ABSTRACT

MEASUREMENT OF $\sigma(p\bar{p} \rightarrow t\bar{t})$ IN THE $\tau + jets$ CHANNEL BY THE D0 EXPERIMENT AT RUN II OF THE TEVATRON COLLIDER

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Since its discovery at the Fermilab Tevatron collider in 1995, the top quark has been one of the most intensely studied topics in High Energy Physics. Investigations of its production rate and properties permit a variety of tests of the Standard Model (SM). We report on a new measurement of $p\bar{p} \rightarrow t\bar{t}$ production cross section at $\sqrt{s} = 1.96$ TeV using 5069.80 pb$^{-1}$ of data collected with the D0 detector between 2002 and 2010.

Our objective is to measure the final state where the $W$ boson from one of the top quarks decays into a $\tau$ lepton and its associated neutrino, while the other $W$ boson decays into a quark-antiquark pair. The $\tau$ being the heaviest lepton, it decays before reaching any detector element, and must be reconstructed from its decay products. $W \rightarrow \tau\nu \rightarrow \ell\nu\nu\nu$ ($\ell = e, \mu$) are difficult to distinguish from $W \rightarrow \ell\nu$, especially in the busy final state of a $t\bar{t}$ event. Therefore, we focus on events where the $\tau$ decays to one or more charged hadrons, zero or more neutral hadrons and a neutrino, which accounts for $\sim 65\%$ of all $\tau$ decays. The observable signature thus consists of a narrow calorimeter shower with associated track(s) characteristic of a hadronic tau decay, four or more jets, of which two are initiated by $b$ quarks accompanying the $W$’s in the top quark decays, and a large net missing momentum in the transverse plane due to the energetic neutrino-antineutrino pair that leave no trace in the detector media. The measured cross section is:

$$\sigma(t\bar{t}) = 8.63 \pm 0.90\text{ (stat)} \pm 0.52\text{ (lumi)} \text{ pb}.$$
MEASUREMENT OF $\sigma(p\bar{p} \rightarrow t\bar{t})$ IN THE $\tau + jets$ CHANNEL BY THE D0 EXPERIMENT AT RUN II OF THE TEVATRON COLLIDER

A THESIS SUBMITTED TO THE GRADUATE SCHOOL IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE MASTER OF SCIENCE

BY

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DEPARTMENT OF PHYSICS

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CHAPTER 1
INTRODUCTION

This thesis presents a new measurement of \( p\bar{p} \rightarrow t\bar{t}X \) production cross section at \( \sqrt{s} = 1.96 \) TeV using 5069.80 pb\(^{-1}\) of data collected with the D0 detector between 2002 and 2010 and the final state where the \( W \) boson from one of the top quarks decays into a \( \tau \) lepton and its associated neutrino, while the other \( W \) boson decays into a quark-antiquark pair. We selected those events in which the \( \tau \) lepton subsequently decays hadronically to one or more charged hadrons, zero or more neutral hadrons and a tau neutrino.

1.1 The Standard Model of Particle Physics

The Standard Model (SM) [1, 2] is the quantum field theory of subatomic particles and their interactions. In the SM particles are divided into fermions and gauge bosons. Fermions have spin-1/2, following Fermi-Dirac statistics and correspond to the matter content of the SM. Fermions themselves are subdivided into quarks and leptons, with each group ordered in three families or generations. To the contrary of leptons, quarks are not found free in nature. They form bound states of either three quarks (barions) or a quark-antiquark pair (mesons). Barions and mesons are generically called hadrons. Additionally, to each fermion in the SM there is a correspondent antifermion. All fermions are shown in Table 1.1.

Gauge bosons are spin-1 particles, following Bose-Einstein, statistics and are the mediators of the interactions among fermions. SM gauge bosons are summarized in Table 1.2 below.

The interactions in the SM are the electromagnetic, weak nuclear and strong nuclear forces. The SM is based on the gauge symmetry \( SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \), where \( SU(N)_C \) means special unitary group of degree \( N \); \( C \) and \( Y \) stands respectively for color charge and weak hypercharge.
quantum numbers and $L$ means that the symmetry only applies to left-handed fermions. The gauge bosons in the SM are the photon ($\gamma$), which carries the electromagnetic force, eight gluons ($g$), that mediate the strong nuclear force and three weak bosons ($W^\pm$ and $Z$) as the mediators of the weak nuclear force.

### Table 1.1: The known quarks and leptons.

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge $2/3$</td>
<td>Charge $-1/3$</td>
</tr>
<tr>
<td>$u$</td>
<td>$0.001–0.005$</td>
</tr>
<tr>
<td>$c$</td>
<td>$1.15–1.35$</td>
</tr>
<tr>
<td>$t$</td>
<td>$172.5 \pm 2.7$</td>
</tr>
</tbody>
</table>

### Table 1.2: Gauge bosons

<table>
<thead>
<tr>
<th>Boson</th>
<th>Charge</th>
<th>Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>photon ($\gamma$)</td>
<td>0</td>
<td>massless</td>
</tr>
<tr>
<td>gluon ($g$)</td>
<td>0</td>
<td>massless</td>
</tr>
<tr>
<td>$W^\pm$</td>
<td>$\pm 1$</td>
<td>$80.40 \pm 0.02$</td>
</tr>
<tr>
<td>$Z$</td>
<td>0</td>
<td>$91.19 \pm 0.01$</td>
</tr>
</tbody>
</table>

Although gravity is one of the fundamental forces in nature, its effects can be safely neglected in all particle experiments at present energies. Since there is no consistent quantum theory of gravity as to-date it is not described in the SM framework. SM forces are summarized in Table 1.3.

### Table 1.3: Fundamental interactions

<table>
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<th>Interaction</th>
<th>Gauge boson</th>
<th>Range</th>
<th>Acts on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational</td>
<td>graviton(?)</td>
<td>$\infty$</td>
<td>all particles</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>photon $\gamma$</td>
<td>$\infty$</td>
<td>charged particles</td>
</tr>
<tr>
<td>Weak</td>
<td>$W^\pm$ and $Z$</td>
<td>$&lt; 10^{-18}$ m</td>
<td>leptons and quarks</td>
</tr>
<tr>
<td>Strong</td>
<td>gluons $g$</td>
<td>$\approx 10^{-15}$ m</td>
<td>hadrons</td>
</tr>
</tbody>
</table>

The way particles and interaction are organized in the SM reflects the way particles interact. Besides electric charge and weak isospin, quarks carry an extra quantum number named color, which represents the strong interaction charge. Thus, quarks experience electromagnetic, weak nuclear
and strong nuclear. The remaining six fermions - leptons - are also found in six different kinds. Three of them have negative charge and weak isospin, then they experience both electromagnetic and weak nuclear forces. The remaining three are neutral and are named neutrinos and only experience the weak nuclear force. For many years neutrinos were thought to be massless until experiments showed they indeed have small masses. However, at high energies the assumption they are massless still is a very good approximation.

All SM bosons would be massless if all the symmetries were intact. But while $U(1)$ and $SU(3)_C$ symmetries are exact, the $SU(2)_L$ symmetry is spontaneously broken in nature. It is postulated that the $SU(2)_L$ symmetry is broken by a complex scalar (spin-0) field that is a $SU(2)_L$ doublet, and has a non-zero expectation value in the lowest energy state of nature. After three of the four degrees of freedom of such a Higgs field is expended in giving mass to the $W$ and $Z$ bosons and leaving the photon and gluons massless, one is left to manifest itself as a physical particle, called the Higgs boson. This Higgs particle, which is electrically neutral but expected to weight more than 115 GeV, is a subject of intense ongoing search \cite{3}. In the SM fermions also acquire mass by interacting with the Higgs field.

The SM postulates only one complex Higgs doublet, which is the simplest scenario. However, the Higgs sector is not constrained to be so simple. Indeed, a richer Higgs sector is required in a number of theories, including supersymmetric models, that seek to extend the SM. In such theories, additional Higgs particles arise as a result of the electroweak symmetry breaking. Some of these are electrically charged. Since there is no fundamental charged boson beside the $W$ in the SM, experimental observation of any charged boson will signal new physics.

Although up to date all SM predictions, such as the $W$ and $Z$ bosons, the charm and top quarks and the gluon have been experimentally confirmed with very high precision, the model is regarded as unsatisfactory to provide a complete explanation of nature. The SM has serious limitations on both experimental and theoretical sides. Some experimental observations do not find an explanation within the model, for example the matter-antimatter asymmetry, dark matter and dark energy, and gravity. On the theoretical side, the model fails in providing an explanation for the particle quantum numbers, the large (19) number of arbitrary parameters, the hierarchy problem and also does not have a quantum theory of gravity. All these facts lead to the belief that there must exist physics beyond the standard model. Search for new physics is one of the most
important topics is experimental research nowadays. And the top quark plays a central role in such searches.

1.1.1 The Top Quark

Since its discovery in 1995 at the Tevatron accelerator at Fermilab, the top quark has been known as the heaviest elementary particle [4, 5]. This makes it a special research topic in high energy physics as a probe for any beyond-SM physics. As a massive fundamental particle its short lifetime ($\approx 5 \times 10^{-25}$s) prevents it from forming hadrons, therefore allowing the study of a bare quark system. Its large mass suggests a stronger coupling to the Higgs boson, thus making the top quark a preferable tool for the study of electroweak symmetry breaking.

Precision measurements of top properties and production can set constraints on Higgs boson production or set limits on possible extensions of the SM.

**Production:** Currently, the world average mass of the top quark is $172.6 \pm 0.8\text{(stat)} \pm 1.1\text{(sys)}$ GeV [6]. Until the recent turn-on of the Large Hadron Collider (LHC) at CERN, in Geneva, only Fermilab’s Tevatron was capable of producing the top quark. Besides strong interaction production, top quarks are also produced singly via electroweak interactions, but at a lower rate than pair production, and are much harder to extract from background noise. Therefore, top pair production is better suited for most decay properties studies of the top quark.

For the strong interaction production, the leading order Feynman diagrams are shown in Fig. 1.1 [7]. The upper diagram shows the quark-antiquark annihilation and the three bottom diagrams are gluon-gluon processes.

We can write the differential cross section of the scattering of two hadrons $A$ and $B$ resulting in a final state $X$:

$$d\sigma_{AB \rightarrow X} = \sum_{a,b} \int_0^1 dx_a \int_0^1 dx_b d\hat{\sigma}(ab \rightarrow X) f_a^A(x_a) f_b^B(x_b),$$  \hspace{1cm} (1.1)
where here \( x_a \) and \( x_b \) are the momentum fractions and \( f^A_a(x_a) \) and \( f^B_b(x_b) \) the parton distribution functions. At the Tevatron the initial state consists of a proton and an antiproton, thus, by taking into account all the parton-level processes that contribute to the top-antitop production we integrate Eq. 1.1 to get:

\[
\frac{d\sigma}{dt\bar{t}}(\bar{p}p \rightarrow t\bar{t}) = \int_{4m_t^2}^{s} d\hat{s} \int_{\hat{s}/s}^{1} dx \frac{1}{xs} [\hat{\sigma}(q\bar{q} \rightarrow t\bar{t}) [u(x)u(\hat{s}/xs) + d(x)d(\hat{s}/xs) + \bar{u}(x)\bar{u}(\hat{s}/xs)]]
\]

\[
+ \hat{d}(x)d(\hat{s}/xs) + 2s(x)s(\hat{s}/xs) + \hat{\sigma}(g\bar{g} \rightarrow t\bar{t})g(\hat{s}/xs)
\]

(1.2)

where we used the fact that \( x_b = \hat{s}/x_a s \) to perform the integration. The minimum energy required to produce a top-antitop pair is \( s = 4m_t^2 \). As \( x \approx 2m_t/\sqrt{s} \), at the Tevatron \( x \approx 0.1765 \).

This means that the largest contribution to the cross section comes from valence quarks. Both gluon-gluon and sea quarks contributions are highly suppressed due to their small \( x \); namely, they do not have enough energy to produce a top-antitop pair.

At the LHC top-antitop pairs are produced from a initial state of two colliding protons. Thus, by performing the same integration of Eq. 1.1 we find:

\[
\frac{d\sigma}{dp} (pp \rightarrow t\bar{t}) = \int_{4m_t^2}^{s} d\hat{s} \int_{\hat{s}/s}^{1} dx \frac{1}{xs} [\hat{\sigma}(q\bar{q} \rightarrow t\bar{t}) [2u(x)u(\hat{s}/xs) + 2d(x)d(\hat{s}/xs) + 2s(x)s(\hat{s}/xs)]]
\]

\[
+ \hat{\sigma}(g\bar{g} \rightarrow t\bar{t})g(\hat{s}/xs)
\]

(1.3)
where the factor 2 means that each proton can contribute either the quark or the antiquark. In the case of the LHC \( x = 0.0247 \), which means that now gluon-gluon fusion processes highly dominate top-antitop production over quark-antiquark ones.

**Top Decay:** In the SM mass eigenstates of quark fields are different from flavor eigenstates of the weak interaction. If this was not true no transition between different quark generations would be observed. Flavor eigenstates are viewed as a rotation of the mass eigenstates:

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} =
\begin{pmatrix}
  V_{ud}V_{us}V_{ub} \\
  V_{cd}V_{cs}V_{cb} \\
  V_{td}V_{ts}V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

(1.4)

The unitary matrix \( V \) is called the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The probability that a quark of type \( i \) decays into a quark of type \( j \) is given by \( |V_{ij}|^2 \). All matrix elements are measured in experiments involving decays via weak interaction. In the specific case of top decays, \( |V_{tb}| = 0.999100^{+0.000034}_{-0.000004} \) [8], meaning that the top quark decays almost exclusively into a \( W \) boson and a \( b \) quark.

In some models, like the Minimal Supersymmetric Model (MSSM), the top quark is expected to decay into a charged Higgs boson rather than into a \( W \) boson [9].

Different final states of a top decay are classified according to the subsequent decay of the \( W \). In this sense we identify three possible final states:

- \( t\bar{t} \rightarrow W^+bW^-b \rightarrow q_1q_2bq_3q_4\bar{b} \) ("all-jets" channel)
- \( t\bar{t} \rightarrow W^+bW^-b \rightarrow l\bar{\nu}bq_1q_2\bar{b} \) or \( q_1q_2b\nu l\bar{\nu} \) ("dilepton" channel)
- \( t\bar{t} \rightarrow W^+bW^-b \rightarrow l_1\nu b l_2\bar{\nu} \) ("lepton+jets" channel)

In Fig. 1.2 the “pie chart” shows all top decays and their respective branching ratios. The present work is the third measurement of the \( t\bar{t} \) cross section in the \( \tau + jets \) channel performed with the D0 detector.

Previous results using p14 and p17 data are summarized in Table 1.4 [10, 11].
Measurement of the process $t \to W b \to \tau \nu b$ is an important tool for probing physics beyond the SM. For instance, the MSSM requires the presence of a pair of charged Higgs bosons $H^\pm$. If the decay $t \to H^+ b$ is kinematically permitted (i.e., if $m_{H^\pm} < m_t - m_b$), then it could compete with $t \to W^+ b$, which essentially the only decay allowed in the SM. Since the Higgs-fermion coupling is proportional to the latter’s mass, $H^+ \to \tau \nu$ would be preferred to $H^+ \to e \nu$ and $H^+ \to \mu \nu$, thus violating the lepton universality characteristic of $W$ decays. More generally, measurement of $\sigma(t\bar{t} \to \tau X)$ is relevant to any direct search of flavor- or mass-dependent coupling of the top quark. Thus, any significant deviation in the cross section from what the SM predicts could be a signal of new physics.

The objective in this thesis is to measure the final state where the $W$ boson from one of the top quarks decays into a $\tau$ lepton and its associated neutrino, while the other $W$ boson decays into a quark-antiquark pair. The $\tau$ being the heaviest lepton, it decays before reaching any detector.

Table 1.4: Previous measurements of $\sigma(t\bar{t})$ using the $\tau + jets$ channel. Only the statistical uncertainties are shown.

<table>
<thead>
<tr>
<th>Data Set</th>
<th>$\int L dt$ (pb$^{-1}$)</th>
<th>Measured $\sigma(t\bar{t})$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p14</td>
<td>349.0</td>
<td>5.05 $^{+4.31}_{-3.46}$</td>
</tr>
<tr>
<td>p17</td>
<td>974.2</td>
<td>6.90 $^{+1.20}_{-1.20}$</td>
</tr>
</tbody>
</table>
element, and must be reconstructed from its decay products. $W \to \tau \nu \to \ell \nu \nu \nu$ ($\ell = e, \mu$) are difficult to distinguish from $W \to \ell \nu$, especially in the busy final state of a $t\bar{t}$ event. Therefore, we focus on events where the $\tau$ decays to one or more charged hadrons, zero or more neutral hadrons and a neutrino, which accounts for $\approx 65\%$ of all $\tau$ decays. When searching for events where a $\tau$ decays hadronically, the main source of background becomes the instrumental, or “fake,” QCD multijet events, where one of the jets is misreconstructed as a $\tau$, while measurements fluctuations give rise to $E_T$. In both cases, the reconstructed $\tau$ candidate can be either genuine or fake. The signal and physics (electroweak) background are modelled by Monte Carlo (MC), while the instrumental (QCD) background is estimated from data. Single top and diboson production are small enough to be ignored. It should be noted that the $\nu$ in the $\tau$ decay does not contribute to the measured energy. As a result, unlike $e$’s and $\mu$’s, the “visible” fraction of a $\tau$’s momentum is significantly less than 1. The presence of another high-$p_T$ neutrino in the event prevents us from resolving either one on an event-by-event basis. Thus, our signal is characterized by 4 high-$p_T$ jets, two of which arise from $b$ quarks, one $\tau$, and large $E_T$.

The main improvements over the previous p17 analysis stem from the use of

- 4 times more data (Run 2b1, Run 2b2),
- a new set of multijet triggers resulting in an increase of $\approx 10\%$ in the signal efficiency,
- vertex-confirmed jets,
- $\tau$ energy scale,
- new tag-rate functions (TRF) for $b$ jets, and
- extensive optimization of the event neural network.
CHAPTER 2
THE TEVATRON COLLIDER AND THE D0 DETECTOR

This chapter describes the Tevatron Accelerator at Fermilab and its acceleration phases. Until its recent shutdown the Tevatron collider complex at Fermi National Accelerator Laboratory was for over 20 years the highest energy hadron particle collider on the planet. It accelerated proton and antiproton beams to an energy of 0.98 TeV each and collided them at two interaction points, D0 and CDF, two complex multi-purpose particle detectors located at these points study the outcome of these collisions. The analysis presented in this dissertation was performed with the data collected by the D0 experiment.

2.1 The Coordinate System

The coordinate system adopted is the cylindrical \((\rho, \phi, z)\), with its origin matching the center of the detector, with the \(z\) axis pointing in the same direction as the proton beam and the \(y\) axis pointing to the top of the detector. Sometimes it is more convenient to use the spherical coordinate system, where the polar angle \(\theta\) is the angle between the particles coming out from the collision and the direction of the beam and the azimuthal angle \(\phi\) is measured in the plane perpendicular to the direction of the beam as shown in Fig 2.1.

Figure 2.1: Coordinate System.
The rapidity $y$ of a particle with energy $E$ and longitudinal momentum $P_L$ is defined as

$$y = \frac{1}{2} \log \left( \frac{E + P_L}{E - P_L} \right).$$

(2.1)

At the limit of very high energies, where the energy of a particle is much greater than its mass ($E \gg m$), we have $y \approx \eta$, where $\eta$ is the pseudo-rapidity of the particle:

$$\eta = -\ln \left| \tan \frac{\theta}{2} \right|.$$  

(2.2)

The pseudo-rapidity is measured from a perpendicular direction with respect to the $p\bar{p}$ ($\phi = \pi/2$) axis in the opposite direction to the angle $\theta$, and it is commonly used to indicate particular regions of the detector.

In high energy particle collisions, another important variable is the so-called transverse momentum $p_T$, which is the projection of the vector momentum onto the plane perpendicular to the beam axis:

$$p_T = p \sin \theta.$$  

(2.3)

The same reasoning allows us to define what is called is transverse energy $E_T$ of a particle:

$$E_T = \sqrt{p_T^2 + m^2}.$$  

(2.4)
2.2 Luminosity and Cross section

The luminosity $\mathcal{L}$ is a quality factor of a collider reflecting the size and the density of the beam as well as the frequency of collisions, and it determines the observed rate of interactions of a specific type by knowing the cross section $\sigma$ of the process by

$$\frac{dN}{dt} = \sigma \mathcal{L}$$  \hspace{1cm} (2.5)

Luminosity can be expressed in terms of the number of protons and antiprotons in a bunch ($N_P$), the number of bunches ($N_B$), frequency of collisions ($f$) and the beam size at the interaction point ($\sigma_p$) as

$$\mathcal{L} = \frac{f N_B N_P N_{\bar{P}}}{2\pi (\sigma_p^2 + \sigma_{\bar{P}}^2)} \mathcal{F}(\sigma_l/\beta^*)$$  \hspace{1cm} (2.6)

where $\mathcal{F}$ is a form factor depending on $\sigma_l/\beta^*$, the ratio of bunch length to the beta function at the interaction point. The integrated luminosity

$$L = \int_T \mathcal{L} dt.$$  \hspace{1cm} (2.7)

provides the total collider performance over a certain period of time.

The Tevatron collider is in fact the last stage in a chain of different accelerators (Fig. 2.2) which raises the proton’s energy up until it reaches 150 GeV before being sent into the Tevatron Ring:

- Cockroft-Walton preaccelerator - accelerates hydrogen ions to 750 KeV.
- Linear Accelerator - accelerates ions to 400 MeV and removes electrons.
- The Booster Synchrotron - accelerates protons to 8 GeV and also supplies the Anti-proton Source with them.
- The Main Injector - accelerates protons to 150 GeV.
The antiprotons are created in the Antiproton Source and then pass through the Debuncher and Accumulator before entering the Tevatron Synchrotron.

2.3 Detector Overview

The D0 detector (Fig. 2.3) is a general purpose experiment designed for the study of $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV. It ran at the Fermilab Tevatron collider [12] from 1983 to 2011 and it was originally designed for the study of final states containing electrons, muons, jets and neutrinos coming out of the $p\bar{p}$ collisions taking place in its center. The detector underwent an upgrade from 1996 to 2001 for the Run II of the accelerator, being modified to allow precise measurements of momentum, electric charge of particles, vertex tagging of b-jets and also low $p_T$ $B^-$ physics processes. The D0 detector is 13 m high, 12 m wide and 20 m long, weighting 5500 tons and sits on a moving platform in the collision hall to allow its access.
The major subsystems of the D0 detector are:

- the Inner Tracking System
- the Calorimeter
- the Luminosity Monitor
- the Muon System

Fig. 2.4 shows a schematic view of the detector.

2.4 Inner Tracking System

The inner tracking system is the innermost part of the detector and allows measurements of paths of charged particles in a wide range of pseudorapidity. It consists of four subdetectors: the Silicon Microstrip Tracker (SMT), the Central Fiber Tracker (CFT), the Central Preshower (CPS) and the Forward Preshower (FPS) (Fig. 2.5). Both the SMT and the CFT are located in a 2 T solenoidal field.
The two tracking detectors locate the primary interaction vertex with a resolution of about 35 $\mu$m along the beamline. They can tag $b$-quark jets with an impact parameter resolution of better than 15 $\mu$m in $r - \phi$ for particles with transverse momentum $p_T > 10$ GeV at $|\eta| = 0$. The high resolution of the vertex position allows good measurement of lepton $p_T$, jet transverse energy ($E_T$), and missing transverse energy $E_T$.

The Silicon Microstrip Tracker is the closest subdetector to the beam line. It has a total of 912 readout modules, with 792,576 channels and consists of six concentric barrels modules of 4 silicon layers plus disks modules mounted transversely. The SMT provides information about the primary...
vertex with a resolution of 35 $\mu$m along the beamline and b-jets tagging with an impact parameter resolution of about 15 $\mu$m in the plane transverse to the beamline.

The Central Fiber Tracker is based on scintillating fiber technology with visible light photon counter (VLPC) readout [14], which works in an avalanche mode at 9 K. With a total of 77,000 channels the CFT has eight layers of fiber doublets, with each one consisting of two layers of 830 $\mu$m diameter fibers with 870 $\mu$m spacing, offset by half the fiber spacing. The CFT gives position measurements with a resolution of about 100 $\mu$m.

### 2.4.1 Preshower detectors

The central and forward preshower detectors (CPS and FPS) play two roles in the detector. They measure the depositition of energy of charged particles moving towards the calorimeters and at the same time track such particles. The CPS consists of 3 cylindrical layers, each consisting of an array of triangular scintillating fibers equipped with wavelength shifting fibers (WLS) performing a total of 7000 channels. The FPS consists of 2 MIP and 2 shower layers with 15000 channels.

### 2.5 Calorimeter

A calorimeter is a device used to measure the energy deposited by a particle or a cluster (jet) of particles by absorption. When a particle interacts with the material of the calorimeter it generates a cascade of other particles which itself depends on the original particle’s initial energy.

There are two different kinds of calorimeters depending on if the incident particle generates an electromagnetic or a hadronic shower. Each kind is designed to maximize the rejection to the other type of shower.

The D0 calorimetry system consists of a sampling calorimeter which uses uranium as the absorbing material and liquid-argon as the ionizing material and an intercryostat detector, as shown in Fig. 2.6.
As shown in Fig. 2.7, the central calorimeter (CC) covers $|\eta| < 1.2$ and the two end calorimeters, ECN (north) and ECS (south), extend coverage to $|\eta| \approx 4$. Each calorimeter contains an electromagnetic section closest to the interaction region followed by fine and coarse hadronic sections.

The calorimeter is divided in modules, each one with cells containing both absorbing material and signal detectors. Each of these cells contains uranium plates for absorption and signal production through signal boards. The 2.3 mm gap between each plate is filled with liquid argon. The signal system consists of signal boards made of two 0.5 mm-layers of insulating material G10. The external surface of the signal board is covered with resistive epoxy. During operation a tension of 2.0 - 2.5 kV is applied to the resistive surfaces while the uranium plates remain grounded. The signal occurs when charged particles reach the liquid argon and produce ionization tracks, thus the released electrons are collected by the signal boards after a drift time of order of 450 ns.

The CC covers the pseudorapidity region of $|\eta| < 1.2$ and consists of three cylindrical parts of modules. The electromagnetic part has four layers of cells. The first two measure the longitudinal development of the shower until around $2X_0$. The third measures the shower until $7X_0$. The last layer goes until the maximum of $10X_0$. Each calorimeter cell has dimensions of $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$.

$X_0$ is the radiation length of the material.
except the third layer with $\Delta \eta \times \Delta \phi = 0.05 \times 0.05$. The hadronic section of the calorimeter has a length of $7-9\lambda$ and is divided in four layers of cells again with dimensions of $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$. The hadronic part is itself divided in two modules: 16 fine hadronic (FH) that measure hadronic showers and 16 coarse hadronic (CH) that measures any flow of energy escaping from the FH. The FH module covers the first three layers (of lengths of $0.9\lambda$, $1.0\lambda$, $1.3\lambda$ respectively) of the four of the hadronic section. The FH cells have 6 mm-thick plates of uranium-niobium while the CH consists of a single layer of length of $3.2\lambda$ with absorbing plates of 46.5 mm of thickness.

The ends of the calorimeter cover a region of $1.3 < |\eta| < 4.2$. Each end calorimeter consists of three concentrical modules. However their electromagnetic part is a disk-shaped detector towards the innermost part of the hadronic calorimeter. The difference between it and its counterpart in CC is that it measures showers developing until $2.3X_0$ instead $2X_0$. The hadronic part of the EC’s is divided into an internal part, consisting of FH and CH modules, an intermediate part with both FH and CH modules and an external part with only CH modules. All cells have a $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ transverse segmentation. Fig. 2.8 shows how a cell looks like.

$\lambda$ is the so-called nuclear interaction length of the material.
2.6 Luminosity Monitor

Located about 135 cm away from the central interaction point of the D0 and made of 24 scintillator counters which covers the region of $2.7 < |\eta| < 4.4$, the Luminosity Monitor (LM) measures the luminosity delivered by the Tevatron collider to D0 using the observed average number of inelastic collisions per beam crossing $N_{inel}$ and the effective inelastic cross section $\sigma_{eff}^{inel}$ according to $\mathcal{L} = f \frac{N_{inel}}{\sigma_{eff}^{inel}}$ where $f$ is the beam crossing frequency.

2.7 The Muon System

Muons have sufficiently large lifetime to pass through the calorimeter depositing little energy in it. A dedicated muon detection system is needed in addition to the calorimeter.

For muon triggering and measurement, the upgraded D0 detector uses central and two forward systems. The central system uses 10 cm proportional drift tubes (PDTs) while the end systems use 1 cm mini-drift tubes (MDTs). Each system has three layers, one before the toroids and two after it, each with PDT or MDT planes, and scintillation counters. There are typically four wire planes in the layer before the toroids and and three wire planes in the two layers after the toroids.
2.8 The D0 Trigger System

Proton-antiproton collisions at the center of the detector produce data at a rate of $\approx 2$ MHz. Due to the impossibility to record all this data a trigger system is designed to reduce such rate and at the same time accept candidate events to the various physics analysis. In order to perform this task with maximum efficiency the D0 trigger system consists of a 3-level structure: Level 1 or L1, Level 2 or L2 and Level 3 or L3.

The three distinct levels form the D0 trigger system, with each succeeding level examining fewer events but in greater detail and with more complexity. The first stage (L1) comprises a collection of hardware trigger elements that provide a trigger accept rate of about 2 kHz. These trigger elements include calorimeter towers, muon wire and scintillator hits and central tracking information. In the second stage (L2), hardware engines and embedded microprocessors associated with specific subdetectors provide information to a global processor to construct a trigger decision based on individual objects as well as object correlations. The L2 system reduces the trigger rate by a factor of about two and has an accept rate of approximately 1 kHz. Candidates passed by L1 and L2 are sent to a farm of Level 3 (L3) microprocessors where sophisticated algorithms reduce the rate to about 50 Hz, and these events are recorded for offline reconstruction.
CHAPTER 3
OBJECT IDENTIFICATION

We now briefly describe the offline identification of objects used in this study: hadronic \( \tau \) decay candidates, jets, \( b \) jets, and \( E_T \).

3.1 Taus

Hadronic decays of \( \tau \) leptons are reconstructed from clusters of energy in the calorimeter with one or more associated tracks. The algorithm uses a cone of \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.5 \) for cluster-finding, and an inner cone of \( \Delta R = 0.3 \) for calculation of isolation variables. The following quantities are used in the reconstruction [16]:

- Profile, defined as \( \frac{E_1^T + E_2^T}{\sum_i E_i^T} \), where \( E_i^T \) is the \( E_T \) of the \( i \)th highest-\( E_T \) tower in the cluster.
- Energy isolation, defined as \( \frac{E(0.5) - E(0.3)}{E(0.3)} \), where \( E(R) \) is the energy contained in an \( \eta, \phi \) cone of radius \( R \) around the calorimeter cluster centroid.
- Track isolation, defined as scalar sum of the \( p_T \)'s of non-\( \tau \) tracks within \( \Delta R = 0.5 \) of the calorimeter cluster centroid divided by the similar sum for tracks associated with \( \tau \).

These variables are designed to identify the hadronic final states of \( \tau \)'s [17]:

- single charged hadron and 0 neutral hadrons \( (\tau \rightarrow \pi^- \nu_\tau) \), branching fraction \( B = 0.12 \),
- single charged hadron and \( \geq 1 \) neutral hadron(s) \( (e.g. \tau \rightarrow \rho^- \nu_\tau \rightarrow (\pi^0 \pi^-) \nu_\tau) \), \( B = 0.38 \),
- \( \geq 3 \) charged hadrons and \( \geq 0 \) neutral hadrons (so-called “3-prong” decays), \( B = 0.15 \).

These lead to the following classification of a reconstructed \( \tau \) candidate at D0:
1. **Type1**: calorimeter cluster, 1 matched track\(^1\), no associated EM subcluster. Mainly $\tau \rightarrow \pi^- \nu_\tau$.

2. **Type2**: calorimeter cluster, 1 matched track, $\geq 1$ associated EM subclusters. Mainly $\tau \rightarrow \rho^- \nu_\tau \rightarrow \pi^0 \pi^- \nu_\tau$.

3. **Type3**: calorimeter cluster, $\geq 2$ matched tracks. Mainly $\tau \rightarrow \pi^- \pi^- \pi^+ (\pi^0) \nu_\tau$.

In order to provide a better tau identification, a neural network is trained. Due to significant cross-migration during reconstruction, Types 1 and 2 are usually treated together. For each candidate, the output of the NNs provides a set of three variables, one for each type hypothesized. Real $\tau$’s tend to have higher values of the NN, while most QCD jets misidentified as $\tau$’s (fakes) have lower values. For the type 2 hypothesis, a second NN is trained to reject electrons masquerading as $\tau$’s.

### 3.2 Electrons

In D0 an electromagnetic tower (EM) tower is defined by adding the energy measured by the calorimeter in all four EM layers plus the first hadronic (FH1) layer. EM clusters are formed from seed EM towers which have $E_T > 500$ MeV. Neighboring towers are added if they have $E_T > 50$ MeV and if they are within $\Delta R < 0.3$ of the seed tower in the central region of the detector or within a cone radius of 10 cm in the third layer of the EM calorimeter in the end caps. These preclusters are used as starting points for final clusters if their energy exceeds 1 GeV.

In order to identify an EM cluster as electron/photon candidates, the cluster must have $E_T > 1.5$ GeV, more than 40% percent of the cluster energy must be contained in the central most energetic tower, the *EM fraction* must be high ($f_{EM} = E_{EM}/E_{tot} > 0.9$). Electron/photon candidates are required to have isolated fraction $< 0.2$, or:

$$f_{iso} = \frac{E_{tot}(R < 0.4) - E_{EM}(R < 0.2)}{E_{EM}(R < 0.2)} < 0.2. \quad (3.1)$$

---

\(^1\)A matched track is collection of hits caused by the passage of a charged particle in the tracking system that geometrically matches to an energy cluster in the calorimeter.
As electrons and high-$p_T$ photons produce EM showers in the preshower detectors, these are matched to EM clusters passing the above cuts. If there is a match, the position of the preshower cluster is used to determine the direction of the particle momentum. Next, if there is a match to one or more tracks from the central tracking system the candidate is regarded as an electron and assigned an ID = ±11. If no match is found the candidate is regarded as a photon and an ID = 10 is assigned.

Several variables are then used to improve electron identification. They are

- **$H$-matrix $\chi^2$**: this $7 \times 7$ covariance matrix quantifies how similar the shower development of the cluster is to that of an electron and is calculated from suitable correlated variables. For the $H$-matrix $\chi^2$ is calculated. Low values of $\chi^2$ correspond to electrons.

- **Track match $\text{Prob}(\chi^2_{\text{spatial}})$**: the track matching procedure defines a region bewteen the calorimeter cluster and the primary vertex locations and search for a track with $p_T > 1.5$ GeV within this region. Each track found is extrapolated into the EM3 layer of the calorimeter and $\text{Prob}(\chi^2_{\text{spatial}})$ is calculated. The track with the highest $\text{Prob}(\chi^2_{\text{spatial}})$ is considered the track matched to the EM object.

- **Electromagnetic likelihood ($L_{\text{EM}}$)**: this EM likelihood depends on a set of variables defined by combining information from the calorimeter and the tracking system. For electrons $L_{\text{EM}}$ is approximately one and for background it tends to zero.

Based on these variables described above we classify electrons in two types:

**Loose electron**: an electron is regarded as loose if $f_{\text{EM}} > 0.9$, $H$-matrix $\chi^2 < 50$, $f_{\text{iso}} > 0.15$, $\text{Prob}(\chi^2_{\text{spatial}}) > 0.001$, track $p_T > 5$ GeV and $dca < 1$ cm.

**Tight electron**: a tight electron must pass all the isolated electron plus EM-likelihood $L_{\text{EM}} > 0.85$.

### 3.3 Muons

Two parameters are used to characterize muons: **type** and **quality**. The type of a muon is represented by the name $n_{\text{seg}}$ and assumes the values 0, ±1, ±2 and ±3. 0 and positive values of
\( n_{\text{seg}} \) indicate that the local muon matches to a track in the central track system while negative values indicate matching failure.

The muon quality can be “Loose” or “Medium”, as they are defined below:

- \( |n_{\text{seg}}| = 3 \) Medium/Loose: a muon must have at least two A layer wire hits, at least one layer scintillator hit, and at least two BC layer wire hits. A \( |n_{\text{seg}}| = 3 \) is Loose if one the requirements above fail.

- \( |n_{\text{seg}}| = 2 \) Medium/Loose: a muon must have at least one BC layer scintillator hit and at least two BC layer wire hits. The muon is defined as Medium if it fulfills all the above requirements and is located in the bottom part of the muon system.

- \( |n_{\text{seg}}| = 1 \) Medium/Loose: a muon must have at least one scintillator hit and at least two A layer wire hits. The muon is defined as Medium if it fulfills all the above requirements and is located in the bottom part of the muon system or if it has an energy that would range out in the toroid.

Depending on the matching, three qualities of tracks have been defined:

- \textit{track\_loose}: a track is loose when its distance of closest approach in the \( x - y \) plane with respect to the primary vertex is less than 0.2 cm (\( |dca_{xy}| < 0.2 \text{ cm} \)). If the track has a SMT hit the requirement is tightened to \( |dca_{xy}| < 0.04 \text{ cm} \).

- \textit{track\_medium}: a track is medium if it fulfills the loose requirements and if the central track fit has \( \chi^2/ndf < 4 \).

- \textit{track\_tight}: a track is tight if it fulfills the medium requirements and if it has at least one SMT hit.

Decays of \( B \)-hadrons produce background muons (\( B \)-hadron \( \rightarrow \mu\nu_{\mu} + X \)) to signal muons from the decays of \( W \) bosons. To discriminate between these two the concept of muon isolation is applied. Muons from heavy flavor decays tend to be inside jets, thus isolation variables are designed to select muons that are not contained in jets.
3.4 Jets

Jets are identified using the Run 2 cone algorithm with cone size of $\Delta R = 0.5$ [18]. D0 standard jet quality cuts include L1 Trigger information, calorimeter EM fraction and coarse hadronic fraction.

Jets used in this analysis are required to have at least two associated tracks pointing to either the primary vertex or a secondary vertex consistent with a heavy quark decay. This “vertex confirmation” is designed to achieve better agreement between MC and data by rejecting noise jets in the ICD region of the calorimeter. The jet energy scale correction (JES) is applied in order to estimate parton energies from reconstructed jets in data and MC [20]. Jets containing a muon with $\Delta R(\mu, jet) < 0.5$ are associated with heavy quark decays and corrected to take into account the momentum carried away by the muon and the neutrino [21].

3.5 Missing Transverse Energy ($E_T$)

The presence of neutrinos in an event is inferred from an imbalance of net momentum in the plane perpendicular to the beam (transverse plane). This quantity is calculated from the vector sum of transverse momenta of all calorimeter cells, except those in the coarse hadronic layers, which suffer from higher levels of noise. Coarse hadronic cells are only included if they are clustered within a reconstructed jet. This raw $E_T$ is corrected for the energies of other objects, such as photons, electrons, $\tau$’s, and jets in the event. As muons deposit only a small portion of their energy in the calorimeter, their momenta is subtracted from the $E_T$ vector.

3.6 $b$ jets

Since the main sources of background in this analysis are QCD and $W + jets$, requiring the presence of at least one jet having a high probability of resulting from the decay of a $b$-hadron is a very powerful means of background rejection. The $b$-tagging algorithm used in this measurement is
based on a Neural Network (NN)-based discriminant developed by the $b$ identification group [22]. The NN combines 7 characteristic variables of the tagging algorithms into a discriminant function. As in the earlier p17 analysis $^2$, we have chosen the “tight” operating point, which is equivalent to requiring the NN discriminant output to be greater than 0.775. Both the average efficiency and fake rate are comparable between the current p20 version of the algorithm and that used in p17 [23].

Some comments on a few topics are in order:

**b-tagging:** In both data and MC we apply direct tagging by using a data-derived scale factor.

**Light jet mistagging as b’s:** The $b$-tag fake rate from light quarks is computed by measuring the “negative tag rate” as defined in [24]. The method estimates the rates of $b$, $c$, and light jets being tagged as $b$’s by fitting to binned distributions of the output of the $b$-tagging NN in data, and combines them with sample composition estimates derived from data. The $b$- and $c$-jet efficiencies are taken from the standard $b$-id NN tag rate functions (TRF’s).

**Taggability:** The $b$-tag algorithm can only be applied to jets with associated tracks. Such jets are called “taggable” and are defined as calorimeter jets within $\Delta R = 0.5$ to a track jet composed of at least two tracks. Like $b$-tagging, differences in tracking performance between real and simulated events need to be taken into account in modeling taggability for MC events. This is accomplished by applying taggability rate functions that are parametrized in terms of the $p_T$ and $\eta$ of the jet and the $z$ coordinate of the primary vertex. These functions were determined from $Z$ events and provided by the Jet-ID group [25].

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$^2$p17 and p20 are “D0 jargon” words to designate different periods of data collection as well as the version of the algorithm used to reconstruct these data.
CHAPTER 4
DATA MONTE CARLO SAMPLES AND TRIGGER MODELING

This chapter presents the data and simulated samples used in this analysis, as well as standard corrections applied to the simulated samples in order to account for differences in data and MC efficiencies.

4.1 Data Samples

After a period (run) of data acquisition, data samples must be considered “good” in order to be used in further analysis. This data quality procedure consists of a check on the data recorded by each sub-detector during the run period. If in any of them the data is flagged as “bad”, the event, the whole run, or the luminosity block can be discarded. For instance, for each trigger there is a list of bad luminosity blocks based on the calorimeter information. Events found in that list are automatically discarded. All information on the status of all runs is stored in the Offline Run Quality Database.

In this analysis we used the 3JET skim extracted by the Common Samples Group from data recorded between August 2002 and May 2010 (runs 151817 - 270116) [26]:

- CSG_CAF_3JET_PASS2_p21.05.00_all_fixed2007,
- CSG_CAF_3JET_PASS4_p21.10.00_p20.12.00,
- CSG_CAF_3JET_PASS4_p21.10.00_p20.12.01,
- CSG_CAF_3JET_PASS4_p21.10.00_p20.12.02,
- CSG_CAF_3JET_PASS4_p21.10.00_p20.12.04
• CSG_CAF_3JET_PASS4_p21.12.00_p20.12.05_allfix,

• CSG_CAF_3JET_PASS5_p21.18.00_p20.16.07_fix,

• CSG_CAF_3JET_PASS5_p21.21.00_p20.16.07_summer2010.

The analysis is based on the \texttt{vjets\_cafe v05-05-12e} framework, Release p21.20.00.

4.2 Monte Carlo Samples

We use p20 certified MC samples as produced by CSG and reconstructed with p21.11.00 (version12) \cite{27}. All W/Z and $t\bar{t}$ were generated with ALPGEN v2.11 \cite{28} interfaced with Pythia v6.409 \cite{29} for production of parton-level showers and hadronization. EvtGen \cite{30} is used to model b hadrons decays and TAUOLA \cite{31} is used to model tau lepton decays.

ALPGEN is a leading order (LO) generator. In order to correct it to match with next-to-leading order (NLO) cross sections we apply correction factors to MC samples in order to get the correct normalization. These correction factors were taken from the \texttt{vjets\_cafe} framework and are described in Ref.\cite{32}. There are two kinds of correction factors: \textit{k-factors}, which are the result of the ratio between NLO and LO cross sections ($\sigma_{NLO}/\sigma_{LO}$) and \textit{heavy flavor factors}, which are in turn the ratio between k-factors for HF+$0lp$($incl$) and $2lp$($incl$) process from MCFM \cite{33}. Here HF denotes $Z+bb$, $Z+cc$, $W+bb$ or $W+cc$ and $lp$ stands for \textit{light parton}. Heavy flavor factors are applied on top of k-factors in order to provide the correct normalization for processes where heavy quarks are present. For $Z$ production, samples are split into $Z$ + light jets, $Z+bb$ and $Z+cc$. $Z$ + light parton cross sections are multiplied by a k-factor of 1.3, while $Z+bb$ and $Z+cc$ are multiplied by additional heavy flavor factors of 1.52 and 1.67 respectively. $W$ + jets samples are also split the same way: $W$ + light jets, $W+bb$ and $W+cc$. In $W$ + light jets case a k-factor of 1.3 is applied while an additional heavy flavor factor of 1.47 is applied to both $W+bb$ and $W+cc$ samples. Table 4.1 summarizes the correction factors applied.
Table 4.1: Correction factors for MC.

<table>
<thead>
<tr>
<th>Process</th>
<th>correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W + \text{light partons}$</td>
<td>1.3</td>
</tr>
<tr>
<td>$W + bb$</td>
<td>$1.3 \times 1.47$</td>
</tr>
<tr>
<td>$W + cc$</td>
<td>$1.3 \times 1.47$</td>
</tr>
<tr>
<td>$Z + \text{light partons}$</td>
<td>1.3</td>
</tr>
<tr>
<td>$Z + bb$</td>
<td>$1.3 \times 1.52$</td>
</tr>
<tr>
<td>$Z + cc$</td>
<td>$1.3 \times 1.67$</td>
</tr>
</tbody>
</table>

4.3 Trigger and Trigger Modeling

We chose the three jets trigger JT2.3JT15L.IP.VX based on its prior use in the p17 analysis and its availability of modeling. Table 4.2 shows the L1, L2 and L3 requirements of the trigger. Improved tuning resulted in a gain of 10% in signal efficiency compared to p17.

Table 4.2: Level-by-level description of trigger JT2.3JT15L.IP.VX.

<table>
<thead>
<tr>
<th>Level</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CSWJT(3,8,3.2)CSWJT(2,15,2.4)CSWJT(1,30,2.4)</td>
<td>L2JET(3,6) L2HT(75,6) SPHER(0.1) OR L2JET(1,30,2.6) L2JET(2,15,2.6) L2JET(3,8) L2HT(75,6) MJT(10,10) OR L2JET(1,30,2.6) L2JET(2,15,2.6) L2JET(3,8) L2HT(100,6) OR L2JET(1,20,2.4) L2HT(35,6) MJT(20,10) L2ACO(168.75)</td>
<td>L3JET(3,15,3.6) JT(2,25,3.6) $</td>
</tr>
<tr>
<td>Name</td>
<td>JT2.3JT15L.IP.VX</td>
<td>JT2.3JT15L.IP.VX</td>
<td>JT2.3JT15L.IP.VX</td>
</tr>
</tbody>
</table>

The CSWJT(x,y,z) term in Table 4.2 corresponds to x L1 jets above y GeV and within $|\eta| < z$. The JT(x,y,z) term corresponds to x jets reconstructed at L2 or L3 with $p_T > y$ GeV and $|\eta| < z$. The HT(x,y) term is used only at L2 and requires that the sum of the transverse momenta of L2 jets with $p_T > y$ GeV is above x GeV. The SPHER(0.1) term requires the event sphericity calculated from L2 jets to be greater than 0.1. The MJT(x,y) term corresponds to a missing transverse energy
> x GeV calculated from jets with $E_T > y$ GeV. The STTIP(1,5.5,3) term requires one L2STT track with an impact parameter significance greater than or equal to three and a $\chi^2 < 5.5$. The L2ACO(168.75) requires that nowhere in the event there is a pair of jets with $E_T > 5$ GeV which is back-to-back within a window of 11.25 degrees. The $|z_{PV}| < 35$ cm term requires the primary vertex reconstructed at L3 to be within 35 cm of the center of the detector and the BTAG(0.4) term is used only at L3 and corresponds to a cut of 0.4 on the probability for the event to not contain a $b$-quark.

The efficiency of this trigger is not calculated by the caf_trigger package, but we use the modeling developed by the Higgs group for the $h \to b\bar{b}$ analysis [34]. The Higgs group has parametrized the terms of JT2, JT15L_IP, VX in three instantaneous luminosity bins ($10^{30}$ cm$^{-2}$s$^{-1}$): low ($\mathcal{L} < 77$), medium ($77 \leq \mathcal{L} < 124$) and high ($\mathcal{L} \geq 124$). To model the trigger efficiency, we account for both the trigger probabilities and the $b$-tag probabilities. The trigger probabilities for 0, 1, 2 and 3 or more $b$-tagged jets are multiplied by the probabilities of 0, 1, 2 and 3 or more jets being tagged, and added. The second set of probabilities are derived from $b$-tag scale factors.

The trigger efficiency is computed as a probability as follows:

$$P_{\text{trigger}} = \sum_i P_{t_i} \cdot P_{b_i}, \quad (i = 0, 1, 2, \geq 3),$$

where $P_{t_i}$ is the trigger probability for the event if it has $i$ $b$-tags, while $P_{b_i}$ is the probability of having $i$ $b$-tags in the offline event reconstruction. This probability acts as a weight (TrigWeight) on each MC event.

We now give a brief description of how the trigger probabilities at each level were calculated. Single-object turn-on curves were determined using muon-triggered events from the TOPJETTRIG skim. Some turn-on curves are found in Appendix A. A more complete description can be found in [34].

### 4.3.1 Level 1

Level 1 consists of jet terms only: One jet with $E_T > 30$ GeV and $|\eta| < 2.4$, a second jet with $E_T > 15$ GeV and $|\eta| < 2.4$ and a third jet with $E_T > 8$ GeV and $|\eta| < 3.2$. The probability of an
event satisfying this requirement is calculated by combining the parametrized probabilities of real (a L1 jet matched to an offline counterpart within $\Delta R = 0.5$) and noise jets (for which no such match is found) meeting the thresholds. L1 jets that matched offline ones had their turn-on curves parametrized as functions of offline jet $p_T$'s. The number of noise jets per event was parametrized as a function of offline $H_T$.

### 4.3.2 Level 2

As seen in Table 4.2, for both the v15 and v16 trigger versions, the JT2.3JT15L IP VX trigger uses five basic L2 terms: L2JET, L2HT, MJT, L2SPHER, and L2ACO. The v16 version has an additional STTIP term. The first three of these, namely those based on jets, $H_T$, and $E_T$ calculated from jets are the most important ones for this analysis. They have been modeled for the $h \to b\bar{b}$ analysis and are used here [34]. At L2, like at L1, jets matching offline counterparts were weighted according to the turn-on curves parametrized as functions of offline jet $p_T$'s. Jet that have no offline match are treated as “noise” jets, whose number in each event is parametrized as a function of offline $H_T$. The L2STTIP was measured for events in v16 that passed the L1, the rest of L2, and the L3 (without the b-tag term) trigger requirements as well as 3-5 jets reconstructed offline. The efficiency was parametrized as a function of the invariant mass of the two leading jets, separately for 0, 1, 2 and 3 offline tight NN b-tagged events, in the three different luminosity bins, as shown in Appendix A.

### 4.3.3 Level 3

At L3, we have a jet part and a b-tag part. Turn-on curves for the first were determined from events passing both L1 and L2 requirements. Efficiencies for the second were measured in two different ways depending on whether the trigger list was v15 or v16. For v15, events were recorded with JT2.4JT20 and JT2.3JT12L/MM3_V triggers, whose L1 and L2 conditions were exactly the same. They were further required to satisfy the rest of the L3 conditions of JT2.3JT15L IP VX, and the offline event selection. For v16, efficiencies were measured in a similar fashion, but using
the JT4.3JT15L_VX trigger, which has no L2STT or L2BTAG requirements. Events were then required to have fired at least one of the three L2 branches of JT2.3JT15L_IP_VX, and to have 3-5 jets reconstructed offline.

The integrated luminosities corresponding to the trigger are given in Table 4.3.

Table 4.3: Integrated luminosities of the Run 2b 3JET data skim passing the JT2.3JT15L_IP_VX trigger.

<table>
<thead>
<tr>
<th>Trigger list</th>
<th>$\int \mathcal{L} dt$ (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delivered</td>
</tr>
<tr>
<td>v15.x</td>
<td>1682.08</td>
</tr>
<tr>
<td>v16.x</td>
<td>4059.92</td>
</tr>
<tr>
<td>Total</td>
<td>5742.00</td>
</tr>
</tbody>
</table>
CHAPTER 5
EVENT SELECTION

5.1 Preselection

This step is an attempt to reduce the background without incurring any significant penalty in signal efficiency. The selection criteria listed below, which are similar to those used in the p17 analysis, are applied to MC and data samples described in Chapter 4 [11].

- Duplicate events are removed and each event is required to be of good quality.
- At least 4 jets with $p_T > 15$ GeV and $|\eta| < 2.5$, with leading (in $p_T$) jet $p_T > 35$ GeV and second and third jets have $p_T > 25$ GeV.
- A primary vertex with $\geq 3$ associated tracks and $|z| \leq 60$ cm.
- No isolated electron or muon in the event. This “lepton veto” is applied in order to ensure orthogonality with cross sections measurements in other channels involving electrons and muons ([35] and [36]). Likewise, events that pass the all-jets analysis preselection cuts are rejected [37].
- $15 \text{ GeV} \leq E_T \leq 500 \text{ GeV}$.
- at least one $\tau$ with $\text{NN} > 0.3$ and $p_T > 10$ GeV.
- $E_T$-significance $(\sigma(E_T)) \geq 1.5$, where $\sigma(E_T)$ is a measure of the likelihood of the $E_T$ arising from physical sources, such as the presence of a neutrino, rather than measurement fluctuations (primarily of the jets in the event). The $E_T$-significance is computed from resolutions of objects such as jets, electrons, muons and unclustered energy. This cut is relaxed for optimization studies.
The preselection reduces the initial data set from \( \sim 535 \) million events to \( \sim 3.3 \) million. Table 5.1 shows the cut flow for a \( \sim 5\% \) slice of the 5.0 fb\(^{-1}\) data sample.

### Table 5.1: Representative preselection cut flow for data.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Events</th>
<th>Fraction Remaining (%)</th>
<th>Relative</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>30307443</td>
<td>91.70 ± 0.01</td>
<td>91.70 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Quality</td>
<td>27785487</td>
<td>91.70 ± 0.01</td>
<td>91.70 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Trigger</td>
<td>8628557</td>
<td>31.04 ± 0.01</td>
<td>28.47 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Jet</td>
<td>2294713</td>
<td>26.59 ± 0.02</td>
<td>7.57 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>Vertex</td>
<td>2293558</td>
<td>99.95 ± 0.01</td>
<td>7.57 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>e veto</td>
<td>2293372</td>
<td>99.98 ± 0.02</td>
<td>7.57 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>( \mu ) veto</td>
<td>2293372</td>
<td>99.99 ± 0.01</td>
<td>7.57 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>( E_T )</td>
<td>1036978</td>
<td>45.22 ± 0.03</td>
<td>3.42 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>( \tau )</td>
<td>189400</td>
<td>18.26 ± 0.04</td>
<td>0.62 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>( \sigma(\sqrt{E_T}) )</td>
<td>20624</td>
<td>10.89 ± 0.01</td>
<td>0.07 ± 0.01</td>
<td></td>
</tr>
</tbody>
</table>

Preselection for Monte Carlo events has an additional requirement that is based on the MC truth information. For this we use the “Particle Selector” package tool to select a specific \( t \bar{t} \) final state. At least one of the two \( W' \)s is required to decay leptonically and decays to each lepton flavor are tracked separately to assess its contribution to the total. For \( W \rightarrow \tau \) decays, only events where at least one \( \tau \) decays hadronically are kept in the \( \tau + jets \) sample. Events where the \( \tau \) decays to an \( e \) or a \( \mu \) were put into the \( e + jets \) and \( \mu + jets \) samples. As in p17, we grouped all the events where the top quark decays into two leptons in a single “dilepton” \( (l_1l_2) \) sample. As noted earlier, \( t \bar{t} \) MC events were generated using ALPGEN, which produces separate samples based on the number of associated light parton production. To simulate a physical example, one must combine these with proper respective weights. Table 5.2 shows the ALPGEN weights for \( t \bar{t} \rightarrow l + jets + X \) and \( t \bar{t} \rightarrow l_1l_2 + X \) events subsamples, respectively.

Table 5.3 shows the preselection cut flow for the \( t \bar{t} \) samples. It should be noted that only the ALPGEN weights are applied at this stage. The trigger weight and others discussed in Section 4.3 are applied later.
Table 5.2: ALPGEN weights for $t\bar{t}$ Monte Carlo events.

<table>
<thead>
<tr>
<th>Process</th>
<th>$t\bar{t} \rightarrow l + jets$</th>
<th>$t\bar{t} \rightarrow l_1l_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Events</td>
<td>$\sigma \cdot B$ (pb)</td>
</tr>
<tr>
<td>$t\bar{t} + 0lp$</td>
<td>1495664</td>
<td>1.422</td>
</tr>
<tr>
<td>$t\bar{t} + 1lp$</td>
<td>923963</td>
<td>0.578</td>
</tr>
<tr>
<td>$t\bar{t} + \geq 2lp$</td>
<td>635707</td>
<td>0.283</td>
</tr>
</tbody>
</table>

Table 5.3: Cut flow for $t\bar{t}$ Monte Carlo.

<table>
<thead>
<tr>
<th>Selection</th>
<th>$t\bar{t} \rightarrow \tau + jets$</th>
<th>$t\bar{t} \rightarrow e + jets$</th>
<th>$t\bar{t} \rightarrow \mu + jets$</th>
<th>$t\bar{t} \rightarrow l_1l_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Events Efficiency (%)</td>
<td>Events Efficiency (%)</td>
<td>Events Efficiency (%)</td>
<td>Events Efficiency (%)</td>
</tr>
<tr>
<td>Initial</td>
<td>11629</td>
<td>11629</td>
<td>11629</td>
<td>2858</td>
</tr>
<tr>
<td>Part. sel.</td>
<td>2512</td>
<td>21.60</td>
<td>4569</td>
<td>39.29</td>
</tr>
<tr>
<td>Quality</td>
<td>2415</td>
<td>96.16</td>
<td>4393</td>
<td>96.13</td>
</tr>
<tr>
<td>Jet</td>
<td>1500</td>
<td>62.09</td>
<td>2247</td>
<td>51.15</td>
</tr>
<tr>
<td>Vertex</td>
<td>1486</td>
<td>99.07</td>
<td>2226</td>
<td>99.08</td>
</tr>
<tr>
<td>$e$ veto</td>
<td>1471</td>
<td>99.04</td>
<td>1229</td>
<td>55.19</td>
</tr>
<tr>
<td>$\mu$ veto</td>
<td>1470</td>
<td>99.92</td>
<td>1228</td>
<td>99.95</td>
</tr>
<tr>
<td>$E_T$</td>
<td>1395</td>
<td>94.86</td>
<td>1176</td>
<td>95.76</td>
</tr>
<tr>
<td>$\tau$</td>
<td>777</td>
<td>55.68</td>
<td>716</td>
<td>60.88</td>
</tr>
<tr>
<td>$\sigma(E_T)$</td>
<td>629</td>
<td>80.98</td>
<td>600</td>
<td>83.86</td>
</tr>
<tr>
<td>Trigger</td>
<td>84.80</td>
<td>4.59</td>
<td>84.09</td>
<td>4.35</td>
</tr>
</tbody>
</table>

5.2 $b$ and $\tau$ selections

After preselection, we apply tight requirements on the presence of $\tau$ and $b$-jet candidates in our events. For tagging $b$ jets we use the “tight” operating point, which corresponds to $NN_b > 0.775$. If there are more than one $\tau$ candidate in the event, then we choose only the one with the highest $NN_\tau$. Also we require a $\tau$-jet separation, whereby a $\tau$ candidate is only used in the measurement if it is separated from the closest jet by $\Delta R > 0.5$. At this stage of the analysis, we separated the data sample into two channels according to which type of $\tau$ the candidate with highest $NN_\tau$ is. Events with $\tau$’s of Types 1 or 2 are treated together mainly because of the large cross-migration between them [16]. Events with the Type 3 $\tau$’s, which are expected to have much higher fake rate from
QCD, and thus yield a weaker cross section measurement, are treated separately. Measurements in the two channels are combined in the end to get the final result.

After the $\sigma(E_T) > 1.5$ cut is applied, out of the 3.3 million events approximately 357000 events survive. We divide these into three mutually exclusive (but not exhaustive) subsamples based on their $b$ and $\tau$ contents:

- **The “$b$-tag” or “cross section” sample**: These events have a “tight” $\tau$ candidate: Type 1 or 2 with $NN_{\tau} > 0.90$ or Type 3 with $NN_{\tau} > 0.95$, and at least one “tight” $b$-tagged jet. The $NN_{\tau}$ cuts were chosen based on previous studies involving hadronic decays of $\tau$’s [38, 39]. This sample is used to extract the cross section. Jets matched to $\tau$ candidates are not eligible for $b$ tagging, although they still count as jets (this is done so as to make the number of jets independent of the $\tau$ quality). There are 1002 events with Type 1 or 2 $\tau$’s and 1709 with Type 3 $\tau$’s in this sample.

- **The “fake $\tau$” or “loose − tight $\tau$” (background) sample**: Same selection as above is applied, but with $0.3 < NN_{\tau} < 0.7$ for all $\tau$’s. The lower threshold of 0.3 (instead of 0) is intended to minimize any bias in the event properties (e.g. jets, $E_T$) stemming from characteristic differences between jets that are likely to fake $\tau$’s and those that are not. The upper cut is kept at 0.7, somewhat below 0.95 or 0.90 to suppress contamination from genuine $\tau$’s. There are 4800 events with Type 1 or 2 $\tau$’s and 17604 with Type 3 in this sample. Of these events, about half were used as QCD background template for training the event NN on events with $\tau$’s of Types 1 or 2 and about one fifth for Type 3 (so as to train the NN for either type of events with roughly 2300 background events). For both, the rest of the events are reserved as QCD background samples to be used for fitting based on the event NN output.

- **The “$b$ veto” sample**: Events are required to have a tight $\tau$ the same way as the signal sample, but no jet with a tight $b$-tag. We use this as the control sample to validate the QCD modeling. The $b$ veto requirement ensures that this sample, which contains 7010 events with Type 1 or 2 $\tau$’s and 13921 with Type 3, is almost purely background.
One extra condition applied along with the $NN_{\tau}$ cut described above was the so called $NN_{\text{elec}} > 0.9$ cut on Type 2 $\tau$’s in order to minimize the number of fakes from electrons.

The number of events in each sample for the cross section, fake $\tau$, $b$ veto, and MC samples are shown on Tables 5.4 and 5.5 for tau Types 1 & 2 and 3 respectively. We see that the numbers of genuine $\tau$’s in the “fake $\tau$” samples, which are used for modeling QCD, are not entirely negligible. About 2.0% of the loose-tight sample with $\tau$’s of Type 1 or 2, and 1.0% of that with Type 3, are actually $t\bar{t}$ events (assuming SM prediction of $\sigma_{t\bar{t}} = 7.46$ pb). Likewise, $W/Z + jets$ contribute 0.9% and 0.3% respectively. Although this signal contamination in the “fake $\tau$” should be considered when measuring the cross section, here in this work we do not take it into account when performing the measurement.
Table 5.4: Number of preselected events after requiring $\sigma(\mathbb{E}_T) > 1.5$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events</th>
<th>Samples</th>
<th>cross section</th>
<th>fake $\tau$</th>
<th>$b$ veto</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t} \rightarrow \tau(\text{had}) + jets$</td>
<td>57.57 ± 0.53</td>
<td></td>
<td>49.39 ± 0.49</td>
<td>39.71 ± 0.29</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow e + jets$</td>
<td>28.90 ± 0.36</td>
<td></td>
<td>24.90 ± 0.34</td>
<td>20.89 ± 0.22</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow \mu + jets$</td>
<td>3.74 ± 0.14</td>
<td></td>
<td>21.67 ± 0.34</td>
<td>2.67 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow l_1 l_2$</td>
<td>4.21 ± 0.07</td>
<td></td>
<td>3.29 ± 0.08</td>
<td>1.54 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>$W_{bb} \rightarrow \ell \nu_{bb}$</td>
<td>8.56 ± 0.08</td>
<td></td>
<td>9.78 ± 0.10</td>
<td>13.27 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>$W_{cc} \rightarrow \ell \nu_{cc}$</td>
<td>5.19 ± 0.05</td>
<td></td>
<td>7.21 ± 0.07</td>
<td>41.48 ± 0.30</td>
<td></td>
</tr>
<tr>
<td>$W_{jj} \rightarrow \ell \nu_{jj}$</td>
<td>6.93 ± 0.08</td>
<td></td>
<td>18.11 ± 0.23</td>
<td>243.76 ± 2.12</td>
<td></td>
</tr>
<tr>
<td>$Z_{bb} \rightarrow \tau \tau_{bb}$</td>
<td>1.56 ± 0.06</td>
<td></td>
<td>1.19 ± 0.05</td>
<td>1.96 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>$Z_{cc} \rightarrow \tau \tau_{cc}$</td>
<td>0.81 ± 0.02</td>
<td></td>
<td>0.88 ± 0.04</td>
<td>5.28 ± 0.13</td>
<td></td>
</tr>
<tr>
<td>$Z_{jj} \rightarrow \tau \tau_{jj}$</td>
<td>1.77 ± 0.06</td>
<td></td>
<td>3.38 ± 0.12</td>
<td>31.86 ± 0.80</td>
<td></td>
</tr>
<tr>
<td>$Z_{bb} \rightarrow e e_{bb}$</td>
<td>0.20 ± 0.01</td>
<td></td>
<td>0.08 ± 0.01</td>
<td>0.32 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>$Z_{cc} \rightarrow e e_{cc}$</td>
<td>0.08 ± 0.01</td>
<td></td>
<td>0.04 ± 0.01</td>
<td>0.65 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>$Z_{jj} \rightarrow e e_{jj}$</td>
<td>0.08 ± 0.01</td>
<td></td>
<td>0.04 ± 0.01</td>
<td>3.96 ± 0.15</td>
<td></td>
</tr>
<tr>
<td>$Z_{bb} \rightarrow \mu \mu_{bb}$</td>
<td>0.03 ± 0.01</td>
<td></td>
<td>0.06 ± 0.01</td>
<td>0.04 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>$Z_{cc} \rightarrow \mu \mu_{cc}$</td>
<td>0.01 ± 0.01</td>
<td></td>
<td>0.04 ± 0.01</td>
<td>0.10 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>$Z_{jj} \rightarrow \mu \mu_{jj}$</td>
<td>0.01 ± 0.01</td>
<td></td>
<td>0.04 ± 0.01</td>
<td>0.43 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>$Z_{bb} \rightarrow \nu \nu_{bb}$</td>
<td>0.02 ± 0.01</td>
<td></td>
<td>0.86 ± 0.11</td>
<td>0.04 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>$Z_{cc} \rightarrow \nu \nu_{cc}$</td>
<td>0.04 ± 0.01</td>
<td></td>
<td>0.36 ± 0.04</td>
<td>0.35 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>$Z_{jj} \rightarrow \nu \nu_{jj}$</td>
<td>0.02 ± 0.01</td>
<td></td>
<td>0.46 ± 0.03</td>
<td>1.10 ± 0.18</td>
<td></td>
</tr>
<tr>
<td>data</td>
<td>1002</td>
<td></td>
<td>4800</td>
<td>7010</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.5: Number of preselected events after requiring $\sigma(E_T) > 1.5$ and applying the respective $b$-tagging and $\tau$ identification requirements in the “cross section”, “fake $\tau$”, and “$b$ veto” bins for MC samples and data for Type 3 taus.

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cross section</td>
<td>fake $\tau$</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow \tau$(had) + jets</td>
<td>28.34 ± 0.39</td>
<td>67.98 ± 0.53</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow e + jets$</td>
<td>5.02 ± 0.16</td>
<td>53.96 ± 0.47</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow \mu + jets$</td>
<td>4.11 ± 0.14</td>
<td>62.63 ± 0.52</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow l_1l_2$</td>
<td>2.77 ± 0.06</td>
<td>2.87 ± 0.08</td>
</tr>
<tr>
<td>$Wbb \rightarrow \ell\nu bb$</td>
<td>5.87 ± 0.07</td>
<td>12.62 ± 0.10</td>
</tr>
<tr>
<td>$Wcc \rightarrow \ell\nu cc$</td>
<td>3.40 ± 0.04</td>
<td>11.24 ± 0.08</td>
</tr>
<tr>
<td>$Wjj \rightarrow \ell\nu jj$</td>
<td>4.97 ± 0.07</td>
<td>22.76 ± 0.23</td>
</tr>
<tr>
<td>$Zbb \rightarrow \tau\tau bb$</td>
<td>1.14 ± 0.04</td>
<td>0.95 ± 0.04</td>
</tr>
<tr>
<td>$Zcc \rightarrow \tau\tau cc$</td>
<td>0.78 ± 0.03</td>
<td>0.91 ± 0.04</td>
</tr>
<tr>
<td>$Zjj \rightarrow \tau\tau jj$</td>
<td>1.38 ± 0.05</td>
<td>2.74 ± 0.10</td>
</tr>
<tr>
<td>$Zbb \rightarrow ee bb$</td>
<td>0.01 ± 0.01</td>
<td>0.06 ± 0.01</td>
</tr>
<tr>
<td>$Zcc \rightarrow ee cc$</td>
<td>0.01 ± 0.01</td>
<td>0.04 ± 0.01</td>
</tr>
<tr>
<td>$Zjj \rightarrow ee jj$</td>
<td>0.01 ± 0.01</td>
<td>0.03 ± 0.01</td>
</tr>
<tr>
<td>$Zbb \rightarrow \mu\mu bb$</td>
<td>0.00 ± 0.00</td>
<td>0.12 ± 0.01</td>
</tr>
<tr>
<td>$Zcc \rightarrow \mu\mu cc$</td>
<td>0.00 ± 0.00</td>
<td>0.09 ± 0.01</td>
</tr>
<tr>
<td>$Zjj \rightarrow \mu\mu jj$</td>
<td>0.01 ± 0.01</td>
<td>0.09 ± 0.01</td>
</tr>
<tr>
<td>$Zbb \rightarrow \nu\nu bb$</td>
<td>0.09 ± 0.02</td>
<td>1.98 ± 0.14</td>
</tr>
<tr>
<td>$Zcc \rightarrow \nu\nu cc$</td>
<td>0.10 ± 0.02</td>
<td>1.84 ± 0.09</td>
</tr>
<tr>
<td>$Zjj \rightarrow \nu\nu jj$</td>
<td>0.06 ± 0.01</td>
<td>1.46 ± 0.05</td>
</tr>
<tr>
<td>data</td>
<td>1709</td>
<td>17604</td>
</tr>
</tbody>
</table>
Efficiencies of the $\tau$ id, trigger, and $b$ tagging are tabulated in Table 5.6.

Table 5.6: Efficiencies, with statistical uncertainties, of the $\tau$ id, trigger, and $b$ tagging selections for the $t\bar{t}$ MC.

<table>
<thead>
<tr>
<th>Channel ($\tau$ types)</th>
<th>Sample</th>
<th></th>
<th>Efficiency (%)</th>
<th></th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Relative (sequential)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau$ id</td>
<td>Trigger</td>
<td>$b$ tagging</td>
<td>$\tau$ id</td>
<td>Trigger</td>
</tr>
<tr>
<td>1,2</td>
<td>$t\bar{t} \rightarrow \tau$+jets</td>
<td>$13.96 \pm 0.11$</td>
<td>$84.78 \pm 0.37$</td>
<td>$62.74 \pm 0.37$</td>
<td>$13.96 \pm 0.11$</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t} \rightarrow e$+jets</td>
<td>$7.79 \pm 0.10$</td>
<td>$84.06 \pm 0.54$</td>
<td>$61.71 \pm 0.55$</td>
<td>$7.79 \pm 0.10$</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t} \rightarrow \mu$+jets</td>
<td>$2.68 \pm 0.11$</td>
<td>$83.26 \pm 1.52$</td>
<td>$62.21 \pm 1.56$</td>
<td>$2.68 \pm 0.11$</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t} \rightarrow l_1l_2$</td>
<td>$15.87 \pm 0.30$</td>
<td>$78.85 \pm 0.90$</td>
<td>$63.21 \pm 0.91$</td>
<td>$15.87 \pm 0.30$</td>
</tr>
<tr>
<td>3</td>
<td>$t\bar{t} \rightarrow \tau$+jets</td>
<td>$7.05 \pm 0.09$</td>
<td>$85.64 \pm 0.51$</td>
<td>$60.50 \pm 0.51$</td>
<td>$7.05 \pm 0.09$</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t} \rightarrow e$+jets</td>
<td>$1.40 \pm 0.04$</td>
<td>$83.97 \pm 1.20$</td>
<td>$59.84 \pm 1.21$</td>
<td>$1.40 \pm 0.04$</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t} \rightarrow \mu$+jets</td>
<td>$3.05 \pm 0.11$</td>
<td>$84.77 \pm 1.41$</td>
<td>$58.90 \pm 1.41$</td>
<td>$3.05 \pm 0.11$</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t} \rightarrow l_1l_2$</td>
<td>$10.24 \pm 0.25$</td>
<td>$79.05 \pm 1.04$</td>
<td>$64.26 \pm 1.07$</td>
<td>$10.24 \pm 0.25$</td>
</tr>
</tbody>
</table>

5.3 The Event Neural Network

We determine the signal and background contributions to the cross section sample as follows.

1. Start by assuming that the $\tau$ veto sample is purely QCD background. Corrections needed to account for the (small) inaccuracy in this assumption are made later.

2. Choose a set of variables that characterize an event as a whole, i.e. the so-called “shape” and “scale” variables, which have the least sensitivity to the modeling of particular objects, such as $\tau$’s and $E_T$.

3. Using a “sensible” baseline threshold for $\sigma(E_T)$, find the subset of the input variables that gives the best agreement between true and fitted signal events in a large number of pseudo-experiments. This step is necessary because the available background training samples are too small to use all the variables simultaneously.

4. The $\sigma(E_T)$ threshold is similarly tuned using the optimal set of variables.

5. The electroweak ($W/Z$) contribution to the cross section sample is estimated by using both the shape and normalization given by MC.
6. The NN output distribution of the remainder of the cross section sample is fitted to estimate the signal and QCD contributions. The signal contribution to the fake $\tau$ sample used for QCD modeling is estimated using MC shape and data-based normalization for signal. For the last step, we start with the theoretical prediction for $\sigma(tt)$, then iterate until the estimated contamination is fully consistent with the fitted value.

This procedure is the same in spirit as the one followed in the p17 analysis but differs mainly in two details. First, a rigorous effort is made to select the optimal set of input variables for the NN and, second, the signal contamination in the $\tau$ veto sample is taken into account.

### 5.3.1 Choice of input variables for the event NN

We consider the following variables:

- $\sigma(E_T)$ - Calculated from known resolutions of reconstructed jets, electrons, muons and unclustered energy, this quantity corresponds, roughly, to the number of standard deviations the true $E_T$ is from zero [11, 40]. Since the QCD background has no high-$p_T$ neutrinos, $E_T$ significance tends to be small for those events, but high for events with high-$p_T$ neutrinos, such as our signal.

- $H_T$ - The scalar sum of $p_T$’s of all jets in the event, including any $\tau$ candidate. Our signal events tend to have a higher $H_T$ than background.

- Aplanarity ($A$) [41] - The normalized momentum tensor of an event is defined as

$$M_{ab} \equiv \frac{\sum_i p_{ia} p_{ib}}{\sum_i p_i^2},$$

where $\vec{p}_i$ is the momentum of the $i$th object and the indices $a, b$ label the cartesian components. All jets, including the $\tau$ is included in the calculation of $M$. The eigenvalues $\lambda_i$ of $M$, $\lambda_1 \geq \lambda_2 \geq \lambda_3$, satisfy $\lambda_1 + \lambda_2 + \lambda_3 = 1$. The event aplanarity is defined as $A = \frac{3}{2} \lambda_3$ and serves as a measure of the flatness of the event. $0 \leq A \leq 0.5$. This is a good discriminant because
events like $t\bar{t}$ that contain cascade decays of high-mass objects, tend to be more aplanar on average than QCD events where the jets result primarily from gluon radiation.

- **Sphericity ($S$)** [41] - Defined as $S = \frac{3}{2}(\lambda_2 + \lambda_3); \ 0 \leq S \leq 1.0$, sphericity is a measure of the “roundness” of an event. For the same reason as for aplanarity, $t\bar{t}$ events tend to be more spherical than QCD events.

- **Centrality ($C$)** - Defined as $\frac{H_T}{H}$, where $H$ is the sum of energies of all jets in the event. On average, our signal events will be more central than QCD events, where the jets tend to be more forward.

- **Top and W mass $\chi^2(m_{m_t},m_W)$** - This is a $\chi^2$-like variable defined as $L = \left(\frac{m_{3j} - m_t}{\sigma_t}\right)^2 + \left(\frac{m_{2j} - m_W}{\sigma_W}\right)^2$, where $m_t, m_W, \sigma_t, \sigma_W$ are $t$ and $W$ masses (172.4 GeV and 81.02 GeV respectively) and resolution values (19.4 GeV and 8.28 GeV respectively). $m_{3j}$ and $m_{2j}$ are masses of 2- and 3-jet combinations that minimize $L$ subject to the constraint that the two jets used in forming $m_{2j}$ must be a subset of the three forming $m_{3j}$. This variable is expected to have lower values for events containing all-hadronic decay of at least one top quark, such as our signal, and higher for QCD fakes.

- **$\cos \theta^*$** - Cosine of the angle between the beam axis and the highest-$p_T$ jet in the rest frame of all the jets in the event. $t\bar{t}$ events tend to have lower values of $\cos \theta^*$ than QCD events.

- **$m_{jets}$** - The invariant mass of all jets in the event, including the $\tau$. For reasons akin to those cited for $A$ and $S$, $t\bar{t}$ events are expected to have lower values of $m_{jets}$ than QCD events.

Obviously, many of the above variables are very strongly correlated. Therefore their optimal exploitation calls for a multivariate discriminant like Artificial Neural Networks that are good at taking such correlations into account.

We use half of the “fake $\tau$” data sample as the background template for events with $\tau$’s of Types 1 or 2, one fifth for type 3 and a third of the $t\bar{t} \rightarrow \tau + jets$ MC sample as the signal template to train the NN’s. The rest are used as the test samples in the cross section measurement. The “$b$ veto” sample is used as an orthogonal control sample to check the validity of background modeling. Distributions of all the variables described above for the various samples are presented in Appendix B.
For training the Neural Network we used the Multilayer Perceptron program [46]. Figure 5.1 shows the usual plots the program produces for checking the weights, convergence, and performance expectations after a training session for a typical set of variables.

Figure 5.1: Training of event Neural Network output.
5.3.2 NN optimization

In trying to find the optimal set of input variables for the event NN, we limited ourselves to no more than 5 variables so as to ensure adequate training with the modest size of background samples available.

![Figure 5.2: MET significance ($\sigma(E_T)$) distribution for $t\bar{t}$ signal, electroweak and QCD backgrounds.](image)

The $\sigma(E_T)$ distributions for $t\bar{t}$ signal, electroweak and QCD background are shown in Fig. 5.2. To get adequate signal enhancement with respect to QCD background, we required $\sigma(E_T) > 2.0$. Then we tried 13 different combinations of input variables. For each, we created an ensemble of 20000 pseudo-datasets, each containing events picked randomly, according to the appropriate Poisson distributions, from QCD, $W/Z$, and $t\bar{t}$ templates. Each of these ensembles was treated like real data, i.e., we applied all the cuts and doing the shape fit of event NN. QCD templates used in the fit were drawn from the “fake $\tau$” sample. We used

$$f \equiv \frac{n_{fit} - n_{true}}{n_{true}},$$

as a figure of merit, where $n_{fit}$ is the number of $t\bar{t}$ events given by the fit and $n_{true}$ is the true number of $t\bar{t}$ events put in that ensemble. If everything is done right, the distribution of $f$ for a given choice of input variables and $\sigma(E_T)$ should have a normal distribution centered at zero. Both
here, and later in the optimization of $\sigma(E_T)$, the choice for which $f$ had the smallest RMS was picked.

In order to check the validity of our ensemble tests procedure, we plot the distribution of the fitted number of $tt$ events and the “pull”, defined as $p = \frac{(N_{\text{fit}} - N_{\text{true}})}{\sigma_{\text{fit}}}$, in Fig. 5.3. Both look reasonable.

![Figure 5.3: Left: Distribution of the fitted number of $tt$. Right: The corresponding pull distribution.](image)

Figure 5.3: Left: Distribution of the fitted number of $tt$. Right: The corresponding pull distribution.
Table 5.7: Width and mean of \( f \equiv \frac{(n_{fit} - n_{true})}{n_{true}} \) distributions from an ensemble of 20000 pseudo-datasets, with a varied set of input variables used in the event NN. \( \sigma(E_T) > 2.0 \) was required for all.

<table>
<thead>
<tr>
<th>Set</th>
<th>Variables used in NN</th>
<th>( f \equiv \frac{(n_{fit} - n_{true})}{n_{true}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \sigma(E_T) ) ( H_T ) ( A ) ( S ) ( C ) ( \chi^2_{m_t,m_W} ) ( \cos \theta^* ) ( m_{jets} )</td>
<td>RMS</td>
</tr>
<tr>
<td>1</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>2</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>7</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>8</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>10</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td>( \checkmark ) ( \checkmark )</td>
</tr>
<tr>
<td>11</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td>( \checkmark )</td>
</tr>
<tr>
<td>12</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td>( \checkmark ) ( \checkmark )</td>
</tr>
<tr>
<td>13</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark ) ( \checkmark )</td>
<td>( \checkmark ) ( \checkmark ) ( \checkmark )</td>
</tr>
</tbody>
</table>
The choices of input variables together with the corresponding RMS and mean of $f$ are shown in Table 5.7. We select Set 1, which has the lowest RMS, and use it to optimize the $\sigma(E_T)$ threshold following the same procedure. The results are summarized in Table 5.8 and Fig. 5.4. Distributions of $f$ used in the optimization of the event NN can be found in Appendix C.

Table 5.8: Width and mean of $f \equiv \frac{\langle n_{\text{fit}} - n_{\text{true}} \rangle}{n_{\text{true}}}$ distributions from an ensemble of 20000 pseudo-datasets, with Set 1 of NN input variables ($\sigma(E_T), H_T, A, m_{jets}$) for different $\sigma(E_T)$ thresholds.

<table>
<thead>
<tr>
<th>$\sigma(E_T)$</th>
<th>RMS</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.1665</td>
<td>0.0002</td>
</tr>
<tr>
<td>1.0</td>
<td>0.1558</td>
<td>0.0024</td>
</tr>
<tr>
<td>1.5</td>
<td>0.1479</td>
<td>0.0004</td>
</tr>
<tr>
<td>2.0</td>
<td>0.1564</td>
<td>0.0025</td>
</tr>
<tr>
<td>2.5</td>
<td>0.1543</td>
<td>0.0014</td>
</tr>
<tr>
<td>3.0</td>
<td>0.1562</td>
<td>0.0016</td>
</tr>
<tr>
<td>3.5</td>
<td>0.1660</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

From Tables 5.7 and 5.8 we conclude that Set 1 with $\sigma(E_T) > 1.5$ is our optimal choice. Figure 5.5 show the neural network output distributions with this choice for signal, the most important $W/Z+\text{jets}$ processes, QCD background, and data for “Type 1 or 2 $\tau$” and “Type 3 $\tau$” channels. A good agreement between data and SM predictions is seen in both.
Figure 5.4: RMS of $f \equiv \frac{(n_{\text{fit}} - n_{\text{true}})}{n_{\text{true}}}$ distributions from an ensemble of 20000 pseudo-datasets, with Set 1 of NN input variables ($\sigma(E_T), H_T, A, m_{\text{jets}}$) as a function of the $\sigma(E_T)$ threshold.

Figure 5.5: The event Neural Network output for signal and background processes, as well as data, in the “Type 1 or 2 $\tau$” channel (top) and the “Type 3 $\tau$” channel (bottom).
CHAPTER 6
CROSS SECTION CALCULATION

The final number of events in data together with estimated contributions from $t\bar{t}$, $W/Z$+jets, and QCD after all selections are shown Table 6.1. We can now perform the measurement. The cross section is defined by

$$\sigma(t\bar{t} \to \tau + jets) = \frac{\text{Number of measured } t\bar{t} \text{ pairs}}{\epsilon(t\bar{t} \to \tau + jets) \text{BR}(t\bar{t} \to \tau + jets) \mathcal{L}} \quad (6.1)$$

where $\epsilon(t\bar{t} \to \tau + jets)$ is

$$\epsilon(t\bar{t} \to \tau + jets) = \frac{\text{Final number of events}}{\text{Initial number of events}} \quad (6.2)$$

$\text{BR}(t\bar{t} \to \tau + jets)$ is the branching ratio of $t\bar{t} \to \tau + jets$ when $t\bar{t}$ decays to tau hadronic/electron/muon + jets and dilepton are included and $\mathcal{L}$ is the luminosity of the sample. If all terms in Eq. 6.1 are available we are then ready to measure the cross section. However we are not doing a counting experiment here, but want to use the entire range of the NN output. The cross section is measured by minimizing the sum of the negative log-likelihood functions for each bin of both the “Types 1, 2” and the “Type 3” $\tau$ channels.

$$L(\sigma, \tilde{N}_i, N_{i}^{\text{obs}}) \equiv -\ln \left( \prod_i \frac{\tilde{N}_i^{N_{i}^{\text{obs}}}}{N_{i}^{\text{obs}}} e^{-\tilde{N}_i} \right), \quad (6.3)$$

where $\tilde{N}_i \equiv \sigma \times BR \times \epsilon tt_i \times \mathcal{L} + N_{i}^{\text{bkg}}$ is the number of events predicted in bin $i$ of the event NN output distribution in data and $N_{i}^{\text{obs}}$ is the observed number in that bin. The $\sigma$ that minimizes $L$ is the most probable cross section. The resultant cross sections are
Type 1 or 2 $\tau$+jets channel: $\sigma(t\bar{t}) = 9.52^{+1.01}_{-0.98}$ (stat) $\pm 0.58$ (lumi) pb,

Type 3 $\tau$+jets channel: $\sigma(t\bar{t}) = 4.40^{+2.02}_{-1.90}$ (stat) $\pm 0.27$ (lumi) pb,

All $\tau$+jets channels combined: $\sigma(t\bar{t}) = 8.63^{+0.90}_{-0.87}$ (stat) $\pm 0.52$ (lumi) pb.

In cross sections shown above only statistical and luminosity uncertainties are included. Systematics were not measured for this present work.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\tau$ Types 1, 2</th>
<th>$\tau$ Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>data</td>
<td>$n_{MC}$ $n_{fit}$</td>
<td>$n_{MC}$ $n_{fit}$</td>
</tr>
<tr>
<td>W+jets</td>
<td>20.68 $\pm$ 0.12</td>
<td>14.24 $\pm$ 0.11</td>
</tr>
<tr>
<td>Z+jets</td>
<td>4.72 $\pm$ 0.09</td>
<td>3.60 $\pm$ 0.08</td>
</tr>
<tr>
<td>$t\bar{t} \to \tau$(had)+jets</td>
<td>86.36 $\pm$ 0.43</td>
<td>42.51 $\pm$ 0.30</td>
</tr>
<tr>
<td>$t\bar{t} \to e$+jets</td>
<td>43.35 $\pm$ 0.32</td>
<td>7.53 $\pm$ 0.12</td>
</tr>
<tr>
<td>$t\bar{t} \to \mu$+jets</td>
<td>5.61 $\pm$ 0.12</td>
<td>6.16 $\pm$ 0.12</td>
</tr>
<tr>
<td>$t\bar{t} \to l_1l_2$</td>
<td>6.31 $\pm$ 0.08</td>
<td>4.16 $\pm$ 0.06</td>
</tr>
<tr>
<td>$t\bar{t}$ total</td>
<td>141.64 $\pm$ 0.56</td>
<td>60.37 $\pm$ 0.35</td>
</tr>
<tr>
<td>QCD</td>
<td>$788.13 \pm 19.95$</td>
<td>$1654.00 \pm 17.00$</td>
</tr>
</tbody>
</table>

Table 6.1: The final number of events in data, estimated contributions from $t\bar{t}$, $W/Z$+jets, and QCD.

A comment on the size of the statistical uncertainty is in order here. A cursory comparison of our final result with that from p17 may suggest that we have achieved a 55% reduction in the statistical uncertainty despite a 5-fold increase in the integrated luminosity. However, that would not be a fair statement. The differences between the two analyses have been noted earlier. The algorithmic refinements to various object identification and corrections, as well as the optimizations internal to this analysis would improve the accuracy of our measurement, but are not expected to
affect the statistical precision significantly. Similarly, accounting for signal contamination in the background sample would only correct for a bias. The new element that accounts for the difference in statistical uncertainty is the “NNelec > 0.9” cut on Type 2 τ’s, which was not used in the p17 analysis. As single-prong candidates with associated EM cluster, Type 2 τ’s receive a significant contribution from electrons that fail the tight electron selection. The NNelec cut is designed to minimize this contribution. This is done by training a NN to distinguish Type 2 τ’s from electrons. However, this handle was not available at the time of the p17 analysis. Therefore, that measurement was based on a larger spectrum of t¯t decays - specifically, it included a fairly substantial number of t¯t → e+jets events where the e failed the tight electron selection, but passes the NN-based τ identification as Type 2, which was only trained to discriminate against QCD jets. To demonstrate the validity of this argument, we repeated the analysis removing the NNelec requirement. The yields in this case are shown in Table 6.2 and must be compared with the ones given in Table 6.1.

<table>
<thead>
<tr>
<th>Source</th>
<th>τ Types 1, 2</th>
<th>n_{MC}</th>
<th>n_{fit}</th>
</tr>
</thead>
<tbody>
<tr>
<td>data</td>
<td></td>
<td></td>
<td>1424</td>
</tr>
<tr>
<td>W+jets</td>
<td></td>
<td>45.22 ± 0.11</td>
<td></td>
</tr>
<tr>
<td>Z+jets</td>
<td></td>
<td>7.17 ± 0.11</td>
<td></td>
</tr>
<tr>
<td>t¯t → τ(had)+jets</td>
<td></td>
<td>102.03 ± 0.46</td>
<td></td>
</tr>
<tr>
<td>t¯t → e+jets</td>
<td></td>
<td>199.30 ± 0.66</td>
<td></td>
</tr>
<tr>
<td>t¯t → μ+jets</td>
<td></td>
<td>10.94 ± 0.16</td>
<td></td>
</tr>
<tr>
<td>t¯t → l_1l_2</td>
<td></td>
<td>13.21 ± 0.11</td>
<td></td>
</tr>
<tr>
<td>t¯t total</td>
<td></td>
<td>325.46 ± 0.83</td>
<td>353.32 ± 25.33</td>
</tr>
<tr>
<td>QCD</td>
<td></td>
<td></td>
<td>1018.28 ± 25.33</td>
</tr>
<tr>
<td>Signal significance</td>
<td></td>
<td></td>
<td>8.62</td>
</tr>
<tr>
<td>S/π</td>
<td></td>
<td></td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 6.2: The final number of events in data, estimated contributions from t¯t, W/Z+jets, and QCD in τ Type 1,2 channel with the NNelec cut removed.
The cross sections measured without the NNelec > 0.9 requirement on Type 2 $\tau$’s are

Type 1 or 2 $\tau$+jets channel: \[ \sigma(t\bar{t}) = 7.75^{+0.57}_{-0.54} \text{ (stat)} \pm 0.47 \text{ (lumi)} \text{ pb}, \]

All $\tau$+jets channels combined: \[ \sigma(t\bar{t}) = 7.54^{+0.55}_{-0.53} \text{ (stat)} \pm 0.46 \text{ (lumi)} \text{ pb}. \]

We find that the statistical uncertainty decreases by roughly a factor of $\sqrt{5}$ compared to p17 as a result of the 5-fold increase in data, as one would expect. With the statistical uncertainty dominating the measurement with purer $\tau$’s, this is indeed a significantly stronger result, and a legitimate one in its own right, especially in the context of the SM. However, the new result with purer Type 2 $\tau$’s, albeit a statistically weaker result, should be of greater interest when one considers physics scenarios beyond the standard model that are expected to preferentially enhance $t\bar{t} \rightarrow \tau + X$ final states.
CHAPTER 7
CONCLUSION

This note presents the measurement of $\sigma(t\bar{t})$ at $\sqrt{s} = 1.96$ TeV from DØ Run II. The decay channel studied involves one hadronically decaying $\tau$ lepton, two b-jets, two light jets and $E_T$. The trigger used was JT4_3JT15L_VX with integrated luminosity $5069.80 \text{ pb}^{-1}$.

The main challenge was to reject the very large QCD multijet background, while at the same time properly handling the physical electroweak background. In order to achieve this, NN-based $\tau$ ID and b-tagging algorithms were employed. In addition, the relevant topological variables were combined into a NN trained to differentiate the signal from QCD. Type 1 or 2 $\tau$ and type 3 $\tau$ were treated as independent channels and then combined.

In the end we measured the cross section (assuming a top mass of 172.5 GeV) to be

$$\sigma(t\bar{t}) = 8.63^{+0.90}_{-0.87} \text{ (stat)} \pm 0.52 \text{ (lumi)} \text{ pb},$$

which is in a good agreement with other DØ measurements with a top mass of 172.5 GeV [42, 43, 45].
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URL http://schwind.home.cern.ch/schwind/MLPfit.html
APPENDIX A

TURN-ON CURVES FOR TRIGGER JT2_3JT15L_IP_VX
Here are shown all turn-on curves for all three levels of the trigger JT2_3JT15L_IP_VX as described in Chapter 4.3.

Level 1 jet turn-on curves for trigger JT2_3JT15L_IP_VX

Figure A.1: Level 1 jet turn-on curves, low luminosity.

Figure A.2: Level 1 jet turn-on curves, medium luminosity.
Figure A.3: Level 1 jet turn-on curves, high luminosity.

Level 2 jet turn-on curves for trigger JT2_3JT15L_IP_VX

(a) Low luminosity $p_T > 8$ GeV  (b) Medium luminosity $p_T > 8$ GeV  (c) high luminosity $p_T > 8$ GeV

Figure A.4: Level 2 $p_T > 8$ GeV jets turn-on curves.
Level 2 $H_T$ turn-on curves for trigger JT2.3JT15L.IP.VX

Figure A.5: L2 $H_T$ turn-on curves, low luminosity.

Figure A.6: L2 $H_T$ turn-on curves, medium luminosity.

Figure A.7: L2 $H_T$ turn-on curves, high luminosity.
Level 2 $E_T$ turn-on curves for trigger JT2_3JT15L_IP_VX

Figure A.8: L2 $E_T$ turn-on curves, low luminosity.

Figure A.9: L2 $E_T$ turn-on curves, medium luminosity.

Figure A.10: L2 $E_T$ turn-on curves, high luminosity.
Level 2 Sphericity turn-on curves for trigger JT2.3JT15L.IP.VX

![Sphericity turn-on curves for different luminosities](image)

(a) Sphericity $> 0.1$ turn-on curve, low luminosity
(b) Sphericity $> 0.1$ turn-on curve, medium luminosity
(c) Sphericity $> 0.1$ turn-on curve, high luminosity

Figure A.11: L2 Sphericity turn-on curves.

Level 2 STTIP turn-on curves for trigger JT2.3JT15L.IP.VX

![STTIP efficiency in low luminosity range](image)

(a) L2STTIP, 0 and 1 tight NN tags
(b) L2STTIP, 2 and 3 tight NN tags

Figure A.12: L2STTIP efficiency in the low luminosity range. Left: events with 0 (red) and 1 (black) tight NN b-tags. Right: events with 2 (red) and 3 (black) tight NN b-tags.

![STTIP efficiency in medium luminosity range](image)

(a) L2STTIP, 0 and 1 tight NN tags
(b) L2STTIP, 2 and 3 tight NN tags

Figure A.13: L2STTIP efficiency in the medium luminosity range. Left: events with 0 (red) and 1 (black) tight NN b-tags. Right: events with 2 (red) and 3 (black) tight NN b-tags.
Figure A.14: L2STTIP efficiency in the high luminosity range. Left: events with 0 (red) and 1 (black) tight NN b-tags. Right: events with 2 (red) and 3 (black) tight NN b-tags.
Level 3 jet turn-on curves for trigger JT2_3JT15L_IP_VX

(a) $p_T > 15$ GeV
(b) $p_T > 25$ GeV

Figure A.15: L3 jet turn-on curves, low luminosity.

(a) $p_T > 15$ GeV
(b) $p_T > 25$ GeV

Figure A.16: L3 jet turn-on curves, medium luminosity.

(a) $p_T > 15$ GeV
(b) $p_T > 25$ GeV

Figure A.17: L3 jet turn-on curves, high luminosity.
Level 3 b-tag on curves for trigger JT2_3JT15L_IP_VX

Figure A.18: (a) Efficiency of the L3 b-tag (Level3 Event $b$-tag< 0.4) for the low luminosity range in triggerlist v15. The selected events passed the rest of the trigger and offline event selection and had zero (red) or one (black) offline NN (TIGHT) $b$-tags. (b) Same for events with 2(red) and 3(black) offline NN (TIGHT) $b$-tags.

Figure A.19: (a) Efficiency of the L3 b-tag (Level3 Event $b$-tag< 0.4) for the medium luminosity range in triggerlist v15. The selected events passed the rest of the trigger and offline event selection and had zero (red) or one (black) offline NN (TIGHT) $b$-tags. (b) Same for events with 2(red) and 3(black) offline NN (TIGHT) $b$-tags.
Figure A.20: (a) Efficiency of the L3 $b$-tag (Level3 Event $b$-tag < 0.4) for the high luminosity range in triggerlist v15. The selected events passed the rest of the trigger and offline event selection and had zero (red) or one (black) offline NN (TIGHT) $b$-tags. (b) Same for events with 2(red) and 3(black) offline NN (TIGHT) $b$-tags.

Figure A.21: (a) Efficiency of the L3 $b$-tag (Level3 Event $b$-tag < 0.4) for the low luminosity range in triggerlist v16. The selected events passed the rest of the trigger and offline event selection and had zero (red) or one (black) offline NN (TIGHT) $b$-tags. (b) Same for events with 2(red) and 3(black) offline NN (TIGHT) $b$-tags.

Figure A.22: (a) Efficiency of the L3 $b$-tag (Level3 Event $b$-tag < 0.4) for the medium luminosity range in triggerlist v16. The selected events passed the rest of the trigger and offline event selection and had zero (red) or one (black) offline NN (TIGHT) $b$-tags. (b) Same for events with 2(red) and 3(black) offline NN (TIGHT) $b$-tags.
Figure A.23: (a) Efficiency of the L3 $b$-tag (Level3 Event $b$-tag $< 0.4$) for the high luminosity range in triggerlist v16. The selected events passed the rest of the trigger and offline event selection and had zero (red) or one (black) offline NN (TIGHT) $b$-tags. (b) Same for events with 2(red) and 3(black) offline NN (TIGHT) $b$-tags.
APPENDIX B

DISCRIMINANT VARIABLES USED IN EVENT NN TRIALS
Figure B.1 shows the distributions of the variables used in the various trials of the event NN for $t\bar{t}$ signal, $W/Z$+jets, and QCD background. The histograms are normalized to unit area.
Figure B.1: Discriminant variables used in the Event NN's.
APPENDIX C

OPTIMIZATION OF THE EVENT NN
Figures C.1 show the distribution of the figure of merit $f \equiv \frac{(n_{fit} - n_{true})}{n_{true}}$ (Eq. 5.2), which is used to find the optimal set of input variables to the event NN, as described in Section 5.3.2, with $\sigma(E_T) > 1.5$. The mean and RMS of these are tabulated in Table 5.7. Figure C.2 shows the distributions of $f$ when the $\sigma(E_T)$ threshold is varied from 0.0 to 3.5 for the optimal set of variables (Set 1: $\sigma(E_T), H_T, A, m_{jets}$). The mean and RMS of these are tabulated in Table 5.8.
Figure C.1: Distribution of the figure of merit for Sets 1-15, with $\sigma(E_T) > 2.0$. 
Figure C.2: Distribution of the figure of merit for Set 1 and different values of the $\sigma(\mathbb{E}_T)$ threshold.
APPENDIX D

DISTRIBUTIONS OF EVENT NN VARIABLES: DATA V. MODEL
Figures D.1 - D.2 (D.3- D.8) show the distribution in the cross section (b-veto control) sample of variables tested as inputs to the event NN, together with estimated contributions from the various signal and background sources normalized according to Table 6.1. The samples are defined in Sec. ??. $E_T$ is also shown although it was not tested. The error bars represent statistical uncertainties only.

Signal sample plots

This sample, which is used to extract the signal cross section, consists of 9.4% of $\tau$’s of Type 1 or 2 events and 2.1% of Type 3 events.
Figure D.1: $A$ and $H_T$ in the signal sample with $\tau$'s of Type 1 or 2 (top) and Type 3 (bottom).
Figure D.2: $C$ and $S$ in the signal sample with $\tau$’s of Type 1 or 2 (top) and Type 3 (bottom).
Figure D.3: $m_{\text{jets}}$ and $\cos \theta^*$ in the signal sample with $\tau$’s of Type 1 or 2 (top) and Type 3 (bottom).
Figure D.4: $E_T$ and $\sigma(E_T)$ in the signal sample with $\tau$'s of Type 1 or 2 (top) and Type 3 (bottom).
Control (b-veto) sample plots

The $b$-veto sample is used to test our modeling of the QCD events. With its requirement that there be no $b$-tagged jet in an event, the $t\bar{t}$ content of this sample is very small: 0.6% for $\tau$’s of Type 1 or 2 and 0.2% for Type 3.
Figure D.5: $A$ and $H_T$ in the $b$-veto sample with $\tau$’s of Type 1 or 2 (top) and Type 3 (bottom).
Figure D.6: $C$ and $S$ in the signal sample with $\tau$’s of Type 1 or 2 (top) and Type 3 (bottom).
Figure D.7: $m_{\text{jets}}$ and $\cos \theta^*$ in the signal sample with $\tau$'s of Type 1 or 2 (top) and Type 3 (bottom).
Figure D.8: $E_T$ and $\sigma(E_T)$ in the signal sample with $\tau$'s of Type 1 or 2 (top) and Type 3 (bottom).