events for the EM15.2JT15 trigger. These are events that passed the L1 and L2 requirements of the trigger, but where no trigger requirements were made at L3. Thus this efficiency is measured on objects that have passed the L1 and L2 electron requirements, and look like electrons offline. In Figure 6.6(a) its turn-on curve is shown, for events that have already passed the L1 & L2 requirements discussed above. Figure 6.6(b) shows its efficiency as a function of detector $\eta$ for electrons that have $p_T > 20$ GeV.

Figure 6.6: Efficiency for an electron to fire the L3Ele(SH,15) trigger term, as a function of offline electron $p_T$ (a) and detector $\eta$ (b). This is for electrons that have already passed the L1 and L2 electron requirements.

**Jet objects**

The Level 1 efficiency for jets to fire the CJT(1,5) term is shown in Figure 6.7 as a function of the reconstructed jet $p_T$ and detector $\eta$. All offline jet energies and momenta are corrected with the Jet Energy Scale, which is described in Chapter 7. There are dips in the efficiency in the ICD region (around $|\eta_D| = 1.1$) because the gain of the trigger readout is too low in this region. The efficiency falls off rapidly for $|\eta_D| > 2.4$ because the trigger readout was not instrumented in that region.

The efficiency for a jet that has passed L1 CJT(1,5) to fire the L2 jet trigger with a threshold of 10 GeV is shown in Figure 6.8(a) as a function of the reconstructed jet $p_T$. 
Figure 6.7: Efficiency for a jet to fire the CJT(1,5) trigger term, as a function of offline jet \( p_T \) (a) and detector \( \eta \) (b). The plot as a function of detector \( \eta \) is for jets with an offline \( p_T > 30 \) GeV.

The Level 3 jet efficiency as a function of reconstructed jet \( p_T \) is shown in Figure 6.8(b) for a Level 3 jet threshold of 15 GeV. This is for jets that have already passed L1 CJT(1,5) and the L2 jet trigger at 10 GeV.

No parameterization was used for the jet turn-on curves. The full \( \eta \) and \( p_T \) dependent trigger curve is folded with the simulated MC jets distribution in order to obtain the jet part of the trigger efficiency for \( tt \) events.

### 6.3.4 EM15.2JT15 efficiency

For the analysis, we require that the electron is in the Central Calorimeter (see Chapter 8). Thus in this section where the final trigger efficiency is derived, trigger turn-on curves are used where the electron was required to be in the CC.

The turn-on curves for the EM and the jet terms for the three levels of trigger combined can be observed in Figures 6.9(a) and 6.9(b) respectively. For the electrons, we take only the \( p_T \) dependence into account, because there is not enough statistics to use the full \( \eta \) and \( p_T \) dependence. It should be noted that the \( \eta \) dependence is rather flat in the region used (\( |\eta_D| < 1.1 \)). The parametrization used for the \( p_T \) dependence is shown in the figure. For the jets, we take the full \( \eta \) and \( p_T \) dependence of the trigger...
Figure 6.8: The efficiency for a jet to fire the L2 (a) and L3 (b) jet trigger, as a function of offline jet $p_T$.

efficiency into account, which is shown in Figure 6.10\(^5\). To obtain the trigger efficiency for the $t\bar{t}$ events, we assume that the trigger terms factorize:

$$
\varepsilon_{t\bar{t}} = \varepsilon_{EM} \times \left[1 - \prod_{jets}(1 - \varepsilon_{jet})\right].
$$

(6.4)

When we fold the measured single object trigger efficiencies into the $t\bar{t}$ signal MC (using the above equation), we find a total trigger efficiency of $92 \pm 1\%$.

The assumption of factorization could break down in the case where a jet fires part of the electron trigger. We studied the effect where the jet fires the L1×L2 EM requirement, and the electron fires the L3 EM requirement. This could happen if the electron goes through a L1 trigger tower that is dead. By looking at the trigger turn-on curve for jets to fire the EM trigger (see Figure 6.11) it was shown that at most 50% of the electron L1×L2 inefficiency can be recovered by this scenario. Therefore we will quote a 2% systematic uncertainty due to factorization. Thus the final trigger efficiency used is $92 \pm 1 \pm 2\%$. The number given is the efficiency corresponding to those events passing all selection criteria and cuts.

\(^5\)In this figure we can again see the low gain in the ICD region.
Figure 6.9: The combined $L1 \times L2 \times L3$ trigger efficiency for electrons (a) and jets (b), as a function of offline $p_T$.

### 6.3.5 Other triggers

In addition to the EM15.2JT15 trigger other triggers were used. Examples of these are a single electron trigger, which was used in the analysis described in Chapter 8 to estimate the bias on the number of jets in an event introduced by requiring a jet in the trigger, and a two electron trigger used to define $Z \rightarrow ee$ samples for electron identification studies described in Chapter 7. Other examples are the muon based triggers, which were used to select unbiased samples for calorimeter trigger studies. The efficiency for these triggers was not derived, because the studies that they were used for do not depend on the trigger efficiency.

### 6.4 Data processing

After having passed the L3 trigger, events are written to tape in the raw data format. These events are later reconstructed on a dedicated farm of computers by the DØ reconstruction program (d0reco). This program takes the raw data from the detector and reconstructs physics objects (electrons, tracks, jets), writing out these objects into a mini-DST, the so-called Thumbnail format. The next step is to select interesting events from this full set of events, based on simple requirements on the physics objects.
Figure 6.10: The combined L1×L2×L3 jet trigger efficiency as a function of offline $p_T$ and $\eta$.

Figure 6.11: The efficiency for jets to fire the L1, L2 and L1×L2 EM trigger as a function of offline jet $p_T$. The shape of the L2 efficiency is due to the EM fraction cut at L2.
or by requiring that the events passed a certain trigger. This process is called skimming. The skimmed samples (which are still in Thumbnail format) are now processed through a program called top.analyze, which applies all the required energy corrections to the objects (see the next chapter), applies most of the object identification criteria, and does an even tighter selection of events. For the events selected in the top.analyze stage, a root tuple is written out containing all the information about the physics objects in the event. The final stage is a set of root macros that extracts the results from these root tuples.

6.5 Signal and background simulation

Apart from the actual data events, we also need simulated events. These events are used for estimating acceptances and certain efficiencies.

We simulated the $tt$ signal and the $W+\text{jets}$ background processes using ALPGEN 1.1 [110] for calculating the matrix elements, and PYTHIA [13] to perform the parton showering and hadronization of the ALPGEN partons. PYTHIA was also used to generate simulated $Z \to ee$ events. The output of PYTHIA is then processed through d0gstar (a GEANT simulation of the D0 detector). This step propagates the PYTHIA particles through a computer model of the detector, calculating how much energy the particles deposit in the material they traverse.

The next step in the simulation, d0sim, models the response of active material in the detector to these energy deposits. It also models the electronics that reads out these responses. In addition, it adds minimum bias events to the events. This models the fact that during any bunch crossing, except for the hard collision, there might also be one or more soft proton-antiproton collisions. The number of added minimum bias events is taken from a Poisson distribution with a mean of 0.8 events, which corresponds to the rate expected for the luminosity at which the data used for the analysis in this thesis was taken. Finally, d0sim writes out a raw data format that is equivalent to the raw data format that comes from the detector. These simulated events can thus now be processed exactly the same as real data events.

Simulated events that are produced in this way are called Monte Carlo (MC) events.