Measurement of the Top Quark Polarization in the Top Quark Pair Production using the Dilepton Final State Events at the Tevatron

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Measurement of the Top Quark Polarization in the Top Quark Pair Production using the Dilepton Final State Events at the Tevatron

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Abstract

In this thesis, we present a measurement of the top quark polarization in the $t\bar{t}$ pair production in $p\bar{p}$ collisions at the Fermilab Tevatron collider at $\sqrt{s}=1.96$ TeV. We use the full Run II data sample corresponding to $9.1\, fb^{-1}$ of integrated luminosity collected with the CDF detector. We select the final state events containing two high transverse momentum leptons (electron or muon), two jets and large missing $E_T(E_T)$.

We measure the top quark polarization through the two dimensional distribution of lepton angles along the spin quantization axis. In order to reconstruct the angular distribution of top quark decay products, we perform full kinematic reconstruction using predicted distributions of $P_t^{t\bar{t}}, P_T^{t\bar{t}}$ and $M_{t\bar{t}}$. We make signal templates using NLO POWHEG Monte Carlo simulation and background templates from admixture of Monte Carlo simulations and data-based background modellings. Then, we perform binned likelihood fit of two dimensional angular distribution of data to signal and background templates and obtain a measurement of the top quark polarization.

We consider two different axes for the top quark polarization measurement: the helicity axis, and the transverse axis. Two measurements of $\alpha P$ in each basis, the product of the leptonic spin analyzing power and the top quark polarization, are performed assuming that the polarization is introduced by either a CP conserving (CPC) or a CP violating (CPV) production process. We measure the top quark polarizations of
\[
\alpha_{P_{hel}}^{CPC} = -0.130 \pm 0.114^{+0.114}_{-0.109}(\text{stat.}) \pm 0.111(\text{syst.}) \\
\alpha_{P_{hel}}^{CPV} = -0.046 \pm 0.123(\text{stat.}) \pm 0.040(\text{syst.}) \\
\alpha_{P_{trans}}^{CPC} = -0.077 \pm 0.177(\text{stat.}) \pm 0.098(\text{syst.}) \\
\alpha_{P_{trans}}^{CPV} = -0.111 \pm 0.146(\text{stat.}) \pm 0.055(\text{syst.}) \\
\]

which are consistent with standard model predictions of negligible polarization.

**keywords**: Top quark polarization, Top quark, Fermilab, Top Dilepton Channel, Likelihood method, CDF experiment, Tevatron

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Chapter 1

Introduction

In particle physics, we study the ultimate materials and laws that make up our universe. It is also called high energy physics because exploring a small world requires high energy. According to cosmology, particle physics research of the smallest world is also the largest of the worlds, since the early universe created by the Big Bang was very high temperature.

As of now, the Standard Model (SM), a theory that describes these elementary particles and interactions, has been very successful. Particle physics have been using particle colliders to investigate the fundamental particles and the interactions. The Tevatron is a proton-antiproton (p\bar{p}) collider located at the Fermi National Accelerator Laboratory (Fermilab). It is a powerful enough to produce top quarks. At the Tevatron, top quarks are predicted to be produced in pairs via the strong force, and decay via the electroweak force. The
top quark is by far the heaviest fundamental particle in the Standard Model. Because of its large mass, the top quark has several unique properties and could provide hints for the origin of mass and physics beyond the Standard Model.

Top quark and tau neutrino are observed in 1995 [1, 2] and in 2000 [3] respectively. Finally, in 2013, CERN observed the Higgs boson, and all standard model particles were observed. Despite being the most successful theory of particle physics to date, the Standard Model is an incomplete theory. There are fundamental physical phenomena in nature that the SM does not adequately explain (gravity, dark matter/dark energy, neutrino mass, matter-antimatter asymmetry).

The CDF and DØ experiments at the Fermilab Tevatron have measured the asymmetry between yields of forward- and backward-produced top and antitop quarks based on their rapidity difference and the asymmetry between their decay leptons. The combined inclusive and differential asymmetries are consistent with recent the Standard Model(SM) predictions [16]. Other top spin related quantity(top polarization) can be an alternative tool to study SM precisely.

The measurement of one of the top quark properties, the top quark polarization, is important for the Standard Model confirmation or beyond Standard Model searches in the top quark sector.

Additional, the initial state is different to the LHC and polarizations along
some quantization axes from the \( pp \) collisions are expected to be larger than those for \( pp \) collisions \cite{38,17}, therefore offering greater sensitivity than the LHC.

There are strong motivations for the measurement of the top quark polarization at the Tevatron.

This thesis is organized as follows. Chapter 1 describes the Standard Model and top quark physics. Chapter 2 provides the description of the experimental apparatus, that is the Tevatron accelerator and the CDF detector. Chapter 3 describes the data and simulation samples and events selection requirements. Chapter 4 is the main part of this thesis, the measurement techniques for the top quark polarization are described. Chapter 5 presents statistical and systematic uncertainties. The final results are presented in the Chapter 6 and the conclusion is in the Chapter 7.

1.1 The Standard Model

The Standard Model of elementary particle physics is a quantum field theory that describes the fundamental particles and the interactions between them. It includes the strong, weak and electromagnetic force. The model itself is a combination of the theory of quantum chromodynamics (QCD) and the Glashow-Salam-Weinberg (GSW) theory of electroweak interactions.

The strong force is described by quantum chromodynamics (QCD), a quan-
tum field theory with an $SU(3)_C$ gauge group, and an asymptotically free coupling. Asymptotic freedom means that the strong force is weak at high energies or small distances, and only become strong at low energies or large distances. The strong force becomes strong enough at large distances that when colored quarks and gluons become separated, the binding energy between them is large enough to create new quarks and gluons. All the free quarks and gluons ultimately become bound into hadrons. This process of hadronization has a characteristic scale of $\lambda_{QCD} \sim 200$ MeV, which corresponds to a time scale of $\frac{1}{\lambda_{QCD}} \sim 10^{-24}$ s.

The electromagnetic and weak forces are combined together into a single electroweak force which obeys an $SU(2)_L \otimes SU(1)_Y$ gauge group. The $SU(2)_L$ group has three generators and the $SU(1)_Y$ group has one, corresponding to four gauge bosons that mediate the electroweak force: $W^1_\mu, W^2_\mu, W^3_\mu$ for $SU(2)_L$ and $B_\mu$ for $SU(1)_Y$. The $SU(2)_L \times SU(1)_Y$ symmetry of the electroweak interaction is spontaneously broken through its coupling to the scalar higgs field. The higgs field has a degenerate ground state at a finite value of the field and thus spontaneously breaking turn into three massive gauge bosons ($W^+, W^-, Z^0$) and the massless photon which obeys an unbroken $SU(1)_{EM}$ gauge symmetry.

The Standard Model contains the strong interaction which is represented as $SU(3)_C$ and the electroweak interaction which is represented as $SU(2)_L \otimes SU(1)_Y$. Therefore, the Standard Model is described as follows, and is locally
invariant under transformations of the group.

\[ G = SU(3)_C \otimes SU(2)_L \otimes SU(1)_Y \]  

(1.1)

There is another known force in the nature, graviton, but its interaction is too weak to be detected in the subatomic experiments. Therefore gravitation is not understood in terms of particle physics, and has not been included the Standard Model.

The fundamental particles are categorized into two categories, spin \( s = \frac{1}{2} \) fermions which are the constituents of normal matter, and spin \( s = 1 \) bosons which mediate the force between fermions.

Spin \( s = \frac{1}{2} \) fermions are classified into quarks and leptons. There are six types of quarks: up \( (u) \), down \( (d) \), charm \( (c) \), strange \( (s) \), top \( (t) \) and bottom \( (b) \). Similarly, there are six types of leptons: electron \( (e) \), muon \( (\mu) \), tau \( (\tau) \), and their respective neutrinos \( (\nu_e, \nu_\mu, \nu_\tau) \). These fermions are classified into the three generations of left-handed and right-handed quarks and leptons. The left-handed fermions are in weak isospin doublets, while the right-handed fermions are in weak isospin singlets:

**1st Generation:**

\[
L_e = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \quad R_e = e^-_R, \quad L^{(1)}_q = \begin{pmatrix} u \\ d' \end{pmatrix}_L, \quad R^{(1)}_u = u_R, \quad R^{(1)}_d = d_R
\]

**2nd Generation:**
\[ L_\mu = \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \quad R_\mu = \mu^- R, \quad L_q^{(2)} = \begin{pmatrix} c \\ s' \end{pmatrix}, \quad R_u^{(2)} = c_R, \quad R_d^{(2)} = s_R \]

**3rd Generation:**

\[ L_\tau = \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}, \quad R_\tau = \tau^- R, \quad L_q^{(3)} = \begin{pmatrix} t \\ b' \end{pmatrix}, \quad R_u^{(3)} = t_R, \quad R_d^{(3)} = b_R \]

These fermions are characterized with weak isospin (I) and weak hypercharge (Y) through the relation \( Q = I_3 + \frac{1}{2} Y \), where \( Q \) is the electric charge. The mass eigenstates of the left-handed down-type quarks \((d', s', b')\) are related to flavor eigenstates \((d, s, b)\) through the Cabibbo-Kobayashi-Masukawa matrix \([4, 5]\):

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

(1.2)

The fundamental properties of fermions are summarized in Table 1.1.

The interaction between fermions is mediated by spin \( s = 1 \) gauge bosons. The photon\((\gamma)\) carry electromagnetic force, the \( W^\pm \) and \( Z \) bosons carry the weak force, and the gluons \((g)\) carry the strong force. The photon is massless, while the \( W^\pm \) and \( Z \) bosons are massive particles. In the Standard Model, the \( W^\pm \) and \( Z \) bosons acquire the mass as a result of the electroweak symmetry breaking through the Higgs mechanism. The gluon is the massless bi-colored particle and influences only quarks. The properties of bosons are summarized in Table 1.2.
Table 1.1: Fundamental properties of fermions [6].
The Standard Model has been successful in describing interactions of the particles described above, all of which have been discovered experimentally. In addition, many of the predicted properties of these particles have been confirmed, some to a high degree of precision. However, in order for the symmetry described in Equation 1.1 to be exact, the fermions and the W and Z bosons would have to be massless. In order for the Standard Model to be compatible with the large masses of the W and Z bosons and thus the large division between the effective weak coupling constant (the Fermi constant) and the electromagnetic coupling constant (the fine structure constant), spontaneous symmetry breaking must occur. This symmetry breaking would additionally be responsible for the mass hierarchy observed in the fermions. This Electroweak Symmetry Breaking (EWSB) is accomplished by the introduction of a scalar field known as the Higgs field [7]. The existence of a massive scalar particle,
the Higgs boson, would be associated with the Higgs field.

1.2 The Top Quark

Since the discovery of the bottom quark in 1977, as all other quarks and leptons have a same family partner, the existence of the top quark was anticipated. The existence of the top quark was inferred for several reasons. For one, the renormalizability of the Standard Model requires that the sum of electric charges of all left-handed fermions must equal zero. This condition is only satisfied with the existence of a sixth quark with an electric charge of +\( \frac{2}{3} \). In addition, the precise measurements involving the isospin of the b-quark can be made at \( e^+e^- \) colliders, which can be used to exclude the possibility of the b-quark being a member of a singlet [10].

The experimental discovery of the top quark took much longer than originally anticipated because the top quark was not expected to be so heavy. The top quark was observed at Fermilab in 1995 by the CDF and \( D\emptyset \) collaborations [1, 2]. After the discovery, a lot of effort has been put into measuring top quark mass, nowadays the precision is gained by combination among the experiments achieving precision under 0.5 % \( (m_t = 173.34 \pm 0.27(\text{stat.}) \pm 0.71(\text{syst.}) \text{ GeV}) \) [9].
1.3 Top Quark Production

Top quark has a large mass. Therefore, the top quarks can currently be produced at two accelerators in the world: the Tevatron accelerator and the now operational and running LHC accelerator. At the Tevatron, the top quark is produced predominately in top antitop pairs via the strong interaction. There are two different mechanisms on the top quark pair production. They are the quark-antiquark annihilation process \((q\bar{q} \rightarrow t\bar{t})\) and the gluon fusion process \((gg \rightarrow t\bar{t})\). At a center of mass energy \(\sqrt{s}\) of 1.96 TeV, the processes \((q\bar{q} \rightarrow t\bar{t})\) and \((gg \rightarrow t\bar{t})\) occur approximately 85% ± 5% and 15% ± 5% of the time, respectively [15]. The leading order diagrams for two processes are shown in Figure 1.1.

![Leading Order Top Pair Production](image)

Figure 1.1: Leading Order Top Pair Production

The top quark pair production via the \(q\bar{q}\) annihilation has a different spin state from that produced via the gluon fusion. When top quark pairs are pro-
duced near kinematic threshold (approximately 345 GeV), the pairs produced via $q\bar{q}$ annihilation and gluon fusion are in the following total angular momentum states, respectively [8]:

\[ q\bar{q} : J = 1, \ J_z = \pm 1, \]

\[ gg : J = 0, \ J_z = 0, \]

where $z$ denotes the initial parton direction.

Therefore, in the case of $q\bar{q}$ annihilation, the top quark and the antitop quark have the aligned spin on the beam axis, while they have the opposite spin on any axis in the case of gluon fusion. In the actual $p\bar{p}$ collisions, top quark pairs can be produced at center-of-mass energies significantly above threshold. Then, for $q\bar{q} \rightarrow t\bar{t}$ process, for top and antitop quark spin states, $(\uparrow\downarrow)$ and $(\downarrow\uparrow)$ dominate, but a little bit the $(\uparrow\uparrow)$ and $(\downarrow\downarrow)$ spin configuration exist in the beamline basis. On the other hand, for $gg \rightarrow t\bar{t}$ process, the unlike spin configuration between top and antitop quark is mitigated so that top quark pairs slightly anti-correlated spins in the beamline basis. The theoretical prediction of the $t\bar{t}$ production cross section at next-to-leading order (NLO) is $\sigma^{NLO} (p\bar{p} \rightarrow t\bar{t}X) = 6.7^{+0.7}_{-0.9}$ pb at $M_t = 175$ GeV/$c^2$ [15]. At a center-of-mass energy of 1.96 TeV, the most precise measurement by the CDF and the D0 collaborations is $7.6\pm0.41$ pb [53].
1.4 Top Quark Decay

The top quarks decay almost completely into a W boson and a b-quark. Other decay channels are permitted in the Standard Model, but are heavily suppressed by factors of $|V_{ts}|^2/|V_{tb}|^2 \sim 10^{-3}$ and $|V_{td}|^2/|V_{tb}|^2 \sim 5 \times 10^{-4}$, where $V_{ij}$ is the element of the Cabibbo-Kobayashi-Masukawa (CKM) weak-mixing matrix [5]. The large mass of the top quark results in a very rapid decay with a mean lifetime of $\tau_t \sim 10^{-24}$ s. As this is shorter than the time scale required for quarks to form bound states (or “hadronize”), the top quark essentially decays as a “free” quark. Therefore, top quark retain its original polarization at the production until decay, and due to the decay via parity violating weak interaction, the information of the parent top polarization is transferred to decay products.

The b-quark resulting from the decay will then proceed to hadronize and manifest itself in the detector as a jet, or a collimated stream of hadrons. The W boson will decay rapidly into either a pair of quarks or a pair of charged lepton and a neutrino. Thus, for the case of a $t\bar{t}$ pair production and decay, there are six objects: two b-quarks and two decay products from each of the W boson. Figure 1.2 shows the tree level diagram of $t\bar{t}$ production and decay in the subprocess $q\bar{q} \rightarrow t\bar{t}$. It is the decay mode of the W bosons that defines the decay channels of the $t\bar{t}$ system used in its experimental study. These decay channels are classified as:
Figure 1.2: The Tree level diagram of $t\bar{t}$ production and decay

- All-hadronic channel, where both W bosons decay to quark-antiquark pairs, resulting in a final state having an experimental signature of six jets. This decay mode carries the largest branching ratio of 46 %, but suffers from the largest amount of irreducible QCD background.

- Lepton+jets channel, where one W decays to a lepton-neutrino pair and the other to quarks, resulting in an experimental signature of a high momentum lepton, four jets, and a missing transverse energy associated with the neutrino. Due to the difficulty of identifying $\tau$ leptons at a hadron collider, only leptonic states with an electron or muon in the final state are considered. This channel carries a branching ratio of 30 %.

- Dilepton channel, where both W bosons decay to leptons, resulting in
an experimental signature of two high momentum leptons, two jets, and large missing transverse energy associated with two neutrinos. As with the lepton+jets channel, only leptonic states with an electron or muon in the final state are considered. This channel carries a branching ratio of 4%. The remaining 20% of $t\bar{t}$ decays involve the production of a lepton that does not decay to an e or $\mu$. While measurements in this so-called “$\tau + X$” channel are possible, they do not afford nearly the same precision that any of the other three channels does.

1.5 Top Quark Polarization

The polarization of the top is reflected in the kinematic distributions of its daughters, as the top decays before hadronization effects can wash away this information. Thus top polarization $P_n$ along a chosen axis $\hat{n}$ can be measured by the angular distribution of the top decay products with respect to that axis, measured in the top rest frame [23]:

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta_{i,n}} = \frac{1}{2} (1 + \alpha_i P_n \cos \theta_{i,n})$$ (1.3)

where $P_n = \pm 1$ for tops completely polarized (anti-) parallel with the chosen axis, $\alpha_i$ is the spin analyzing power of decay product $i$, and $\theta_i$ is the direction of each daughter with respect to the chosen axis, as measured in the rest frame of the top.
Due to parity conservation in the strong production of $t\bar{t}$, the SM predicts a negligible longitudinal polarization of the top quark [54]; however, many BSM models used to explain the anomalous forward-backward asymmetry ($A_{FB}$), measured by the CDF [55] and DØ [56, 57] experiments at the Tevatron, include a parity violating chiral coupling to the top quarks that predict a larger longitudinal polarization of the top quark in $t\bar{t}$ production than the SM. The
<table>
<thead>
<tr>
<th>particle</th>
<th>$\alpha_i^{LO}$</th>
<th>$\alpha_i^{NLO}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>charged lepton</td>
<td>1.00</td>
<td>0.998</td>
</tr>
<tr>
<td>d quark</td>
<td>1.00</td>
<td>0.93</td>
</tr>
<tr>
<td>b quark</td>
<td>-0.41</td>
<td>-0.39</td>
</tr>
<tr>
<td>u quark</td>
<td>-0.31</td>
<td>-0.31</td>
</tr>
</tbody>
</table>

Table 1.3: Predicted tree level values of the spin analyzing power, $\alpha_i$, for the top quark final state decay products

motivation for performing a measurement of the longitudinal polarization of the top quark in $t\bar{t}$ production is two fold: to validate the SM prediction and to distinguish between the various BSM models proposed for $t\bar{t}$ production if a non-negligible polarization is measured. At the most basic level, the longitudinal polarization of the top quark may be used as a probe for the structure of the couplings responsible for the production of $t\bar{t}$.

The high sensitivity of the charged lepton is convenient, because of all the top decay products it is the easiest to identify and measure. The purpose of this section is to point out that simple variables constructed from the leptons in dileptonic $t\bar{t}$ events have hitherto untapped power to distinguish between competing explanations of the observed asymmetry even at the Tevatron, and have the potential to significantly strengthen the case for new physics beyond the standard model.
If physics beyond the Standard Model (BSM) is really responsible for the top asymmetry then it would be desirable to probe its particle content directly by producing any new states on-shell and then measuring their masses and couplings. Depending on the model, such searches may proceed in $t\bar{t}$ resonances or top-light jet resonances, and interesting signals may be discovered shortly. However, excesses in the nonresonant $t\bar{t}$ cross-section alone allow for observations of departures from the SM [58].

In an attempt to explain the $A_{FB}$ result from the Tevatron, BSM production mechanisms for $t\bar{t}$ that involve chiral couplings to top quarks have been introduced [20]. Due to the nature of their chiral couplings, they produce longitudinally polarized top quarks. The BSM models considered are required to generate the $A_{FB}$ while producing a cross section for $t\bar{t}$ production that is consistent with experimental measurements. Two classes of models are considered, a color singlet t-channel production mechanism ($W'$ vector boson) and a color octet s-channel production mechanism (axigluon vector bosons), each of which has parity violating couplings to the $t\bar{t}$ initial and final states. The axi-gluons comprise three cases, each having a different coupling to the top quarks: a fully axial coupling ($G_A$), left-handed coupling ($G_L$), and right-handed coupling ($G_R$).

The BSM models used to explain the $A_{FB}$ predict values for $P$ that are significantly different from the SM prediction. If a BSM model is responsible for the $A_{FB}$, it will impact the shape of the $\cos \theta$ distribution, making this
analysis sensitive to the production mechanism of $t\bar{t}$. Moreover, many of the BSM models predict varying degrees of longitudinal polarization, allowing this analysis to distinguish between the models by measuring $\alpha_P$.

Each BSM model’s prediction for the longitudinal polarization (in the helicity basis) of the top quark in $t\bar{t}$ production was calculated and their results are tabulated in Table 1.4.

<table>
<thead>
<tr>
<th>models</th>
<th>selection cuts</th>
<th>$m_{t\bar{t}} &gt; 450$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>4 % (6.5 %)</td>
<td>6 % (10 %)</td>
</tr>
<tr>
<td>$G_A$</td>
<td>5 %</td>
<td>7 %</td>
</tr>
<tr>
<td>$G_L$</td>
<td>1 %</td>
<td>-1 %</td>
</tr>
<tr>
<td>$G_R$</td>
<td>8 %</td>
<td>12 %</td>
</tr>
<tr>
<td>$W'$</td>
<td>14 %</td>
<td>21 %</td>
</tr>
</tbody>
</table>

Table 1.4: Predicted net polarization of dileptonic channel in the helicity basis at Tevatron [22]. In parentheses are $1\sigma$ statistical errors uncertainties on an asymmetry measurement centered about the predicted SM value assuming 5.1 fb$^{-1}$. 
1.6 Motivation of Top Quark Polarization Measurement

As presented in the previous section, the Standard Model predicts nearly zero top quark polarization in top-antitop production from unpolarized hadron collisions, due to the parity-conserving nature of QCD [17, 18, 19], and the top quark polarization practically can be neglected even with the electroweak corrections. On the other hand, some physics beyond the Standard Model (BSM), like axi-gluon, are able to generate non-negligible top quark polarization from interference between new physics and the SM, with good agreement of the top-antitop production cross section with SM predictions [20, 21].

The measurement of the polarization of the top quark properties is important for the Standard Model confirmation or beyond Standard Model searches in the top quark sector. Additional, the initial state is different to the LHC and polarizations along some quantization axes from the pp collisions are expected to be larger than those for pp collisions, therefore offering greater sensitivity than the LHC. The polarization is measured for the first time at CDF experiment.

There are strong motivations for the measurement of the top quark polarization at the Tevatron.
Chapter 2

Experimental Apparatus

The Fermilab Tevatron Collider was the world’s highest energy accelerator, before the Large Hadron Collider (LHC) have turned on since 2010, colliding anti-protons with protons at a center of mass energy of $\sqrt{s} = 1.96$ TeV. The Tevatron was shut down at 2011. LHC has been started operating since March 2010 at a center-of-mass-energy 7 TeV and increase the center-of-mass-energy to 14 TeV in 2014. The Tevatron is located about 50 km west of Chicago in Fermilab, a scientific laboratory run by a consortium of universities (URA) and by the University of Chicago (“Fermi Research Alliance”) on behalf of the American Department of Energy (DOE). The CDF (Collider Detector at Fermilab) experiment is an international collaboration of about 500 physicists from universities and national laboratories from 12 countries. The CDF II detector is a general purpose detector which measures most of the interesting
particles that come out of the $p\bar{p}$ collision. Two intense beams of protons and anti-protons meet head-on in the center of the CDF detector, and a few collisions occur every time 2 bunches cross which happens every 120 ns.

2.1 The Tevatron Accelerator

The Tevatron collider obtained the first collisions in 1985. In the course of time it provided several physics runs as shown in Figure 2.2. The accelerator complex at Fermilab consists of several key components, that can be concep-
tually separated into a series of accelerators that prepare the protons, produce and store anti-protons and finally accelerate both protons and anti-protons to a center-of-mass-energy of 1.96 TeV and orchestrate the collisions. Figure 2.3 shows the schematic view of the accelerator chain to create the powerful particle beams.

![Luminosity Graph](image)

Figure 2.2: Total integrated luminosity delivered by the Tevatron and recorded by the CDF [28]

### 2.1.1 Tevatron

The Tevatron is a 1 km radius circular synchrotron employing superconducting bending magnets, where the protons and anti-protons beams orbit in the
same pipe in opposite directions. Undesired bunch crossings are avoided by electrostatic separators.

The beam revolution time is $21\, \text{us}$. The beams are split in 36 bunches organized in 3 trains each containing 12 bunches. Within a train the time spacing between bunches is $396\, \text{ns}$. An empty sector 139 buckets-long ($2.6\, \text{us}$) is provided in order to allow the kickers to raise to full power and abort the full beam into a dump in a single turn. This is done at the end of a run or in case of an emergency.
The Tevatron receives 150 GeV protons and anti-protons from the Main Injector and accelerates them to 980 GeV, or one Tera electron volt (1 TeV). Traveling only 200 miles per hour slower than the speed of light, the protons and anti-protons circle the Tevatron in opposite directions. The beams cross each other at the centres of the 5000-ton CDF and \( D\Phi \) detectors located inside the Tevatron tunnel, creating bursts of new particles.

### 2.1.2 Proton Source

The protons that are used in collisions and to produce anti-protons all begin in a small bottle of hydrogen gas. Hydrogen atoms drawn from this bottle are ionized to form \( H^- \) ions. The \( H^- \) ions are accelerated from rest to an energy of 750 KeV by a Cock-croft Walton pre-accelerator that applies an electric field to the ions [24].

The \( H^- \) ions are then injected into the Linac (approximately 500 feet long), a linear RF accelerator, which further accelerates them to an energy of 400 MeV [25]. At this point, the electrons are removed from the \( H^- \) ions, leaving behind bare protons.

The protons then enter the Booster, a synchrotron with a circumference of 474 m. The Booster utilizes magnets to bend the protons along a circular path while RF cavities accelerate them to an energy of 8 GeV [26].

At this time, the protons enter the Main Injector, a synchrotron 3 km in circumference. The Main Injector can accelerate the protons either to 150
GeV [27] for injection into the Tevatron, or to 120 GeV for usage in anti-proton production. The Main Injector can also stack anti-protons produced in the anti-proton source and accelerate them to 150 GeV prior to usage in the Tevatron.

2.1.3 Anti-proton Source

One of the most technically daunting tasks in the collider operations at Fermilab in the production and storage of anti-protons. Because of its difficulty, the production of anti-protons remains the limiting factor in the luminosity of colliding beams at the Tevatron. The anti-proton source at Fermilab consists of a target for production and three accelerators used to cool and store: the Debuncher, the Accumulator and the Recycler.

Anti-protons are produced by striking 120 GeV protons from the Main Injector upon a nickel target. These collisions yield a shower of particles from which anti-protons are separated using magnetic spectroscopy. The particles are subject to a magnetic field causing particles of different mass and charge to take paths of different radii. This allows anti-protons to be separated out. Approximately 100,000 protons are needed to successfully produce and store one anti-proton. The resulting anti-protons have an average energy of 8 GeV.

The anti-protons produced at the target are then sent to the Debuncher [29], a triangular synchrotron with a mean radius of 90 m. The beam of anti-protons sent into the Debuncher has a large spread of momenta. The Debuncher is
tasked with reducing this spread in momenta, forming a continuous beam. The anti-protons are sent to the Accumulator, another triangular synchrotron that shares a tunnel with the Debencher. Here, the anti-protons are stored, or “stacked”, as more are produced. In addition, a process known as stochastic cooling is used to further reduce the spread in momenta of the anti-protons. When a sufficient number of anti-protons for colliding beam operations have been stacked at the Accumulator, they can then be sent to the Main Injector for further acceleration.

**Electron Cooling**

Electron cooling is a technique which used a beam of electrons run alongside a beam of anti-protons to reduce the longitudinal momentum of the anti-protons. While the method was first proposed in 1966 and has been utilized for now-energy beams, its implementation at Fermilab in 2005 is the first successful application of electron cooling to a relativistic beam. The electron cooling system in use utilizes a 4.3 MeV beam of electrons that is run alongside a 20m length of the Recycler. This system has been in operation since late 2005 and is expected to help increase luminosities for the colliding beams by up to 100% from pre-electron cooling peak luminosity.
2.1.4 Linac

The Fermilab Linear Accelerator (Linac) is a negative hydrogen ion, 400 MeV accelerator. It includes a 25 KeV H-minus ion source, a 750 KeV electrostatic accelerating column, a 116 MeV drift-tube (Alverez) linac operating at 201.25 MHz, and a 401 MeV side-coupled cavity linac operating at 805 MHz. Many details can be obtained from the nice picture displays listed in the sidebar to the left. The Fermilab Linac provides beam for Booster operation at frequencies from 0.1 to 5 Hz. Several times per week, we provide 66 MeV protons to the Fermilab Neutron Therapy Facility (NTF). This outstanding cancer treatment facility has been part of the Linac for over 30 years. We estimate that on the 25th anniversary of the beginning of NTF in 2001, Linac had provided 4.0E21 protons to NTF for the generation of the neutrons they use for tumor treatment.

2.1.5 Booster

The Fermilab Booster is a synchrotron accelerator with a circumference of 474 meters. Beam is injected into the Booster from the 400 MeV transport line which carries the 400 MeV beam output from the Linac accelerator. The Booster accelerates a proton beam from 400 MeV to 8 GeV in less than 67 milliseconds for the Main Injector accelerator. Booster also provides beam for the MiniBooNE experiment and the NuMI facility and MINOS experiment.
The FNAL Booster accelerator is approximately 150 m diameter proton synchrotron with an injection energy of 400 MeV and an extraction energy of 8 GeV. It is considered a “fast cycling” machine, current waveform to excite the magnets. The Booster is made up of 96 combined function magnets in a series of 24 repeating periods. Their magnetic field varies from about 740 gauss at injection to 7,000 gauss at extraction. The Booster tunnel is a concrete tunnel 8 feet high and 10 feet wide, covered by 15 feet of earth shielding. The 400 MeV line transfers the beam from LINAC to the Booster, bending the beam vertically fifteen feet. A multiple turn system increases the Booster intensity by stacking successive turns of LINAC beam layered on top of each other. RF(radio frequency) energy, delivered by up to 17 ferrite-tuned cavity resonators, accelerates the proton beam over the 33 ms rising portion of the sinusoidal current waveform. Beam can be extracted from Booster at two locations, depending on its destination. An extraction at Long 13 transfers beam to the Booster dump. An extraction at Long 3, initiated by kickers in Long 2, transfers beam to the Main Injector via the MI-8 line.

2.1.6 Main Injector

The Main Injector has been a decade in the making. The initial design work started in 1987, when a small group of physicists undertook a study of how Fermilab could enhance the performance of the Tevatron beyond its original performance goals, by integrating a new accelerator or accelerators within the
existing complex. Funding for the Main Injector Project was approved starting in October 1991. After an extended design and R&D period, the construction really got under-way in the spring of 1993. In the spring of 1999 the Main Injector is ready for high energy physics research at Fermilab.

The addition of Main Injector to the Fermilab accelerator complex marks a dramatic increase in the physics capabilities of the Fermilab High Energy Physics Programs.

- There will be a dramatic increase in the number of proton-antiproton collisions that can be created and observed in the Tevatron, by increasing the beam current in the Main Injector, its reliability and the cycling rate over the Main Ring which it replaces. This extends the physics “reach” to higher mass and rarer particles that will, if discovered, expand our understanding of the nature of matter and the forces that hold it together.

- The Main injector will operate simultaneously in fixed target and antiproton production modes. A very intense 120 GeV beam can be extracted. Targeting this beam will create an intense beam of neutrinos that will be used to study the basic question: do neutrinos have mass? An intense beam of K-mesons can also be created and rare decay modes studied. Greater understanding of the basic quark structure of matter and the nature of the matter-antimatter asymmetry in the Universe will emerge from these studies.
2.1.7 Recycler

The Recycler Ring was added to the Main Injector Project in the spring of 1997. The Recycler Ring will increase the collision rate in the Tevatron collider by a factor of three to five beyond that with the Main Injector alone. Without the Recycler, the precious anti-protons left at the end of a collider “store” (8-12 hour period of time when the beams are in collision) must be thrown away. The Recycler will allow Fermilab to recover these anti-protons and re-use them in a later store. As an added benefit, the Recycler will also allow the existing Anti-proton Source to perform more efficiently and produce more anti-protons per hour.

The Recycler is a permanent-magnet 3.3 km anti-proton storage ring. It receives 8.9 GeV/c anti-protons from the Accumulator and stores them until the Tevatron is ready for its next store. The Recycler has both stochastic and electron cooling systems. Its mission is to prepare anti-proton bunches suitable for extraction and transport to the Tevatron. Presently, a typical number of stored anti-protons in the Recycler is 200 - 300E10. The design goal is to store and cool 600E10 anti-protons.

2.2 The CDF Detector

The CDF II detector, upgraded CDF detector from Run I in 1992 - 1995 period, is an azimuthal and forward-backward symmetric apparatus designed to study
$p\bar{p}$ collisions at the Tevatron. It is a general purpose cylindrical detector which combines precision charged particle tracking with fast projective calorimeters and fine grained muon detection. Figure 2.4 shows the CDF II detector.

![CDF II detector diagram](image)

Figure 2.4: Elevation view of one half of the CDF detector

Tracking systems are contained in a superconducting solenoid, 1.5 m in radius and 4.8 m in length, which generates a 1.4 T magnetic field parallel to the beam axis. Calorimetry and muon systems are all outside the solenoid. The main features of the detector systems are summarized below. I use a coordinate system where the polar angle $\theta$ is measured from the proton direction, the az-
imuthal angle $\phi$ is measured from the Tevatron plane, and the pseudo-rapidity is defined as $\eta = -\ln(\tan(\theta/2))$.

The CDF II detector is used to identify and reconstruct the properties of the final state objects, i.e., electrons, muons, collimated clusters of hadrons (jets), as well as the imbalance of $E_T$ which is caused by undetectable particles such as neutrinos. The object identification and reconstruction techniques have been used in hundreds of analyses published by the collaboration, so we will not describe them in detail here, but point the reader to Refs. [30, 31, 32]. The main idea of the object identification is to look for an expected set of detector responses from a specific object. For example an electron will leave a charged particle trajectory through the tracking chamber, then deposit almost all of its energy in the electromagnetic calorimeter. The signature responses in the detector from various objects are summarized in Figure 2.5.

2.2.1 The CDF Coordinate System

The origin of the CDF coordinate system $(x,y,z) = (0,0,0)$ cm (Figure 2.6) is at the nominal point of collision, in the center of the detector. The positive $z$ direction points in the direction of the proton beam (west to east), the positive $y$ direction points upward (south to north) and the positive $x$ direction points out of the ring.

Given that the energy spectrum of quarks inside the protons is very broad, the hard collision rest frame will be boosted, in general, along the beam direc-
Figure 2.5: The signature responses in the detector from various objects

...tion with respect to the lab frame. Therefore it is appropriate to use variables invariant under boosts along z direction. The detector solid angle segmentation, described by the angular coordinates $\eta$ and $\phi$, satisfies this requirement. $\phi$ is the azimuthal angle about the z-axis. $\eta$ is the pseudo-rapidity and is related to the polar angle $\theta$ through the relation:

$$\eta \equiv -\ln(\tan\frac{\theta}{2}) \quad (2.1)$$

Based on this definition, negative $\eta$ corresponds to the west side of the detector, positive $\eta$ to the east side of the detector, while $\eta = 0$ is the transverse x-y plane. The pseudo-rapidity $\eta$ is precisely the rapidity of a particle in the limit of $m \ll p$, where $m$ is the particle rest mass and $p$ its momentum.
Figure 2.6: a) Isometric view of the CDF detector in Run II, b) The coordinate system of the CDF II detector

magnitude. The rapidity is defined as

\[ y \equiv \frac{1}{2} \ln \frac{E + P_z}{E - P_z} \]  \hspace{1cm} (2.2)

Using the relations between the hyperbolic and trigonometric functions,

\[ \sinh \eta = \cot \frac{\theta}{2} \]  \hspace{1cm} (2.3)
\[ \cosh \eta = \frac{1}{\sin \theta} \]  \hspace{1cm} (2.4)

and the notation \( \alpha \equiv \frac{m}{p_T} \), where \( p_T = p \sin \theta \), one can rewrite the energy as

\[ E = \sqrt{m^2 + \frac{p_T^2}{\sin^2 \theta}} \]  \hspace{1cm} (2.5)
and further the rapidity as
\[ y = \frac{1}{2} \ln \frac{\sqrt{\cosh^2 \eta + \alpha^2 + \sinh \eta}}{\sqrt{\cosh^2 \eta + \alpha^2 - \sinh \eta}} \] (2.6)

If \( m \ll p \), then as \( \alpha \to 0 \), and the expansion on \( y \) in terms of \( \alpha \) becomes
\[ y \approx \eta - \frac{1}{2} \alpha^2 \tanh^2 \eta + O(\alpha^3) \] (2.7)

So for \( \alpha = 0 \), \( y = \eta \). Under a Lorentz transformation to another frame moving at velocity \( \beta \), \( y \) transforms as
\[ y \to y + \frac{1}{2} \ln \frac{1 - \beta}{1 + \beta} = y + \text{constant} \] (2.8)

This implies that the segmentation in rapidity in Lorentz invariant, \( dy \to dy \) under a boost along beam direction. Still, the rapidity is a function of the particle’s mass and polar angle. The pseudo-rapidity is used to define the angular segmentation. It depends only on the polar angle and is approximately Lorentz invariant under \( z \) boosts for high \( p_T \) particles. Also \( \phi \) is invariant under \( z \) boosts, as it is a transverse plane variable.

### 2.2.2 Tracking Systems

The tracking system consists of a silicon microstrip system and of an open-cell wire drift chamber that surrounds the silicon system. The silicon microstrip detector consists of seven layers (eight layers for \( 1.0 < |\eta| < 2.0 \)) in a barrel
geometry that extends from a radius of \( r = 1.5 \) cm from the beam line to \( r = 28 \) cm.

The core of the CDF II detector is an 8 layer silicon micro-strip tracker. The design of the upgraded silicon system provides improved impact parameter resolution and increased acceptance in the forward regions. This translates into better tracking and heavy flavor tagging efficiencies. Of critical importance is also the system’s ability to trigger on displaced tracks, enhancing the CDF II B-physics program.

**Central Outer Tracker (COT)**

Central Outer Tracker (COT) is the 3.1 m long cylindrical drift chamber, which covers the radial range from 40 to 137 cm and provides 96 measurement layers, organized into alternating axial and ±2° stereo superlayers. The COT provides coverage of \(|\eta| < 1\). The hit position resolution is approximately 140 \( \mu m \) and the momentum resolution is \( \sigma(P_T)/P_T^2 = 0.0015 \) (GeV/c)\(^{-1}\).

**Time of Flight System (TOF)**

The Time of Flight System (TOF) detector is incorporated into the CDF detector in order to identify particles up to 1.5 GeV/c. By measuring the time it takes for a collision product to reach the TOF, we can separate particles which have different masses, such as \( \pi^\pm \) and \( K^\pm \). This detector is located between the COT and the superconducting solenoid at a radius of 140 cm with a coverage
in $|\eta| \leq 1.0$. In this analysis, we do not use for particles discrimination but use for the event veto coming from cosmic rays.

**Superconducting Solenoid**

The superconducting solenoid operated at a current of about 4650 A produces an uniform magnetic field of 1.4 T parallel to the z-axis. The conductor is made of Al-stabilized NbTi. This strong magnetic field bends the trajectory of high-$P_T$ charged particles, allowing us to reconstruct their momentum using the tracking system.

**2.2.3 Calorimeter**

Outside the solenoid, scintillator-based calorimetry covers the region $|\eta| < 3.0$ with separate electromagnetic and hadronic measurements. The CDF calorimeters measure electron, photon energies and jet energies [33, 34].

The central calorimeters (and the endwall hadronic calorimeter) cover the pseudo-rapidity of $|\eta| < 1.1(1.3)$ and the plug calorimeters cover $1.1 < |\eta| < 3.6$. It is a scintillator sampling systems with tower segmentation: each tower is 15° in azimuth by about 0.11 in pseudo-rapidity. The calorimeter consists of an electromagnetic (EM) section followed by a hadronic (HAD) section. The EM sections are all lead/scintillator sampling.

In both sections the active elements are scintillator tiles read out by wavelength shifting (WLS) fibers embedded in the scintillator. The WLS fibers
are spliced to clear fibers, which carry the light out to photomultiplier tubes (PMT) located on the back plane of each endplug. The EM calorimeter is a lead/scintillator sampling device with a unit layer composed of 4.5 mm thick lead and 4 mm scintillator. There are 23 layers in depth for a total thickness of about 21 $X_0$ (radiation lengths) at normal incidence. The detecting elements are arranged in a tower geometry pointing back towards the interaction region.

The energy resolution of the EM section is approximately $16\% / \sqrt{E}$, where $E$ is in GeV, with 1 % constant term. The scintillator tiles of the first layer of the EM section are made of 10 mm thick scintillator and are read out by multi-anode photomultipliers (MAPMTs). They act as a pre-shower detector. A position detector is located at the depth of the EM shower maximum and is made of scintillator strips read out by WLS fibers.

The hadron calorimeter is a 23 layer iron/scintillator sampling device with a unit layer composed of 50 mm iron and 6 mm scintillator. The existing iron of the CDF endplugs is used in the hadron calorimeter: stainless steel disks are attached to the inner 10° cone to extend the coverage to 3°. Two additional stainless steel disks are added behind the electromagnetic section to increase the thickness of the hadron calorimeter. The energy resolution of the hadronic calorimeter is $74\% / \sqrt{E}$ with 1 % constant term.
Central Calorimeters

The central region (0 < |\eta| < 1.1 or 143° < |\theta| < 37°) is the most important to high transverse momentum physics, being at large polar angle with respect to the beamline. For example top pair-production events tend to be central, top and anti-top being produced almost at rest. The central calorimeter (the electromagnetic (CEM) and hadronic (CHA, WHA)) is retained largely unchanged from Run I other than the electronics, new in Run II. The consists of 2 barrels (one for the positive and one for negative \eta range), which are divided azimuthally into 24 wedges, each covering 15° in \eta 15° in \phi and extending 2.5 m along the beam axis on either side of the detector. The wedge modules are stacked into four freestanding “C”-shaped arches to allow easy access to the inner components. One module is notched to allow access to the superconducting magnet. This affects tower 9, which is not a full size tower and is not used for election identification in the dilepton analysis. Each wedge module is divided transversely into 10 projective towers, each subtending \Delta \eta = 0.1 units in pseudorapidity. Towers are segmented in depth, each depth being read out by separate electronics channels. A CEM module is composed of 31 layers of 3.175 mm thick lead absorber interleaved with 5 mm thick layers of polystyrene scintillator. For each tower there are two wavelength shifters (WLS), one on each side in azimuth \eta, which guide the green (490 nm) waveshifted light to photomultiplier tubes (PMT). Each tower is read out by 2 PMTs. The signal balance between PMTs allows further determination of \eta for a single particle
to 1° precision. In the Level 1 trigger, the energy is calculated as the average of the two tower energies, while in Level 3 and offline, the tower energy is a geometric mean of the two PMT energies.

The Central Electromagnetic Strip Chamber (CES) is embedded between the eighth lead layer and ninth scintillator layer. It is a proportional wire chamber that measures the positions and the transverse shower shapes of electromagnetic clusters in both r-z and r-φ planes. The CES is positioned at the average maximum longitudinal development of an electromagnetic shower, at about 5.9 radiation lengths from the inner radius of the CEM. There are 128 cathode strips that lie perpendicular to the beam direction measuring the z position of the shower. There are 64 anode wires, grouped in pairs, that lie parallel to the proton beam and measure the x coordinate. The position resolution is about 2 mm. The CES also provides position information for the identification of photons within particle showers. The detector is mostly unchanged from Run I, but the readout has been modified to accommodate the higher Run II collision rates. The detector has many cracks, or regions with low response. The region $-0.05 < |\eta| < 0.05$ near the 90° crack where the detector halves meet, is not used, as the chambers are not fully efficient near the edges. This result in a loss in acceptance of about 5.0 %. For the same reason the showers with a distance less than 1 from $\phi$ boundary between wedges are not considered. This translates into the requirement that the CES wire cluster closest to the extrapolated electron track be located at less than 21 cm from
the center of the strip chamber in the r-φ plane. The loss in the acceptance is $24 \times 2^\circ / 360^\circ = 13.3\%$. Also the region $0.82 < |\eta| < 1.0, 75^\circ < \phi < 90^\circ$ is explicitly excluded as it is uninstrumented. This is known as chimneymodule and is the access point for the cryogenic supply of the superconduction coil. The loss is 0.4 %. The total acceptance loss due to the fiducial requirements is 18.7 % odd the geometrical acceptance for the central electron.

2.2.4 Muon Detector

The muon system resides outside the calorimetry [35, 36]. Four layers of planar drift chambers, the Central Muon detector (CMU), detect muons with $P_T > 1.4$ GeV/c which penetrate the five absorption lengths of calorimeter steel. An additional four layers of planar drift chambers, the Central Muon Upgrade detector (CMP), instrument 0.6 m of steel outside the magnet return yoke and detect muons with $P_T > 2.0$ GeV/c.

The CMU and CMP chambers each provide coverage in the pseudo-rapidity range $|\eta| < 0.6$. The Central Muon Extension detector (CMX) covers the range $0.6 < |\eta| < 1.0$. The Intermediate Muon detectors (IMU) are covering the region $1.0 < |\eta| < 1.5$. The IMU provide coverage sufficient to identify isolated high $P_T$ tracks as muons or hadrons. The IMU consists of a barrel of drift chambers and scintillation counters around the toroid steel, with additional counters between the toroids and on the endwall to provide additional projectivity at the trigger level. The IMU counters are virtually identical to the
existing central muon detectors and use the same readout electronics.

### 2.3 Triggers and Data Acquisition

The trigger plays an important role in hadron collider experiments because the collision rate is to the crossing rate of 7.6 MHz while the tape writing speed will be less than 50 Hz. The role of the trigger is to efficiently extract the most interesting physics events from the large number of minimum bias events. For example, the total $t\bar{t}$ cross section is approximately nine orders of magnitude smaller than the minimum bias cross section.

Due to changes in the detector and the accelerator the entire trigger system used in run must be replaced for run II. The primary reason for replacing the trigger electronics along with all CDF front-end electronics, is the reduction in the accelerator bunch spacing from 3.5 $\mu$s to $132 \sim 396$ ns. In the past, trigger signals from the calorimeters were sent to the control room, where they were processed, with the trigger decision sent back to the detector before the next beam crossing. As a result, the data from only one crossing needed to be stored on the detector. In RUN II there will not be enough time to send detector signals to the control room between bunch crossings, let alone make a trigger decision and distribute it back to the detector. In addition most of the old trigger is incompatible with new or upgraded detector elements.

The trigger and data acquisition systems are designed to accommodate the
high rates and large data volume of Run II. Trigger systems of CDF consists of three level triggers and the data is decreased by progressing to the next level. Figure 2.7 shows the functional block diagram of the readout electronics. To accommodate 132 ns bunch-crossing time and a 4 µs decision time for the first trigger level, all front-end electronics are fully pipelined, with on board buffering for 42 beam crossings. Data from the calorimeters, the central tracking chamber, and the muon detectors are sent to the Level 1 trigger system, which determines whether a $p\bar{p}$ collision is sufficiently interesting to hold the data for the Level 2 trigger hardware.

The Level 1 trigger is a synchronous system with a decision reaching each front-end card at the end of the 42-crossing pipeline. Upon a Level 1 trigger accept, the data on each front-end card are transferred to one of four local Level 2 buffers. The second trigger level is an asynchronous system with an average decision time of 20 µs. Data are collected in DAQ (Data Acquisition system) buffers and then transferred via a network switch to a Level 3 CPU node, where the complete event is assembled, analyzed, and, if accepted, written out to permanent storage.

CDF II uses a tiered “deadtimeless” trigger architecture. An event is considered sequentially at three levels of approximation, with each level providing sufficient rate reduction for the next level to have minimal deadtime. Level 1 and Level 2 use custom hardware on a limited subset of the data and Level 3 uses a processor farm running on the full event readout. The trigger, like the
Figure 2.7: Data flow in the CDF data acquisition system
DAQ, is fully pipelined. The block diagram for the CDF II trigger system is presented in Figure 2.8. Events accepted by the Level 1 system are processed by the Level 2 hardware. The Silicon Vertex Tracker (SVT) provides the ability to trigger on tracks with large impact parameters. The Level 2 system has improved momentum resolution for tracks, finer angular matching between muon stubs and central tracks, and data from the central shower-max detector (CES) for improved identification of electrons and photons. Jet reconstruction is provided by the Level 2 cluster finder. The output of the first level of the trigger is used to limit the rate for accepted events to roughly 18 kHz at the luminosity range of $3 - 7 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$. At the next trigger stage, the rate is reduced further to around 300 Hz. The third and final level of the trigger, with access to the complete event information, uses software algorithms and a computing farm, and reduces the output rate to around 75 Hz, which is written to permanent storage.
Figure 2.8: Block diagram of the Level 1 and Level 2 trigger path
Chapter 3

Data, MC Simulations and Selection

Even after the set of dedicated event selection criteria described in section 3.4, the data are still a mixture of events including events from the process of interest ($t\bar{t} \rightarrow l^+l^-\nu\bar{\nu}b\bar{b}$, signals) as well as events from other processes (backgrounds). In order to properly measure the important physics parameters of interest, we need to model both the signal with (different model parameters) as well as the backgrounds.
3.1 Data

The full Tevatron Run II data sample is analyzed in this measurement. This data were collected with the CDF detector in two major periods: Run IIa (April 2002 – February 2006) and Run IIb (June 2006 – September 2011). The data taking in terms of integrated luminosity is shown in Figure 2.2. The delivered luminosity of $11.9 \text{ fb}^{-1}$ represents the number of collisions by the Tevatron Collider. Unfortunately, not all the time the CDF detector was operational and recording data, which is propagated into the recorded luminosity of $9.1 \text{ fb}^{-1}$. Over 10 billions events were stored by the CDF detector in the Run II period.

The data presented in this thesis are processed with version 6.1.6 of the CDF reconstruction software. (For the MC samples, we use events generated with version 6.1.4mc patch “c” in the run range $141544 < \text{run} < 312510$, as well as samples generated with higher luminosity runs.) Physics objects like electrons, muons, jets and missing transverse energy are as defined by the TopEventModule selection code [64] and saved in “topNtuple” format for data (and Monte Carlo) events.

The data are collected either via the central high $p_T$ electron ($\text{bhelX}$, where $X = 0d, 0h, 0i, mi, mj, mk, mm$ or kp) trigger paths, ELECTRON CENTRAL 18 or muon ($\text{bhmu0X}$) trigger paths such as MUON CMUP18 and MUON CMX18.

We impose that the events pass the version 45 of the good run list, obtained
with bits (1,0,4,1) not including silicon run [66]. This version of the good run list, which includes partially recovered runs, ensures that the CDF detector was in good running condition both for CEM electrons and for CMUP muons. If good running conditions are required also for CMX muons, the luminosity of the samples is reduced slightly as reflected in Table. The data samples used in this analysis are described in Table 3.1. We use “9.1 fb$^{-1}$” of data without good silicon run.

### 3.2 $t\bar{t}$ Signal Modeling

For the purpose of the top quark polarization analysis, the primary simulator of the $t\bar{t}$ production is the POWHEG [46] event generator as our benchmark as it has the most precise SM simulation at NLO.

The detailed kinematic properties of each scenario are simulated using Monte Carlo (MC) event generators. The event generators use calculations based on the Feynman diagrams to create an ensemble of collision events (a sample) that mimic the events we would see in the detector if nature were described by the corresponding Feynman diagram in Figure 3.1.

The hadronization of the outgoing quarks, the process during which the quarks pull apart and recombine quark-anti quark pairs from the vacuum until all particles are in a color-neutral state (parton showering), is also calculated using MC techniques by the HERWIG [49] or PYTHIA [47] programs.
<table>
<thead>
<tr>
<th>Data Sample</th>
<th>Run Range</th>
<th>Luminosity(pb$^{-1}$)</th>
<th></th>
<th></th>
<th></th>
</tr>
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<td></td>
<td></td>
<td><strong>CEM</strong></td>
<td><strong>CMUP</strong></td>
<td><strong>CMX</strong></td>
<td></td>
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<tr>
<td>Through p17</td>
<td>138425-261005</td>
<td>2825.95±169.56</td>
<td>2825.95±169.56</td>
<td>2760.39±165.62</td>
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<td>period 18</td>
<td>261119-264071</td>
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<td>392.72 ± 23.56</td>
<td>402.13 ± 24.13</td>
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<tr>
<td>period 19</td>
<td>264101-266513</td>
<td>208.10 ± 12.49</td>
<td>208.10 ± 12.49</td>
<td>208.11 ± 12.49</td>
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<tr>
<td>period 20</td>
<td>266528-267718</td>
<td>248.17 ± 14.89</td>
<td>248.15 ± 14.89</td>
<td>248.15 ± 14.89</td>
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<td>268155-271047</td>
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<td>264.70 ± 15.88</td>
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<tr>
<td>period 23</td>
<td>272470-274055</td>
<td>170.79 ± 10.25</td>
<td>170.78 ± 10.25</td>
<td>170.79 ± 10.25</td>
<td></td>
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<tr>
<td>period 24</td>
<td>274858-287261</td>
<td>402.21 ± 24.13</td>
<td>402.21 ± 24.13</td>
<td>402.21 ± 24.13</td>
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<tr>
<td>period 25</td>
<td>282976-284843</td>
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<td>period 26</td>
<td>288904-291025</td>
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<td>305.84 ± 18.35</td>
<td>305.84 ± 18.35</td>
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<td>376.10 ± 22.57</td>
<td>376.10 ± 22.57</td>
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<tr>
<td>period 28</td>
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<tr>
<td>period 29</td>
<td>294778-299367</td>
<td>430.12 ± 25.81</td>
<td>431.58 ± 25.89</td>
<td>431.58 ± 25.89</td>
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<tr>
<td>period 30</td>
<td>299368-301303</td>
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<td>305.84 ± 18.35</td>
<td>305.84 ± 18.35</td>
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<tr>
<td>period 31</td>
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<td>period 32</td>
<td>310472-312510</td>
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<td>246.46 ± 14.79</td>
<td>246.46 ± 14.79</td>
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</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>138425-312510</strong></td>
<td><strong>9084.68±545.08</strong></td>
<td><strong>9076.87±544.61</strong></td>
<td><strong>9020.75±541.25</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Run ranges and luminosity for various data taking periods. All of the luminosities includes the correction factor of $1.019 \pm 0.060$ [67].
Figure 3.1: Representative subset of diagrams for the next to leading order (NLO) contribution to top quark pair production at the Tevatron. The double line is the $t\bar{t}$ pair and the single line is a light (u or d) quark. [40]

To model the effects of multiple $p\bar{p}$ interactions, the MC events are overlaid with events from random $p\bar{p}$ collisions with the same luminosity distribution as data.

Samples from SM calculations at LO generated by other programs, which go by the names of PYTHIA, ALPGEN [48], and HERWIG, are used for cross checks. The differences among the three LO SM event generators are subtle: the PYTHIA generator doesn’t take particle spins into consideration, while the
other two do; also, the HERWIG generator uses a different model to simulate the hadronization of quarks from PYTHIA; the ALPGEN generator does not perform parton hadronization, but it can be set up to pass the simulation results to either HERWIG or PYTHIA for that.

We also use the HERWIG or PYTHIA programs to add in initial- and final-state radiation to simulate the extra jets in the process. Since the Tevatron collides a bunch of protons against a bunch of antiprotons, there could be more than one collision happening during each bunch crossing. The number of extra collisions besides the highest energy collision we are interested in is closely related to the instantaneous luminosity, which reflects how many particles are in a bunch of proton/antiproton. The extra collisions are simulated with the PYTHIA event generator, with the number of extra collisions per event configured to match the profile of the instantaneous luminosity in the actual data taking periods. The simulation of the detector response to the generated events, both the primary collision and extra interactions, is accomplished with a GEANT-based [50] package named CDFSIM [51].

After the simulation of the detector responses, the samples are passed through the same object reconstruction and identification algorithms as data. We note that unless specified otherwise, the POWHEG sample is used throughout this thesis as our default sample for signal modeling.
3.3 Background Modeling

For modeling the background contributions, we use a combination of database-based and MC-based techniques. We need to both estimate the number of events as well as model the kinematic properties for each background component in our data. We mostly follow the same procedure that was used in the $t\bar{t}$ cross section measurement in the same final state [52], but introduce a number of improvements that will be enumerated below. In Table 3.2 we list background MC samples with their corresponding cross section, along with the generator used to create each. We note that instead of using the cross section predicted by the generator, we use standalone calculations of the cross sections for WW, WZ, and ZZ processes at NLO. For cross sections of $W\gamma$ and DY processes, which are calculated at LO, a set of K-factors, which are estimates of the multiplicative corrections on the cross sections for NLO effects not accounted in the corresponding LO calculations, are derived elsewhere and used with the generator calculated cross sections [52]. The K-factors are included in the table. The final cross sections we used are the cross sections listed multiplied by the corresponding K-factors, so all background calculations of the event rates correspond to the SM predictions at NLO. We next outline the key points of the background estimation procedure:

- The diboson (WW, WZ, ZZ and $W\gamma$) backgrounds are estimated by normalizing the corresponding MC samples to the integrated luminosity...
to data with the cross-sections (and K-factors). While each simulation is at LO, we use the PYTHIAMC to add initial- and final-state radiation to simulate the extra jets.

![Feynman diagrams](image)

Figure 3.2: Feynman diagrams of the tree level processes contributing to diboson. [65]

- The $W$+jets background is estimated with a data-driven method, based on a series of probabilities a jet being mis-identified as a lepton, derived from a separate data set. This procedure has been used for many years and is described in detail in Ref. [52].

- The $DY \rightarrow ee/\mu\mu$ and $DY \rightarrow \tau\tau$ backgrounds are estimated with a data-MC hybrid method, with details described in next section 3.3.1. The
method we use is an improvement over the previous method used in Ref. [52].

![Feynman diagram of Drell-Yan processes in association with jets from the initial state radiation (ISR).](image)

Figure 3.3: Feynman diagram of Drell-Yan processes in association with jets from the initial state radiation (ISR). [40]

- Each MC sample is corrected for the trigger efficiency, the object identification efficiency, the vertex z0 reconstruction efficiency, the fake charge rates for electrons in the plug detector, and normalized to the integrated luminosity from the corresponding triggers. These details are described in Ref. [52]. While we mostly follow the same procedure as the $t\bar{t}$ cross section measurement, we have made the following improvements since the previous analyses:

- We consider $t\bar{t}$ events in the lepton+jets final state faking the dilepton final state to be a background to the analysis. To do this, we added a background category denoted as “$t\bar{t}$ non-dilepton”, and estimate it by
normalizing the POWHEG $t\bar{t}$ MC samples to the integrated luminosity to data with the theoretical cross section of 7.4 pb [53].

![Feynman diagram](image)

Figure 3.4: Feynman diagram of a W boson production in association with 3 jets. Such event could fake a top dilepton, if W decays leptonically and one of the three final-state fakes a lepton. [40]

- We note that part of the MC samples we use in this analysis now use the luminosity profile corresponding to the full CDF Run II periods. These include the WW, the DY, and the $t\bar{t}$ POWHEG samples. Studies indicate that not using the full luminosity profile has a negligible effect on the final analysis results.

- We introduce scale factors for DY to correct for mis modeling of cross
3.3.1 Estimation of the Drell-Yan backgrounds in the dilepton + dijet + \( \not{E}_T \) final state

Drell-Yan (DY) production of lepton pairs through a Z and an off-shell photon (Z/\( \gamma^* \)) production, in association with jets, is one of the dominant backgrounds in this analysis. Since DY has very different kinematic distributions from \( t\bar{t} \), it has the potential to systematically bias all our measurements. For these reasons we want to get a robust estimation of the DY background, both in terms of the total number of expected events as well as in the distributions of the kinematic variables in each of the possible final states it produces. In this section we describe the estimation of the contamination of the DY+jets process in the data after the event selection described in section 3.4. We note that this estimation is only used to estimate the expected number of events; the distributions of the kinematic variables will be estimated purely with the MC simulations after normalizing the number of events to the estimated numbers from this appendix. We first describe the reason why a simple estimation with MC method is not good enough for our needs, and why a sophisticated method is required. We note that this estimation method can only be applied to the scenario where the Z/\( \gamma^* \) decays to a pair of electrons or muons, and are reconstructed as a pair of electrons or muons in the detector (denoted
<table>
<thead>
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<th>Cross Section(pb)</th>
<th>K-factor</th>
<th>Generator</th>
</tr>
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<tr>
<td>WW</td>
<td>11.34±0.68</td>
<td>N.A.</td>
<td>PYTHIA</td>
</tr>
<tr>
<td>WZ</td>
<td>3.47±0.21</td>
<td>N.A.</td>
<td>PYTHIA</td>
</tr>
<tr>
<td>ZZ</td>
<td>3.62±0.22</td>
<td>N.A.</td>
<td>PYTHIA</td>
</tr>
<tr>
<td>$W(\rightarrow e\nu)\gamma$</td>
<td>32±3.2</td>
<td>1.36</td>
<td></td>
</tr>
<tr>
<td>$W(\rightarrow \mu\nu)\gamma$</td>
<td>32±3.2</td>
<td>1.34</td>
<td>Baur [59]</td>
</tr>
</tbody>
</table>

| 75GeV < $m_{ll}$ < 105GeV | ee+0p | 157 |
|                          | ee+1p  | 21.5 |
|                          | ee+≤2p | 4.14 |
|                          | $\mu\mu+0p$ | 157 |
|                          | $\mu\mu+1p$ | 21.6 |
|                          | $\mu\mu+≤2$ | 4.12 |
|                          | $\tau\tau+0p$ | 157 |
|                          | $\tau\tau+1p$ | 21.6 |
|                          | $\tau\tau+≤2p$ | 4.13 |

| 20GeV < $m_{ll}$ < 75GeV | ee+0p | 159 |
|                          | ee+1p  | 8.36 |
|                          | ee+≤2p | 1.81 |
|                          | $\mu\mu+0p$ | 160 |
|                          | $\mu\mu+1p$ | 8.30 |
|                          | $\mu\mu+≤2$ | 1.81 |
|                          | $\tau\tau+0p$ | 160 |
|                          | $\tau\tau+1p$ | 8.35 |
|                          | $\tau\tau+≤2p$ | 1.81 |

| 105GeV < $m_{ll}$ < 600GeV | ee+0p | 4.06 |
|                           | ee+1p  | 0.707 |
|                           | ee+≤2p | 0.141 |
|                           | $\mu\mu+0p$ | 4.06 |
|                           | $\mu\mu+1p$ | 0.702 |
|                           | $\mu\mu+≤2$ | 0.141 |
|                           | $\tau\tau+0p$ | 4.06 |
|                           | $\tau\tau+1p$ | 0.710 |
|                           | $\tau\tau+≤2p$ | 0.140 |

| 8GeV < $m_{ll}$ < 20GeV   | ee+0p | 1514 |
|                           | ee+1p  | 19.7  |
|                           | ee+2p  | 6.98  |
|                           | $\mu\mu+0p$ | 1508 |
|                           | $\mu\mu+1p$ | 19.6  |
|                           | $\mu\mu+2p$ | 6.96  |

Table 3.2: Table of background MC samples.
as DY→ ee/µµ → ee/µµ). As explained below, it cannot be applied to the scenarios where the Z/γ* decays to a pair of electrons or muons, but are reconstructed as an electron plus a muon in the detector. We note that this usually happens when a muon bremsstrahlung’s a photon which is collinear with the original muon, thus the energy deposition in the calorimeter by the photon and the muon track combined make an electron candidate. Thus, this scenario is denoted as DY → ee/µµ → e_{fake}µ. Finally, the original estimation method does not apply to the scenario where the Z/γ* decays to a pair of τ leptons, and the τ leptons further decay leptonically into the ee, eµ, or µµ final states. This scenario is denoted as DY→ ττ, which includes all three final states (DY → ττ → ee/µµ/eµ).

Figure 3.5: Feynman diagram of a ττ production with two jets from ISR. [40]
3.4 Event Selection

In this analysis, full data collected by the CDF detector during Run II corresponding to an integrated luminosity of 9.1 fb$^{-1}$ is analyzed using dilepton ($ee$, $\mu\mu$, and $e\mu$) channel. The event selection criteria used are same as in the $t\bar{t}$ production cross section and $A_{FB}$ of $t\bar{t}$ in the dilepton final state measurements. The detailed descriptions on data set, Monte Carlo samples for $t\bar{t}$ signal, and backgrounds, and dilepton selection schemes can be found in in Refs. [40, 41]. Here the dilepton sample selection cuts are briefly summarized in the following.

- Isolated oppositely charged lepton pair (Fig. 3.6)
  - electron $E_T > 20$ GeV
  - muon $p_T > 20$ GeV/c

- Dilepton (Fig. 3.7)
  - $M_{l^+l^-} > 10$ GeV/c$^2$

- At least two jets (Fig. 3.8)
  - $E_T > 15$ GeV
  - $|\eta_{det}| < 2.5$

- $\not{E_T}$ (Fig. 3.9)
Figure 3.6: The kinematic variables of leptons in the $t\bar{t}$ candidates compared with SM expectations.

- $E_T > 25$ GeV if the angle between $E_T$ and any of lepton or jet azimuthal direction is greater than $20^\circ$

- $E_T > 50$ GeV else

- $H_T > 200$ GeV (Fig. 3.9)

- $Z^0$ veto for $ee$ and $\mu\mu$
Figure 3.7: The kinematic variables of dileptons in the $t\bar{t}$ candidates compared with SM expectations.

\[-76 < M_{l^+l^-} < 106 \text{ GeV}/c^2\]
\[-\frac{E_T}{\sqrt{\sum E_T}} > 4 \sqrt{\text{GeV}}\]

The set of requirements are described in detail below.

- Exactly two high energy ($E_T > 20$ GeV) charged leptons consistent with the dilepton final state. At least one of the two charged leptons is required to pass the tight lepton and isolated lepton identification criteria to enhance the purity of the sample, but the second is only required to pass the loose requirement and is not required to be isolated to retain high selection efficiency. This requirement is especially helpful against W + jets backgrounds. It has been found that the requirement of a second lepton is needed, but that only looser, more efficient, requirements are needed since the backgrounds are small enough. Any event with more
than two charged leptons are rejected.

- The two leptons (electrons or muons) have opposite electric charges. This is a signature of $t\bar{t} \rightarrow l^+ l^- \nu \bar{\nu} b \bar{b}$ decay and helps reject against $W + \text{jets}$ events where the charge of the fake lepton is not necessarily opposite in charge from the leptons from the $W$-boson decay.
Figure 3.9: The kinematic variables of the $t\bar{t}$ candidates compared with SM expectations.

- Two or more high energy jets with $E_T > 15$ GeV and $|\eta| < 2.5$. This is helpful in rejecting Diboson+jets and $Z/\gamma^*$+jets events since all jets in those backgrounds are typically at low energy, or have large $|\eta|$, as they are from initial- and/or final-state radiations, and the b-quark jets from the top quark decays are expected to be very energetic.

- Large $E_T$ ($E_T > 25$ GeV) that is consistent with two high energy neutrinos from W-boson decay leaving the detector. This is helpful in rejecting events like $Z/\gamma^* \rightarrow ee/\mu\mu, J/\psi$, or $\Upsilon$, which have no physical source of $E_T$ in the final state.

- Extra large $E_T$ ($E_T > 50$ GeV) when the direction of $E_T$ is within 20° of any lepton or jet, to reject events whose $E_T$ originates from instrumental effects, or $E_T$ produced as part of the decay of a $\tau$ lepton. This is
particularly helpful in rejecting processes with $Z/\gamma^* \to \tau\tau$.

- The summed transverse energy over all the particles in an event ($H_T$) satisfying $H_T > 200$ GeV. The typical $t\bar{t}$ process has at least twice the top mass ($2 \times 175$ GeV = 350 GeV) produced in the collision, so that there are a lot of high energy final state objects. This is not usually the case most of the backgrounds.

- The parameter $E_T$-significance is defined as $\text{METSig} = \frac{E_T}{\sqrt{\sum E_T}}$, where $E_T^{\text{sum}}$ is the scaler sum of the $E_T$ of all the charged leptons and jets in an event. This parameter quantifies the likelihood that the $E_T$ is from a real physical source (e.g. neutrino leaving the detector) rather than instrumental mis-measurement. This variable is motivated by the fact that as more energy that is deposited in the calorimeter, the probability for getting a large absolute value of the $E_T$ rises significantly. The resolution of $E_T$ measurement is proportional to $\sqrt{\sum E_T}$, so the variable METSig effectively quantifies how many standard deviations the measured $E_T$ is away from zero. We require $\text{METSig} > 4\sqrt{GeV}$ for di-electron and di-muon events, but only for events where it is needed, specifically when the invariant mass of the two charged leptons ($m_{l^+l^-}$) is consistent with the Z boson mass ($76$ GeV/$c^2 < m_{l^+l^-} < 106$ GeV/$c^2$) to reject contamination from $Z/\gamma^*$ production in associated with jets.

- To reduce the sample contamination from low mass dilepton resonances
from $J/\psi$ and $\Upsilon$ sources, we require a minimal value of $m_{l^+l^-}$. In analyses that predate this analysis, this requirement was set at 5 GeV [52]. Since we only have $Z/\gamma^* + $ jets simulations with the $m_{l^+l^-} > 8$ GeV, we have raised the dilepton invariant mass cut to 10 GeV to avoid potential mismodelling in the low dilepton invariant mass region.

### 3.5 $t\bar{t}$ Reconstruction

After applying the dilepton event selection cuts, the number of observed candidates in data and the SM expectation of signal and backgrounds are shown to be in good agreements (see Table 3.3). These candidate events are then kinematically reconstructed by constrained leptons, jets, and neutrinos to form $W$ mass, top mass, $E_x$, and $E_y$ while scanning over neutrino momenta. There are six constrains

$$M_{W}^2 = M_{\ell^+\nu}^2 = (E_{\ell^+} + E_{\nu})^2 - (\vec{p}_{\ell^+} + \vec{p}_\nu)^2 \quad (3.1)$$

$$= M_{\ell^-\bar{\nu}}^2 = (E_{\ell^-} + E_{\bar{\nu}})^2 - (\vec{p}_{\ell^-} + \vec{p}_{\bar{\nu}})^2, \quad (3.2)$$

$$M_{t\bar{t}}^2 = M_{\ell^+\nu b}^2 = (E_{\ell^+} + E_{\nu} + E_{b})^2 - (\vec{p}_{\ell^+} + \vec{p}_{\nu} + \vec{p}_{b})^2 \quad (3.3)$$

$$= M_{\ell^-\bar{\nu}b}^2 = (E_{\ell^-} + E_{\bar{\nu}} + E_{b})^2 - (\vec{p}_{\ell^-} + \vec{p}_{\bar{\nu}} + \vec{p}_{b})^2, \quad (3.4)$$

and

$$E_x = (\vec{p}_\nu + \vec{p}_{\bar{\nu}})_x \quad (3.5)$$

$$E_y = (\vec{p}_\nu + \vec{p}_{\bar{\nu}})_y \quad (3.6)$$

66
and six unknown variables (momentum of two neutrinos), so $t\bar{t}$ can be fully reconstructed. Here we used $M_W = 80.4$ GeV/$c^2$, $M_t = 172.5$ GeV/$c^2$, and $M_b = 4.66$ GeV/$c^2$. The likelihood is constructed as

$$L(p_\nu, p_{\bar{\nu}}, E^{trial}_{b}, E^{trial}_{\bar{b}}) = P_{pz}(p_T^{t\bar{t}})P_{pT}(p_T^{t\bar{t}})P_{M}(M_{t\bar{t}})$$

$$\times \frac{1}{\sigma_j^{1}} \exp \left[ -\frac{1}{2} \left( \frac{E^{trial}_{b} - E^{meas}_{j1}}{\sigma_{j1}} \right)^2 \right] \times \frac{1}{\sigma_{j2}} \exp \left[ -\frac{1}{2} \left( \frac{E^{trial}_{\bar{b}} - E^{meas}_{j2}}{\sigma_{j2}} \right)^2 \right]$$

$$\times \frac{1}{\sigma_{E/x}} \exp \left[ -\frac{1}{2} \left( \frac{E^{trial}_{x} - E^{meas}_{x}}{\sigma_{E/x}} \right)^2 \right] \times \frac{1}{\sigma_{E/y}} \exp \left[ -\frac{1}{2} \left( \frac{E^{trial}_{y} - E^{meas}_{y}}{\sigma_{E/y}} \right)^2 \right],$$

where $E^{meas}_{j1(2)}$ is the measured energy of jet 1 (2), assigned to $b (\bar{b})$ jet whose trial energy value is $E^{trial}_{b(\bar{b})}$. The jet energy is corrected with the Level 5 jet correction and the $t\bar{t}$ dilepton event specific correction shown in Figures 3.11 and 3.12. $E^{meas}_{x(y)}$ is the $x (y)$ component of measured $E_T$ and $E^{trial}_{x(y)}$ is the $x (y)$ component of trial $E_T$ from $p_\nu$ and $p_{\bar{\nu}}$. $\sigma_{j1(2)}$ and $\sigma_{E/x(y)}$ are the resolution of energy of jet 1 (2) and $E^{meas}_{x(y)}$ (Figures 3.11, 3.12 and 3.10). $P_{pz}(p_T^{t\bar{t}})$, $P_{pT}(p_T^{t\bar{t}})$, and $P_{M}(M_{t\bar{t}})$ are the probability density distributions of $t\bar{t}$ $p_z$, $p_T$, and mass, respectively, that are obtained from $tt\bar{t}f\bar{p}$ MC sample (Figure 3.13). The solutions are obtained maximizing the likelihood by scanning available neutrino momenta phase space. This method is described in details in Ref. [43].

The methods of estimating the signal and backgrounds follow Ref. [41]. The $t\bar{t}$ signal MC sample is generated with POWHEG, an NLO MC generator [44]. The backgrounds include events from the Drell-Yan production ($Z/\gamma^*+$jets), a $W$ production with jets ($W+$fake lepton), diboson production ($WW$, $WZ$, $ZZ$), and others.
Figure 3.10: Parametrized $\sigma_{E_{x,y}}$ resolution as a function of sum of $E_T$ of two leading jets for dilepton events of the $\tt$ sample. The curve is obtained from fitting the sample distribution with $\exp(p_0 + p_1 x) + p_2$ where $x = E_{T,j1} + E_{T,j2}$.

$ZZ$, and $W\gamma$), and a $t\bar{t}$ decaying to non-dilepton channel. The signal and backgrounds are listed in Table 3.3 which is taken from Ref. [41].
Figure 3.11: Parametrized mean of \( \frac{(E_{T}^{\text{true}} - E_{T}^{\text{reco}})}{E_{T}^{\text{reco}}} \) as a function of \( E_{T}^{\text{reco}} \), where \( E_{T}^{\text{reco}} \) is Level 5 corrected \( E_{T} \) of the jet matched to \( b \) or \( \bar{b} \) within \( \Delta R < 0.4 \), in the dilepton candidate events in ttktfp sample for regions of \(|\eta| < 0.7\), \(0.7 < |\eta| < 1.3\), and \(1.3 < |\eta| < 2.5\). The parameters are obtained from fitting the sample distributions with \( \exp(p_0 + p_1 x) + p_2 \) where \( x = E_{T}^{\text{reco}} \).
Figure 3.12: Parametrized width of $(E_{T}^{\text{true}} - E_{T}^{\text{reco}})/E_{T}^{\text{reco}}$ as a function of $E_{T}^{\text{reco}}$, where $E_{T}^{\text{reco}}$ is Level 5 corrected $E_T$ of the jet matched to $b$ or $\bar{b}$ within $\Delta R < 0.4$, in the dilepton candidate events in $ttKtFp$ sample for regions of $|\eta| < 0.7$, $0.7 < |\eta| < 1.3$, and $1.3 < |\eta| < 2.5$. The parameters are obtained from fitting the sample distributions with $\exp(p_0 + p_1 x) + p_2$ where $x = E_{T}^{\text{reco}}$. 
Figure 3.13: $p_T^t$, $p_T^{t\bar{t}}$, and $M_{t\bar{t}}$ distributions obtained from the dilepton events in $tt\bar{t}$ MC sample. Parametrization functions and parameters are given in the plots.
<table>
<thead>
<tr>
<th>Source</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW$</td>
<td>21.12 ± 4.17</td>
</tr>
<tr>
<td>$WZ$</td>
<td>5.84 ± 0.98</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>3.66 ± 0.53</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>0.73 ± 0.77</td>
</tr>
<tr>
<td>$DY \rightarrow \tau\tau$</td>
<td>17.02 ± 2.80</td>
</tr>
<tr>
<td>$DY \rightarrow ee/\mu\mu$</td>
<td>33.47 ± 3.87</td>
</tr>
<tr>
<td>$W+\text{fake lepton}$</td>
<td>63.81 ± 17.07</td>
</tr>
<tr>
<td>$t\bar{t}$ non-dilepton</td>
<td>14.65 ± 0.75</td>
</tr>
<tr>
<td>Total background</td>
<td>160.31 ± 21.15</td>
</tr>
<tr>
<td>$t\bar{t}$ ($\sigma = 7.4$ pb)</td>
<td>408.16 ± 19.41</td>
</tr>
<tr>
<td>Total SM expectation</td>
<td>568.47 ± 40.33</td>
</tr>
<tr>
<td>Observed ($\mathcal{L} = 9.1$ fb$^{-1}$)</td>
<td>569</td>
</tr>
</tbody>
</table>

Table 3.3: Table of expected and observed numbers of backgrounds and signal events after dilepton selection taken from Ref. [41]. The fake lepton is a jet misidentified as a lepton.
Chapter 4

Measurement of Top Quark Polarization

In Chapter 1, the introduction to the top quark physics and the top quark polarization has been presented together with the motivation for the measurement. In this chapter we measure the top quark polarization from a differential angular distribution of the two decay leptons in the rest frames of their respective top quark and the spin quantization axis.

The weighted signal templates will be discussed in Section 4.3. Using the templates, we fit the angular distribution of data, and we get measured $\alpha_P$ in Section 4.5. The construction of pseudo-experiments will be discussed in Section 4.6.
4.1 Top Quark Polarization

As the life time of top quark is shorter than the time scale for hadronization, the spin state information of top quark remains in the angular distributions of its decay products. So top quark polarization can be measured from the angular distribution of the top quark decay products with respect to a given quantization axis. In thesis, the dilepton channels of top-antitop quark pair decay are used to measure top quark polarization. The double differential angular distribution of two leptons in top(antitop) quark rest frame is given by

\[
\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4} \left( 1 + \alpha_+ P_+ \cos\theta_+ + \alpha_- P_- \cos\theta_- - C \cos\theta_+ \cos\theta_- \right),
\]

where \(\theta_+(-)\) is the opening angle between the positively (negatively) charged lepton from the top (antitop) quark decay to its chosen quantization axis in the top (antitop) quark rest frame, \(C\) is the \(t\bar{t}\) spin correlation coefficient, \(P_+(-)\) is the degree of polarization of the top (antitop) quark along the chosen quantization axis, and \(\alpha_+(-)\) is the spin-analyzing power of the positively (negatively) charged lepton, which is a measure of the sensitivity of the daughter particle to the spin state of the parent [17, 20]. At the leading order, charged leptons and down-type quarks from \(W\) boson decays are predicted to have the largest sensitivity to the spin state of the top quark with a spin-analyzing power of \(\alpha = 1\) [23], while for the \(b\) quark \(\alpha = -0.4\), for the neutrino \(\alpha = -0.3\). We measure the top quark polarization in two bases for quantization axis, helicity and
Figure 4.1: The opening angle $\theta_+ (\theta_-)$ between positively (negatively) charged lepton $l^+ (l^-)$ momentum direction and the quantization axis $\hat{a}$ ($\hat{b}$) in the top (antitop) rest frame.

transverse bases. The detailed definitions of quantization axis are explained in next section 4.2.

4.2 Choice of Quantization Axis Basis

In the thesis, the spin polarization of top quark is measured in the helicity and transverse bases. In the helicity basis, the momentum directions of the top and antitop quarks in the $t\bar{t}$ center-of-mass frame are defined as the quantization
axes. In the transverse basis, the polarization of the top and antitop quarks perpendicular to the production plane is measured. The quantization axis of the top quark in the transverse basis is defined as the cross product of the proton momentum direction and the top quark momentum direction \([37, 38]\), i.e.,

$$\hat{n}_p = \frac{\hat{p}_p \times \hat{k}}{|\hat{p}_p \times \hat{k}|},$$

(4.2)

where \(\hat{p}_p\) is the unit vector of proton direction in the lab frame and \(\hat{k}\) is the unit vector of the top quark direction in the \(t\bar{t}\) rest frame.

![Figure 4.2: The spin quantization axes in the \(t\bar{t}\) rest frame.](image)

Table 4.1 shows the quantization axes for top \((\hat{a})\) and antitop \((\hat{b})\) in the helicity and transverse bases (see Figure 4.1). To account for the Bose-symmetry of the \(gg\) initial state the signs of \(y_p = \hat{n}_p \cdot \hat{k}\) is required for the transverse basis.
quantization axes [39].

<table>
<thead>
<tr>
<th>Axis</th>
<th>Helicity</th>
<th>Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\hat{a})</td>
<td>(\hat{k})</td>
<td>(\frac{y_p}{</td>
</tr>
<tr>
<td>(\hat{b})</td>
<td>(-\hat{k})</td>
<td>(-\frac{y_p}{</td>
</tr>
</tbody>
</table>

Table 4.1: The quantization axes in the helicity and transverse bases. The axes in the transverse basis is defined as Ref. [38]. \(\hat{a}\) and \(\hat{b}\) are quantization axes for top and antitop quarks, respectively, as shown in Figure 4.1. \(\hat{n}_p\) is defined in Eq. 4.2 and \(\hat{k}\) is unit vector of the top quark direction in the \(t\bar{t}\) rest frame.

### 4.3 Weighted Signal Templates

We use \texttt{ttktfp} MC sample which is generated with POWHEG, an NLO MC, as our basis for the signal templates. \texttt{ttktfp} sample is generated with the standard model strength spin correlation and spin polarization. Figure 4.3 shows the preselection parton level \((\cos \theta_+, \cos \theta_-)\) distributions of \texttt{ttktfp} sample in the beamline, helicity, and transverse bases. To make a signal \((\cos \theta_+, \cos \theta_-)\) template with a specific degree of polarization \(\alpha_+ P_+\) each event in the template
is weighted by

\[
f(\cos \theta^p_+, \cos \theta^p_-; \alpha \pm P \pm) = \frac{1 + \alpha_+ P_+ \cos \theta^p_+ + \alpha_- P_- \cos \theta^p_- - C_{SM} \cos \theta^p_+ \cos \theta^p_-}{1 - C_{temp} \cos \theta^p_+ \cos \theta^p_-},
\]

where \( \theta^p_{+(-)} \) is the angle between the positively (negatively) charged lepton momentum and the respective quantization axis in the \( t(\bar{t}) \)-quark rest frame calculated in the parton level and \( C_{SM} \) and \( C_{temp} \) are the spin correlation coefficients of Standard Model and templates in the given reference frame (see Table 4.2).

<table>
<thead>
<tr>
<th>Basis</th>
<th>Spin Corr.</th>
<th>( \alpha P ) Physical Region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theory</td>
<td>ttktfp</td>
</tr>
<tr>
<td>Beamline</td>
<td>0.804</td>
<td>0.802 ± 0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CPC [-0.098, 0.098]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CPV [-0.902, 0.902]</td>
</tr>
<tr>
<td>Helicity</td>
<td>-0.370</td>
<td>-0.374 ± 0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CPC [-0.685, 0.685]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CPV [-0.315, 0.315]</td>
</tr>
<tr>
<td>Transverse</td>
<td>-</td>
<td>0.168 ± 0.003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CPC [-0.416, 0.416]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CPV [-0.584, 0.584]</td>
</tr>
</tbody>
</table>

Table 4.2: The spin correlation coefficient from theory and physical regions of \( \alpha P \) in the beamline, helicity, and transverse bases for CPC and CPV.

In this analysis, two extreme cases with respect to CP symmetry are considered:

- CP conserved (CPC) : \( \alpha^{P_{CPC}} = \alpha_+ P_+ = \alpha_- P_- \)
- CP maximally violated (CPV) : \( \alpha^{P_{CPV}} = \alpha_+ P_+ = -\alpha_- P_- \)
Figure 4.3: The parton level \((\cos \theta_+, \cos \theta_-)\) distributions of \texttt{ttktf} (\texttt{POWHEG}) preselection sample in (a) beamline, (b) helicity, and (c) transverse bases. In the legends, the polarization\((\alpha P)\) and spin correlation\((C)\) for each bases are extracted by fitting Eq. 4.2 on these plots.

To keep the weighting factor shown in Eq. 4.3 in the physical region, i.e. \(f(\cos \theta_+, \cos \theta_-; \alpha \pm P_\pm) \geq 0\), \(\alpha P\) has to satisfy the following conditions. For the CPC case, \(\alpha P^{CPC}\) can be written as

\[
\alpha P^{CPC} \geq -\frac{1 - C \cos \theta_+ \cos \theta_-}{\cos \theta_+ + \cos \theta_-}
\]  

(4.4)
then the maximum range is at \( \cos^{\theta^p} = -1 \) and \( \cos^{\theta^-} = -1 \)

\[
-\frac{1 - C}{2} \leq \alpha^{CPc} \leq \frac{1 - C}{2}
\] (4.5)

and for the CPC case, \( \alpha^{CPv} \) can be written as

\[
\frac{1}{\cos^{\theta^p} - \cos^{\theta^-}}
\]

(4.6)

then the maximum range is at \( \cos^{\theta^p} = -1 \) and \( \cos^{\theta^-} = +1 \)

\[
-\frac{1 + C}{2} \leq \alpha^{CPv} \leq \frac{1 + C}{2}.
\] (4.7)

Two quantization bases are considered for measuring \( \theta_{\pm} \); the helicity and transverse bases. The beamline basis is not considered since the physical region is small to have a meaningful measurement as the uncertainty on \( \alpha P \) measurement would be larger than the range of the physical region. The physical region of \( \alpha P \) of the beamline, helicity, and transverse bases are shown in Table 4.2. The spin correlation coefficients \( C \) obtained from fitting the preselection parton level \( ttktf \) sample with Eq. 4.2 shows good agreements with theoretical values. The results are shown in Table 4.2. The obtained values for the beamline and helicity bases are \( \sim 1\sigma \) of the theoretical values. There is no theoretically calculated value of \( C \) available for the transverse basis. Therefore we use the value of \( C \) obtained from the fit of preselection \( ttktf \) sample using Eq. 4.2 in the parton level. For the transverse basis the fit yields \( C = 0.168 \).
4.4 Validation of Weighting Function

To check the validity of the weighting function (Eq. 4.3), each event in the preselection ttktfp sample is weighted for $\alpha_P = 0.3$ and $C = -0.37$ for CPV in the helicity basis. Then $\alpha_P$ and $C$ values are extracted from the weighted template and are found to be consistent with the input values (see Figure 4.4).

Figure 4.4: The $(\cos \theta_+, \cos \theta_-)$ distribution of the weighted sample as CPV helicity with $\alpha_P = 0.3$ and $C = -0.37$ from ttktfp.

Figures 4.5 and 4.6 show the reconstructed $(\cos \theta_+, \cos \theta_-)$ distributions with $\alpha_P = 0$ and $\pm 0.3$ in the helicity and transverse bases, respectively. The weighted signal templates in the regions are produced and compared with data to measure the polarization.
The signal templates are generated in the intervals of $\alpha P$ of 0.05 within the ranges shown in Table 4.3.

<table>
<thead>
<tr>
<th>Basis</th>
<th>CPC</th>
<th>CPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helicity</td>
<td>[-0.6,0.6]</td>
<td>[-0.3,0.3]</td>
</tr>
<tr>
<td>Transverse</td>
<td>[-0.4,0.4]</td>
<td>[-0.5,0.5]</td>
</tr>
</tbody>
</table>

Table 4.3: The ranges of $\alpha P$ of weighted templates generated in helicity and transverse bases for CPC and CPV in this analysis. The intervals are 0.05.

4.5 Top Quark Polarization Analysis

The angular distribution from data is compared with the weighted signal template plus backgrounds and fitted to extract the best polarization values. The $(\cos \theta_+, \cos \theta_-)$ distribution of data can be compared with the those of the background and signal templates of various degree of polarization. The angular distributions of two leptons for all backgrounds and $t\bar{t}$ signal are shown in Figures. 4.7, 4.8, 4.9 and 4.10 for helicity and transverse bases. Figures 4.11 and 4.11 (4.13 and 4.14) show the 2 dimensional comparisons for different $\alpha P$ in helicity (transverse) basis. And you can see the one dimensional distributions projected into $\cos \theta_+$ and $\cos \theta_-$ are compared in Figures. 6.1 and 6.2.

The $\alpha P$ is extracted by using a likelihood fitting method. The likelihood is
Figure 4.5: The signal \((\cos \theta_+, \cos \theta_-)\) templates for the helicity basis of (a) CPC and CPV at \(\alpha P = 0\) (b) CPC at 0.3, (c) CPC at -0.3, (d) CPV at 0.3, and (e) CPV at -0.3.
Figure 4.6: The signal $(\cos \theta_+, \cos \theta_-)$ templates for the transverse basis of (a) CPC and CPV at $\alpha P = 0$ (b) CPC at 0.3, (c) CPC at -0.3, (d) CPV at 0.3, and (e) CPV at -0.3.
Figure 4.7: \((\cos \theta_+, \cos \theta_-)\) distributions of two leptons for each background source in helicity basis.
Figure 4.8: (a) $(\cos \theta_+, \cos \theta_-)$ distribution of two leptons for total background in helicity basis. (b) and (c) The background template statistical uncertainty is the uncertainty due to statistical uncertainty of each background template.
Figure 4.9: \((\cos \theta_+, \cos \theta_-)\) distributions of two leptons for each background sources in transverse basis.
Figure 4.10: (a) \((\cos \theta_+, \cos \theta_-)\) distribution of two leptons for total background in transverse basis. (b) and (c) The background template statistical uncertainty is the uncertainty due to statistical uncertainty of each background template.
Figure 4.11: \((\cos \theta_+, \cos \theta_-)\) distribution of two leptons for (a) data and for (b-d) signal \((\alpha P = -0.6)\) and backgrounds for CPC

(c) signal \((\alpha P = 0.0)\) and backgrounds

(d) signal \((\alpha P = 0.6)\) and backgrounds for CPC

Figure 4.11: \((\cos \theta_+, \cos \theta_-)\) distribution of two leptons for (a) data and for (b-d) signal and backgrounds for CPC in helicity basis
Figure 4.12: \((\cos \theta_+, \cos \theta_-)\) distribution of two leptons for (a) data and for (b-d) signal and backgrounds for CPV in helicity basis.

(a) data 9.1 fb\(^{-1}\) in helicity basis  

(b) signal \((\alpha P = -0.3)\) and backgrounds for CPV

(c) signal \((\alpha P = 0.0)\) and backgrounds for CPV

(d) signal \((\alpha P = 0.3)\) and backgrounds for CPV
Figure 4.13: $(\cos \theta_+, \cos \theta_-)$ distribution of two leptons for (a) data and for (b-d) signal ($\alpha P = -0.4$) and backgrounds for CPC

(c) signal ($\alpha P = 0.0$) and backgrounds

(d) signal ($\alpha P = 0.4$) and backgrounds for CPC

91
(a) data 9.1 fb⁻¹ in transverse basis  
(b) signal (αP = −0.5) and backgrounds for CPV  
(c) signal (αP = 0.0) and backgrounds  
(d) signal (αP = 0.5) and backgrounds for CPV  

Figure 4.14: (cos θ₊, cos θ₋) distribution of two leptons for (a) data and for (b-d) signal and backgrounds for CPV in transverse basis
constructed adopting the “pull approach” framework given in Ref. [42] as

\[
L(\alpha P) = \left[ \frac{1}{\sqrt{2\pi}\sigma_s} \exp \left( -\frac{\delta_s^2}{2\sigma_s^2} \right) \right] \left[ \frac{1}{\sqrt{2\pi}\sigma_b} \exp \left( -\frac{\delta_b^2}{2\sigma_b^2} \right) \right] \prod_{i=\text{bin}} \frac{e^{-\lambda_i} \lambda_i^{n_i}}{n_i!} \frac{1}{\sqrt{2\pi}\sigma_{\xi_i}} \exp \left( -\frac{\xi_i^2}{2\sigma_{\xi_i}^2} \right),
\]

(4.8)

where \( n_i \) and \( \lambda_i \) are the numbers of data events and expected, respectively, in the \( i \)th bin, \( \delta_{s(b)} \) is the event “pull” parameter with respect to the total number of signal (background) events to be determined by fitting, \( \sigma_{s(b)} \) is the uncertainty of the number of signal (total background) events shown in Table 3.3, and \( \xi_i \) and \( \sigma_{\xi_i} \) are the pull parameter and the uncertainty coming from the statistical uncertainty of the background templates for the \( i \)th bin, respectively. The number of events in the \( i \)th bin determined by fitting is

\[
\lambda_i = (\nu_s + \delta_s) \rho_{s_i}^{\alpha P} + (\nu_b + \delta_b) \left( \rho_{b_i} + \frac{\xi_i}{\nu_b} \right),
\]

(4.9)

where \( \nu_{s(b)} \) are the expected number of signal (total background) shown in Table 3.3, \( \rho_{s_i}^{\alpha P} \) and \( \rho_{b_i} \) are the normalized event densities of signal with the degree of polarization of \( \alpha P \) and of background, respectively, in the \( i \)th bin. The statistical uncertainty of the background template is calculated as

\[
(\sigma_{\xi_i})^2 = \sum_{j=bkg} \left( c_j \sqrt{N_i^j} \right)^2,
\]

(4.10)

where \( c_j \) is the normalization factor to the expected for the \( j \)th background and \( N_i^j \) is the number of events before the normalization in the \( i \)th bin of the \( j \)th background.
The first two terms in Eq. 4.8 constrain the measured total numbers of signal and background events to their respective expected numbers of events within their uncertainties. The third term is the Poisson probability with the backgrounds constrained within the statistical uncertainty of background template for each bin. By introducing a pull $\xi_i$ for each bin of the total background template, the uncertainty on the background shape coming from the statistical fluctuations in the total background template is accounted for as a penalty to the likelihood. The negative log likelihood, $-\ln \mathcal{L}$, is minimized by varying $\delta_s$, $\delta_b$, and $\xi_i$ to get minimum $-\ln \mathcal{L}$ value for the signal template with a given $\alpha P$ and $\rho_{s_i}^{\alpha P}$.

To extract the $\alpha P$, templates with various $\alpha P$ value are used to fit the data and obtain the $\alpha P$ yielding the minimum $-\ln \mathcal{L}$ value by interpolating the resulting $-\ln \mathcal{L}$. The likelihood fittings are performed for both of helicity basis (Figure 4.16 (a) and (b)) and transverse basis (Figure 4.16 (c) and (d)), for CPC and CPV. The best values of $\alpha P$ are summarized in Table 4.4, which are in agreement with the SM expectations. The uncertainties are the sum of the statistical uncertainty of the data and the background shape uncertainty coming from the background template statistical uncertainty.
Table 4.4: Measured polarization from data in the helicity and transverse bases for CPC and CPV. The uncertainties are from the fit only, therefore, include the statistical uncertainties along with the background template statistical uncertainties and expected signal and background yield uncertainties.

4.6 Linearity and Pull Tests of Weighted Template Method

The linearity of the weighted template method is tested by performing pseudo-experiments. A pseudo-data sample is generated with weighted template with input polarization $\alpha P$ and the background template. The pseudo-events are generated randomly using the Poisson probability with the mean of expected number of events. Each pseudo-data sample is treated like a real data set and $\alpha P$ is extracted from the likelihood fit. Five thousand pseudo-experiments are performed for each input $\alpha P$. The extracted $\alpha P$ is compared to the input $\alpha P$, Fig. 4.18 shows good linearity.
Figure 4.15: Likelihood difference distributions of the fit of (a) CPC helicity and (b) CPV helicity. The dashed line shows the 1σ difference.

Figure 4.16: Likelihood difference distributions of the fit of (c) CPC transverse, and (d) CPV transverse. The dashed line shows the 1σ difference.
Figure 4.17: Input and output $\alpha P$ from pseudoexperiments at various input $\alpha P$ for (a) CPC helicity and (b) CPV helicity. The green bands represent 1$\sigma$ widths of the $\alpha P$ distributions of pseudoexperiments.

Figure 4.18: Input and output $\alpha P$ from pseudoexperiments at various input $\alpha P$ for (c) CPC transverse and (d) CPV transverse. The green bands represent 1$\sigma$ widths of the $\alpha P$ distributions of pseudoexperiments.
Also, the pull distributions from pseudo-experiments are examined and shown to be good within statistics. Figure 4.19 shows the pull distributions of CPC-Helicity.

Figure 4.19: The pull distributions of $\alpha P$ of CPC-Helicity for (a) $\alpha P = -0.3$, (b) 0, and (c) 0.3 from 1000 pseudo-experiments.
Chapter 5

Statistical and Systematic Uncertainties

5.1 Statistical Uncertainty

The likelihood in Eq. 4.8 has pulls for the numbers of signal and background expectations and the expected numbers in each bin of the total background template, each constrained by a Gaussian function to its uncertainty. Therefore, the uncertainties listed in Table 4.4 are not purely statistical in nature and the statistical uncertainty must be calculated by removing the pulls (Eq. 5.1). The statistical uncertainty is obtained by removing the pulls (i.e., fixing all pulls to the expected mean values) from the likelihood in Eq. 4.8 and using the same method of scanning $\alpha P$ as used in Sect. 4.5. The results are shown
\[ \mathcal{L}(\alpha P) = \prod_{i=\text{bin}} \frac{e^{-\lambda_i} \lambda_i^{n_i}}{n_i!} \quad (5.1) \]

<table>
<thead>
<tr>
<th>Helicity</th>
<th>Transverse</th>
</tr>
</thead>
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<td>CPV</td>
</tr>
<tr>
<td>CPC</td>
<td>CPV</td>
</tr>
<tr>
<td>Stat. Uncert.</td>
<td>$^{+0.114}_{-0.109}$</td>
</tr>
</tbody>
</table>

Table 5.1: The statistical uncertainties of $\alpha_P$ fit results in Table 4.4. The uncertainties are obtained by removing pulls in the likelihood in Eq. 4.8.

## 5.2 Systematic uncertainties

The systematic uncertainties on the measurement of $\alpha P$ come from the uncertainties in the shape of the $(\cos \theta_+, \cos \theta_0)$ distributions of signal and background expectations as well as the relative fraction of backgrounds. Here the uncertainties coming from the uncertainties on the signal and backgrounds are calculated separately.

For the signal, the uncertainties are calculated by comparing the result of the set of pseudo-experiments with a specific systematic uncertainty effect implemented to those of a nominal set of pseudo-experiments. The signal MC samples used for the systematic uncertainty calculations are listed in Table 5.2. These systematic uncertainties are described in Sects. 5.2.1 to 5.2.11.
<table>
<thead>
<tr>
<th>Source of Systematic</th>
<th>No. of PE</th>
<th>$C_{hel}$</th>
<th>$C_{trans}$</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDF</td>
<td>PDF weighted</td>
<td>176</td>
<td>-0.370</td>
<td>0.168</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>$\pm 1\sigma$</td>
<td>120</td>
<td>-0.370</td>
<td>0.168</td>
</tr>
<tr>
<td>JES</td>
<td>$\pm 1\sigma$</td>
<td>176</td>
<td>-0.370</td>
<td>0.168</td>
</tr>
<tr>
<td>$\mu$ Scale</td>
<td>$\mu_R = \mu_F = M_{top}$</td>
<td>176</td>
<td>-0.355</td>
<td>0.177</td>
</tr>
<tr>
<td></td>
<td>$\mu_R = \mu_F = 4M_{top}$</td>
<td>176</td>
<td>-0.392</td>
<td>0.178</td>
</tr>
<tr>
<td>Top Quark Mass</td>
<td>$M_{top} = 172.5$ GeV/$c^2$</td>
<td>117</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>$M_{top} = 175$ GeV/$c^2$</td>
<td>84</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>MC Generator</td>
<td>ALPGEN</td>
<td>48</td>
<td>-0.441</td>
<td>0.141</td>
</tr>
<tr>
<td></td>
<td>PYTHIA</td>
<td>116</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Color Reconnection</td>
<td>Apro</td>
<td>116</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Parton Showering</td>
<td>ACRpro</td>
<td>116</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>ALPGEN with PYTHIA PS</td>
<td>48</td>
<td>-0.441</td>
<td>0.141</td>
</tr>
<tr>
<td></td>
<td>ALPGEN with HERWIG PS</td>
<td>55</td>
<td>-0.442</td>
<td>0.155</td>
</tr>
</tbody>
</table>

Table 5.2: Sources of systematic uncertainties of the signal and the innate spin-correlation coefficients. The number of pseudo-experiments (PE) used to calculate the uncertainties are also shown.
Much of the systematic uncertainties of the backgrounds are expected to affect the backgrounds much the same way as the signal, i.e., they are likely positively correlated to the signal. However the background systematic uncertainties cannot be treated like that of the signal due to the unavailability of many of the systematic uncertainty shifted background MC samples. The background specific systematic uncertainties are discussed in Sects. 5.2.1 and 5.2.11.

To generate pseudo-data sets with a specific systematic uncertainty effect, a \((\cos \theta_+, \cos \theta_-)\) distribution with a given \(\alpha P\) value is produced with a signal MC sample with the systematic uncertainty effect following the procedure described in Sect. 4.3. The numbers of events in the signal and total background \((\cos \theta_+, \cos \theta_-)\) distributions are normalized to their nominal expected of 408.16 and 160.31, respectively, and summed. Then events are randomly drawn from the combined distribution with the number of events randomly fluctuated following a Poisson probability with the nominal expected number of events as the mean of the probability distribution. This normalization is

---

1 This assumption is tested with the available systematic uncertainty shifted background MC samples, such as jet energy scale shifted background samples, and found to reduce the systematic uncertainty when the systematic uncertainty shifted background templates are used along with the shifted signal sample template than using signal template alone.

2 The effects of the systematic uncertainties are also evaluated without normalizing the expected numbers of events to the their nominal expected and found to be consistent with our prescribed method.
done to avoid the double-counting of the effects of the systematic uncertainty source from the numbers of signal and backgrounds, as the effects are incorporated in the likelihood function used to extract $\alpha P$ in Eq. 4.8.

The pseudo-data set is analyzed the same way as the data and extract $\alpha P$ value. Each pseudo-experiment for a given $\alpha P$ value is repeated and the mean of $\alpha P$ ($\langle \alpha P \rangle$) is obtained from the distribution of the extracted $\alpha P$ values by fitting it with a Gaussian function (see Fig. 5.1). The number of pseudo-experiments performed for each systematic uncertainty component is determined by the size of the signal sample that pseudo-data sample is made from. However, an exception is made for the renormalization scale uncertainty where the number of pseudo-experiments performed is 176 since the renormalization scale shifted signal sample yields 17 sets of pseudo-experiments.

For NLO MC systematic uncertainty samples the difference between values of $\langle \alpha P \rangle$ of the nominal pseudo-experiment set and of the systematic uncertainty effect pseudo-experiment set is used to calculate the systematic uncertainty for the particular systematic uncertainty source. For LO MC systematic uncertainty samples the difference of $\langle \alpha P \rangle$ between two systematic uncertainty effect pseudo-experiment sets are taken to be the systematic uncertainty.

Then the systematic uncertainties obtained are plotted with respect to the true $\alpha P$ and are fit to a straight line. The systematic uncertainty for the measured $\alpha P$ with data is then extracted by interpolating the fit line at the
Figure 5.1: The results of pseudo-experiments for JES negative shift sample. The mean value of $\alpha_P$, $\langle \alpha_P \rangle$, obtained is used to calculate the systematic uncertainties compared to that of no systematic shift pseudo-experiment.

measured $\alpha_P$ value.

### 5.2.1 Uncertainties of Expected Numbers of Signal and Background Events

The uncertainties due to uncertainties of expected numbers of events for the signal and backgrounds are calculated by shifting the each of expected number of signal and total background events by $\pm 1\sigma$ and performing a fit to the data. Then the average of the differences between the shifted by $\pm 1\sigma$ and the default
$\alpha P$ is taken to be the uncertainty coming from the uncertainty of expected numbers of the signal or total background events. The results are shown in Table 5.3. These uncertainties are small and neglected in the total uncertainty calculations.

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>Helicity</th>
<th>Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CPC</td>
<td>CPV</td>
</tr>
<tr>
<td>Signal Norm.</td>
<td>$\pm 0.0035$</td>
<td>$\pm 0.0013$</td>
</tr>
<tr>
<td>Background Norm.</td>
<td>$\pm 0.0048$</td>
<td>$\pm 0.0019$</td>
</tr>
</tbody>
</table>

Table 5.3: The uncertainties in $\alpha P$ due to uncertainties in the expected numbers of signal and background events.

### 5.2.2 Parton Distribution Function Uncertainties

To evaluate the systematic uncertainty due to the parton distribution function (PDF), sets of pseudo-experiments are performed with the signal samples reweighted for different PDF assumptions. The prescription of this PDF reweighted MC method is given here [45]. In this method each event in the signal MC sample is reweighted by the relative probability on the different PDF set assumption based on the parton momentum fractions, $Q^2$, and initial partons in the event.

The $\alpha P$ weighted pseudo-data samples are generated from the $(\cos \theta_+, \cos \theta_-)$ template constructed with PDF reweighted MC samples. For each $\alpha P$ value, a
set of pseudo-data samples are made and pseudo-experiments are performed.

The reweighting is done for CTEQ6M and its 20 orthogonal PDF sets (CTEQ6MN±) which represent ±90% shifts, where \( N = 1 \sim 20 \). The \( \langle \alpha P \rangle \) are compared for CTEQ6M and CTEQ6MN± and the difference between CTEQ6M and each orthogonal pair is calculated asymmetrically:

- opposite sign shifts: the positive (negative) shift is taken to be the positive (negative) error
- both positive shift: the larger one is taken to be the positive error and the negative error is taken to be 0
- both negative shift: the larger one is taken to be the negative error and the positive error is taken to be 0

The differences are then added in quadrature for the positive and negative uncertainties separately. The results are shown in Fig. 5.2.

### 5.2.3 Initial and Final State Radiation Uncertainty

Extra jets originating from the incoming partons and/or outgoing partons are called initial state radiations(ISR) and final state radiations(FSR).

ISR/FSR uncertainty is calculated with the less ISR/FSR sample (ttktlp) and more ISR/FSR sample (ttktmp). The pseudo-experiments are performed with pseudo-data samples generated with ISR/FSR shifted samples. The aver-
Figure 5.2: Shift of $\langle \alpha P \rangle$ from nominal pseudo-experiment for CTEQ6M and 20 eigenvectors for (a) CPC-Helicity, (b) CPV-Helicity, (c) CPC-Transverse, and (d) CPV-Transverse. The filled circles are for the positive shift and the filled squares are for the negative shift. The red line is obtained from fitting the shift of $\langle \alpha P \rangle$ as function of $\alpha P_{\text{true}}$. The arrows indicate the measured $\alpha P$ of data. The uncertainties are correlated.
age of the absolute differences in $\langle \alpha P \rangle$ between the nominal and shifted samples is taken as the systematic uncertainty. The results are shown in Fig. 5.4.

5.2.4 Jet Energy Scale (JES) Uncertainty

The common systematics on high energy physics comes from jet energy scale uncertainties. The shift in the jet energy scale affects the kinematic distributions and, therefore, the event acceptance.

To estimate the uncertainty from the jet energy scale uncertainty, pseudo-experiments are performed with pseudo-data generated from $tt\bar{t}f_p$ sample.
Figure 5.4: Shift of $\langle \alpha P \rangle$ from nominal pseudo-experiment for initial/final state radiation for (a) CPC-Helicity, (b) CPV-Helicity, (c) CPC-Transverse, and (d) CPV-Transverse. The red line is obtained from fitting the shift of $\langle \alpha P \rangle$ as function of $\alpha P_{true}$. The arrows indicate the measured $\alpha P$ of data. The uncertainties are correlated.
Figure 5.5: Diagram of jet energy deposit in EM and HAD calorimeter
with the jet energy scale shifted by \( \pm 1\sigma \). The average absolute differences in \( \langle \alpha P \rangle \) between the shifted and nominal is taken as the systematic uncertainty. The results are shown in Fig. 5.6.

Figure 5.6: Shift of \( \langle \alpha P \rangle \) from nominal pseudo-experiment for jet energy scale for (a) CPC-Helicity, (b) CPV-Helicity, (c) CPC-Transverse, and (d) CPV-Transverse. The red line is obtained from fitting the shift of \( \langle \alpha P \rangle \) as function of \( \alpha P_{\text{true}} \). The arrows indicate the measured \( \alpha P \) of data. The uncertainties are correlated.
5.2.5 \( \mu \) (Renormalization and Factorization) Scale Uncertainty

The renormalization scale \( (\mu_R) \) and factorization scale \( (\mu_F) \) change the \( t\bar{t} \) spin correlation and, therefore, affect the shape of \( (\cos \theta_+, \cos \theta_-) \) distribution. The nominal sample \( ttktfp \) sample is generated with \( \mu = \mu_R = \mu_F = 2M_{\text{top}} \).\POWHEG\ samples generated with \( \mu = M_{\text{top}} \) (ttktpd) and \( 4M_{\text{top}} \) (ttktpu) are used to estimate the associated uncertainty by performing pseudo-experiments. The average of absolute differences in \( \langle \alpha P \rangle \) between the nominal sample and ttktpd and ttktpu samples is taken to be the uncertainty. The results are shown in Fig. 5.7.

5.2.6 Top Quark Mass

The difference in the top quark mass is evaluated using \PYTHIA\ samples generated with different top quark mass values. Samples generated with \( 172.5 \text{ GeV}/c^2 \) (tttop25) and \( 175.0 \text{ GeV}/c^2 \) (tttop75) are used to generate the pseudo-data samples and the difference in \( \langle \alpha P \rangle \) between pseudo-experiments is taken as the uncertainty. The results are shown in Fig. 5.8.

5.2.7 MC Generator Uncertainty

The uncertainty arising from the choice of the MC generator is accounted for by taking the difference in \( \langle \alpha P \rangle \) between tttop25 sample (\PYTHIA\ with
Figure 5.7: Shift of $\langle \alpha P \rangle$ from nominal pseudo-experiment for the renormalization and factorialization scale for (a) CPC-Helicity, (b) CPV-Helicity, (c) CPC-Transverse, and (d) CPV-Transverse. The $\mu$-scale is varied from $M_{top}$ to $4M_{top}$. The red line is obtained from fitting the shift of $\langle \alpha P \rangle$ as function of $\alpha P_{true}$. The arrows indicate the measured $\alpha P$ of data. The uncertainties are correlated.
Figure 5.8: Shift of $\langle \alpha P \rangle$ for the top quark mass of 172.5 GeV/$c^2$ and 175 GeV/$c^2$ for (a) CPC-Helicity, (b) CPV-Helicity, (c) CPC-Transverse, and (d) CPV-Transverse. The arrows indicate the measured $\alpha P$ of data. The uncertainties are correlated.

$M_{\text{top}} = 172.5$ GeV/$c^2$ and dtkta2 sample (ALPGEN $M_{\text{top}} = 172.5$ GeV/$c^2$) as the systematic uncertainty. The results are shown in Fig. 5.9.

5.2.8 Color Reconnection

A possible color reconnection effect is modeled in PYTHIA based MC. Pseudo-experiments are performed with the Apro tuned ctktsd sample and ACRpro
Figure 5.9: Shift of $\langle \alpha P \rangle$ for the Monte Carlo generators (PYTHIA and ALPGEN) for (a) CPC-Helicity, (b) CPV-Helicity, (c) CPC-Transverse, and (d) CPV-Transverse. The difference between samples generated with PYTHIA and ALPGEN is taken as the uncertainty. The red line is obtained from fitting the shift of $\langle \alpha P \rangle$ as function of $\alpha P_{\text{true}}$. The arrows indicate the measured $\alpha P$ of data. The uncertainties are correlated.
tuned ctktse sample. Pythia tune A is very similar to the tune for CDF nominal, Pythia tune ACR includes color reconnection effect into the tune A. The difference in $\langle \alpha P \rangle$ between two samples is taken to be the uncertainty. The results are shown in Fig. 5.10.

Figure 5.10: Shift of $\langle \alpha P \rangle$ for the color reconnection for (a) CPC-Helicity, (b) CPV-Helicity, (c) CPC-Transverse, and (d) CPV-Transverse. The red line is obtained from fitting the shift of $\langle \alpha P \rangle$ as function of $\alpha P_{true}$. The arrows indicate the measured $\alpha P$ of data. The uncertainties are correlated.
5.2.9 Parton Shower Uncertainty

The parton showering systematic uncertainty is the difference between \( \alpha P \) obtained with ALPGEN MC showered by PYTHIA (dtopa2 sample) and showered by HERWIG (dtopa3 sample). The difference in \( \langle \alpha P \rangle \) is taken as the systematic uncertainty. The results are shown in Fig. 5.11.

Figure 5.11: Shift of \( \langle \alpha P \rangle \) for the parton shower for (a) CPC-Helicity, (b) CPV-Helicity, (c) CPC-Transverse, and (d) CPV-Transverse. An ALPGEN sample showered by PYTHIA and HERWIG are compared. The red line is obtained from fitting the shift of \( \langle \alpha P \rangle \) as function of \( \alpha P_{\text{true}} \). The arrows indicate the measured \( \alpha P \) of data. The uncertainties are correlated.
5.2.10 Background Shape Uncertainty

The uncertainty on the template shape of the total background is calculated by considering the uncertainties in the relative background fractions and statistical uncertainty on the total background template.

Background Fraction Uncertainty

Since the shape of the backgrounds are different, the uncertainties in the relative fraction of each background contribution introduce the uncertainty in the shape of the total background distribution. The expected yield of each background component given in Table 3.3 is shifted by $\pm 1\sigma$ one at a time and the total background is normalized to 160.31 events, and then pseudo-experiments are performed. The absolute value of shifts in $\langle \alpha P \rangle$ from the nominal is taken as the uncertainty. The results are shown in Table 5.4.

Background Template Statistical Uncertainty

Because the limited numbers of events are used to construct the background templates, the statistical fluctuations in the background template introduce the uncertainty in the background shape. This effect is accounted for in Eq. 4.8 in the form of the bin-to-bin pull. To extract the uncertainty value attributed to this effect, the fit to data is performed with with the background template bin-to-bin pulls are fixed to zero, i.e. $\xi_i = 0$ in Eq. 4.8 for all bins. Then the obtained uncertainty of $\alpha P$ from the resulting likelihood distribution is
Table 5.4: The background fraction uncertainty. The expected number of events of each background component in Table 3.3 is shifted by $\pm 1\sigma$ one at a time. The uncertainties are calculated at their respective measured $\alpha_P$ values.

Subtracted in quadrature from the uncertainty of $\alpha_P$ from the fit with the default likelihood.

Since the change in the background fraction usually affects the shape of the total background template, the background fraction uncertainty and template shape uncertainty are added in quadrature and listed as the background shape uncertainty in Table 5.5.
<table>
<thead>
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<th>Helicity CPV</th>
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<th>Transverse CPV</th>
</tr>
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<td>±0.008</td>
<td>±0.006</td>
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<td>+0.038</td>
<td>+0.028</td>
</tr>
<tr>
<td></td>
<td>−0.024</td>
<td></td>
<td>−0.039</td>
<td>−0.027</td>
</tr>
<tr>
<td>Background Shape Sum</td>
<td>+0.029</td>
<td>±0.028</td>
<td>+0.039</td>
<td>±0.028</td>
</tr>
<tr>
<td></td>
<td>−0.028</td>
<td></td>
<td>−0.040</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.5: Systematic uncertainties in $\alpha P$ for CPC and CPV cases in helicity and transverse bases. The uncertainties are evaluated at the resulting $\alpha P$ value shown in the parentheses. The background shape uncertainty is obtained by quadratically subtracting the statistical only uncertainty from the uncertainty obtained from the likelihood maximization.

### 5.2.11 Lepton Identification Scale Uncertainty

The lepton identification scale factor is a lepton acceptance (including identification efficiency) ratio of data to MC. The lepton identification scale factor for each lepton type for the 9.1 fb$^{-1}$ of $tt$ dilepton data sample is given in Ref. [40]. Eight of the lepton types (CEM, PHX, CMUP, CMX, NICEM, NICMUP, CMU, and CMP) are tested for the lepton identification scale uncertainty. For each event of signal and background is examined for the type of lepton. If the event has one lepton that is of the type being tested for the uncertainty, the event is weighted by $1 \pm \frac{\delta_{SF}}{SF}$, whereas both leptons are of the
type being tested the event is weighted by $(1 \pm \frac{\delta SF}{SF})^2$, where $SF$ and $\delta SF$ are the scale factor and its uncertainty for the lepton type.

<table>
<thead>
<tr>
<th>Lepton ID</th>
<th>Helicity</th>
<th>Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM</td>
<td>$\pm 0.00070$</td>
<td>$\pm 0.00155$</td>
</tr>
<tr>
<td>PHX</td>
<td>$\pm 0.00075$</td>
<td>$\pm 0.00151$</td>
</tr>
<tr>
<td>CMUP</td>
<td>$\pm 0.00078$</td>
<td>$\pm 0.00154$</td>
</tr>
<tr>
<td>CMX</td>
<td>$\pm 0.00075$</td>
<td>$\pm 0.00152$</td>
</tr>
<tr>
<td>NICEM</td>
<td>$\pm 0.00070$</td>
<td>$\pm 0.00154$</td>
</tr>
<tr>
<td>NICMUP</td>
<td>$\pm 0.00069$</td>
<td>$\pm 0.00153$</td>
</tr>
<tr>
<td>CMU</td>
<td>$\pm 0.00072$</td>
<td>$\pm 0.00148$</td>
</tr>
<tr>
<td>CMP</td>
<td>$\pm 0.00072$</td>
<td>$\pm 0.00154$</td>
</tr>
<tr>
<td>Total</td>
<td>$\pm 0.00206$</td>
<td>$\pm 0.00432$</td>
</tr>
</tbody>
</table>

Table 5.6: Table of lepton identification scale uncertainty

The results are 0.0007, 0.0015, 0.0014, and 0.0013 for CPC-Helicity, CPV-Helicity, CPC-Transverse, and CPV-Transverse, respectively, regardless of the lepton type in Table 5.6, when using the same random number seed sequence for the pseudo-data generation. Individually these are much smaller than other systematic uncertainties and the fact that the results are independent of the lepton type suggest that these are not true systematic uncertainties but statistical fluctuations associated with pseudo-experiments. The uncertainties of $\langle \alpha P \rangle$ for a set of 176 pseudo-experiments (which is the number of pseudo-
experiments performed for each lepton type) are on the same order of magnitude as the results for the lepton identification scale uncertainty. Therefore, it is prudent to disregard this uncertainty source from the source of systematic uncertainties.

5.3 Total Uncertainty

The statistical and systematic uncertainties are summarized in Table 5.7. Except for the CPC-Helicity case where the statistical and systematic uncertainties are comparable in size, the statistical uncertainty is dominant for the rest of the cases. The total systematic uncertainty is obtained by adding the systematic uncertainties in quadrature. The results are summarized in Table 5.7.
CDF Run II Prelim (9.1 fb⁻¹)  \( \bar{t}t \rightarrow l^+l^- + 2jets + \not{E}_T \)

<table>
<thead>
<tr>
<th>Sources</th>
<th>Helicity</th>
<th>Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CPC</td>
<td>CPV</td>
</tr>
<tr>
<td></td>
<td>(−0.130)</td>
<td>(−0.046)</td>
</tr>
<tr>
<td>PDF</td>
<td>±0.015</td>
<td>+0.002</td>
</tr>
<tr>
<td></td>
<td>−0.016</td>
<td>−0.004</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>±0.018</td>
<td>±0.015</td>
</tr>
<tr>
<td>JES</td>
<td>±0.045</td>
<td>±0.003</td>
</tr>
<tr>
<td>( \mu ) Scale</td>
<td>±0.013</td>
<td>±0.007</td>
</tr>
<tr>
<td>Top Quark Mass</td>
<td>±0.050</td>
<td>±0.006</td>
</tr>
<tr>
<td>MC Generator</td>
<td>±0.076</td>
<td>±0.014</td>
</tr>
<tr>
<td>Color Reconnection</td>
<td>±0.009</td>
<td>±0.013</td>
</tr>
<tr>
<td>Parton Showering</td>
<td>±0.014</td>
<td>±0.012</td>
</tr>
<tr>
<td>Background Shape</td>
<td>+0.029</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>−0.028</td>
<td></td>
</tr>
<tr>
<td>Total Syst.</td>
<td>±0.111</td>
<td>±0.040</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.7: Systematic uncertainties in \( \alpha P \) for CPC and CPV cases in helicity and transverse bases. The uncertainties are evaluated at the resulting \( \alpha P \) value shown in the parentheses.
Chapter 6

Results

The polarization of top quark is measured along the helicity and transverse bases with CP conservation and maximally CP violation assumptions in $t\bar{t}$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, assuming the SM strength spin correlations in $t\bar{t}$. The full data of 9.1 fb$^{-1}$ collected at CDF detector are analyzed using the dilepton channel events. The number of data events is 589 in total and the number of expected signal and backgrounds events are shown in Table 6.1. The distribution of data is good agreements with the expected distribution of signal and backgrounds within statistical fluctuation, as seen in Figure 6.1 and 6.2.

The top quark polarization is measured using binned likelihood by Eq. 4.8. And the systematic uncertainties obtained by performing pseudo experiments. Pseudo data is randomly drawn from the combined distribution with the num-
<table>
<thead>
<tr>
<th>Source</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total background</td>
<td>$160.31 \pm 21.15$</td>
</tr>
<tr>
<td>$t \bar{t}$ ($\sigma = 7.4$ pb)</td>
<td>$408.16 \pm 19.41$</td>
</tr>
<tr>
<td>Total SM expectation</td>
<td>$568.47 \pm 40.33$</td>
</tr>
<tr>
<td>Observed ($\mathcal{L} = 9.1$ fb$^{-1}$)</td>
<td>$569$</td>
</tr>
</tbody>
</table>

Table 6.1: The expected and observed numbers of backgrounds and signal events after dilepton selection cut.

The number of events randomly fluctuated following a Poisson probability with the nominal expected number of events as the mean of the probability distribution. The total systematic uncertainty is obtained by adding the systematic uncertainties in quadrature. The statistical and systematic uncertainties are summarized in Table 6.2. Except for the CPC-Helicity case where the statistical and systematic uncertainties are comparable in size, the statistical uncertainty is dominant for the rest of the cases.

The measured polarizations for the two spin quantization axes and two assumptions are

\[
\alpha_{P_{hel}}^{CP} = -0.130 \pm 0.114(stat.) \pm 0.111(syst.) \tag{6.1}
\]

\[
\alpha_{P_{hel}}^{CPV} = -0.046 \pm 0.123(stat.) \pm 0.040(syst.) \tag{6.2}
\]

\[
\alpha_{P_{trans}}^{CP} = -0.077 \pm 0.177(stat.) \pm 0.098(syst.) \tag{6.3}
\]

\[
\alpha_{P_{trans}}^{CPV} = -0.111 \pm 0.146(stat.) \pm 0.055(syst.) \tag{6.4}
\]
Figure 6.1: (a) \( \cos \theta_+ \) and (b) \( \cos \theta_- \) distributions of CPC helicity and (c) \( \cos \theta_+ \) and (d) \( \cos \theta_- \) of CPV helicity. Data is compared with the signal+background templates of \( \alpha_P = -0.6 \) (−0.3) (red dashed), \( \alpha_P = 0 \) (black dotted), and \( \alpha_P = 0.6 \) (0.3) (blue dashed) for CPC (CPV).

These measured polarizations are consistent with the SM predictions. Figure 6.3 is a summary of measurement of top quark polarization in the dilepton channel at Tevatron.
Figure 6.2: (a) $\cos \theta_+$ and (b) $\cos \theta_-$ distributions of CPC transverse and (c) $\cos \theta_+$ and (d) $\cos \theta_-$ distributions of CPV transverse. Data is compared with signal+background templates of $\alpha P = -0.4 (-0.5)$ (red dashed), $\alpha P = 0$ (black dotted), and $\alpha P = 0.4 (0.5)$ (blue dashed) for CPC (CPV).
CDF Run II Prelim (9.1 fb$^{-1}$) \[ t \bar{t} \rightarrow l^+l^- + 2jets + \not{E}_T \]

<table>
<thead>
<tr>
<th>Sources</th>
<th>CPC (−0.130)</th>
<th>CPV (−0.046)</th>
<th>CPC (−0.077)</th>
<th>CPV (−0.111)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDF</td>
<td>+0.015</td>
<td>+0.002</td>
<td>+0.006</td>
<td>+0.002</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>±0.018</td>
<td>±0.015</td>
<td>±0.030</td>
<td>±0.012</td>
</tr>
<tr>
<td>JES</td>
<td>±0.045</td>
<td>±0.003</td>
<td>±0.005</td>
<td>±0.005</td>
</tr>
<tr>
<td>$\mu$ Scale</td>
<td>±0.013</td>
<td>±0.007</td>
<td>±0.020</td>
<td>±0.031</td>
</tr>
<tr>
<td>Top Quark Mass</td>
<td>±0.050</td>
<td>±0.006</td>
<td>±0.047</td>
<td>±0.014</td>
</tr>
<tr>
<td>MC Generator</td>
<td>±0.076</td>
<td>±0.014</td>
<td>±0.049</td>
<td>±0.016</td>
</tr>
<tr>
<td>Color Reconnection</td>
<td>±0.009</td>
<td>±0.013</td>
<td>±0.011</td>
<td>±0.022</td>
</tr>
<tr>
<td>Parton Showering</td>
<td>±0.014</td>
<td>±0.012</td>
<td>±0.045</td>
<td>±0.012</td>
</tr>
<tr>
<td>Background Shape</td>
<td>+0.029</td>
<td>±0.028</td>
<td>+0.039</td>
<td>±0.028</td>
</tr>
<tr>
<td>Total Syst.</td>
<td>±0.111</td>
<td>±0.040</td>
<td>±0.098</td>
<td>±0.055</td>
</tr>
<tr>
<td>Stat.</td>
<td>+0.114</td>
<td>±0.123</td>
<td>±0.177</td>
<td>±0.146</td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td>+0.159</td>
<td>±0.129</td>
<td>±0.203</td>
<td>±0.156</td>
</tr>
</tbody>
</table>

Table 6.2: Total uncertainties in $\alpha_P$ for CPC and CPV cases in helicity and transverse bases.
Figure 6.3: Summary of measurements of top quark polarization in the dilepton channel at Tevatron.
Chapter 7

Summary and Discussion

In this thesis, we measure the top quark polarization in the $t\bar{t}$ pair production in $p\bar{p}$ collisions at the Fermilab Tevatron collider at $\sqrt{s}=1.96$ TeV. We use the full Run II data sample corresponding to 9.1 fb$^{-1}$ of integrated luminosity collected with the CDF detector. We select the final state events containing two high $P_T$ leptons (electron or muon), two jets and large $E_T$.

We measure the top quark polarization through the two dimensional distribution of lepton angles along the spin quantization axis. In order to reconstruct the angular distribution of top quark decay products, we perform full kinematic reconstruction using predicted distributions of $P^\mu_z$, $P^\mu_T$ and $M_{t\bar{t}}$. We make signal templates using NLO POWHEG Monte Carlo simulation and background templates from admixture of Monte Carlo simulations and data-based background modellings. Then, we perform binned likelihood fit of two dimensional
angular distribution of data to signal and background templates and obtain a measurement of the top quark polarization.

We consider two different axes for the top quark polarization measurement: the helicity axis, and the transverse axis. Two measurements of $\alpha P$ in each basis, the product of the leptonic spin analyzing power and the top quark polarization, are performed assuming that the polarization is introduced by either a CP conserving (CPC) or a CP violating (CPV) production process. In conclusion, the measured polarizations are consistent with the Standard Model (SM) predictions.

The polarization is measured for the first time at CDF experiment. The Tevatron Collider and CDF detector were shut down in September 2011. There is no more data from $p\bar{p}$ collisions to continue with this measurement. Therefore this thesis is a beneficial measurement with potential at the LHC. The uncertainties of this measurements are a dominant statistical uncertainty. If it will be continued this analysis at the LHC and advanced the $t\bar{t}$ reconstruction code, we expect it can be improved the results of top quark polarization.
### Table 7.1: Table of other experiments’ results for the top quark polarization along helicity axis. The uncertainties are obtained by adding the statistical and systematic uncertainties in quadrature.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Data</th>
<th>Final State</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS [60]</td>
<td>4.7 fb$^{-1}$ @ 7 TeV</td>
<td>$l$+jets and dilepton</td>
<td>$-0.034 \pm 0.040$ (CPC)</td>
</tr>
<tr>
<td>CMS [61]</td>
<td>4.7 fb$^{-1}$ @ 7 TeV</td>
<td>dilepton</td>
<td>$+0.005 \pm 0.021$</td>
</tr>
<tr>
<td>CMS [62]</td>
<td>19.5 fb$^{-1}$ @ 8 TeV</td>
<td>dilepton</td>
<td>$-0.022 \pm 0.058$ (CPC)</td>
</tr>
<tr>
<td>DØ [63]</td>
<td>9.7 fb$^{-1}$ @ 1.96 TeV</td>
<td>$l$+jets</td>
<td>$-0.102 \pm 0.061$</td>
</tr>
</tbody>
</table>
Bibliography


[28] Figure taken from http://www.fnal.gov/pub/tevatron/tevatron-accelerator.html.


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[40] Chang-Seong Moon (Seoul National University), “Measurement of Top Dilepton Cross Section with CDF Full data using the DIL Selection,” FERMILAB-THESIS-2011-03.


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