Measurement of $t\bar{t}$ Forward-backward Asymmetry in Large Hadron Collider

by

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Abstract

This thesis presents a measurement of Forward-Backward Asymmetry(A_{FB}) in $t\bar{t}$ production. The data sample corresponds to $19.7\,\mathrm{fb}^{-1}$ of integrated luminosity in proton-proton collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ collected by the CMS experiment at the LHC. Events selected contain a single isolated muon or electron, with four or five jets of which two are b-tagged. A template technique is used to extract the asymmetry from the top quark kinematic distributions. This technique is based upon an extension of the tree-level cross section for $q\bar{q}$ initial states that sensitively isolates $q\bar{q}$ from gg/qg initial states. The measured A_{FB} and relative aboundance of $q\bar{q}$ initiated $t\bar{t}$ are measured and compared to both theoretical calculation and results from D0 and CDF experiments of Tevatron.

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Introduction

Particle physics studies the elementary particles, the fundamental building blocks of the universe, and their interactions. Since the discovery of electron in the end of nineteenth century, with the advancement of experimental apparatus, more elementary particles has been discovered ever since. Theories has been developed along the way, from quantum mechanics to quantum field theory, and now all known elementary particles and forces have been described by a beautiful and unified model called Standard Model (SM) of particle physics. First proposed in 1960s, SM has been proven very successful with the ongoing experimental measurement, highlighted by the discovery of Higgs boson in Large Hadron Collider (LHC) in 2011.

Before the discovery of Higgs boson, the discovery and the following study of another fundamental particle, top quark, is of critical significance. First discovered in 1995 in Tevatron collider at Fermilab, it is the heaviest elementary particle known to date, heavier than Higgs boson. Due to its large mass, top quark is often suspected to be different from all other quarks, and play a special role in Electro-Weak symmetry breaking. In addition, the large mass of top quark indicates a large Yukawa coupling to

Higgs boson, so the top quarks also play an important role in Higgs boson production. For these reasons, and many others, it is of great interest to study many properties of top quark, and it is indeed the focus of this thesis to study one of the property of top quark pair production process.

Since 2011, LHC has been running successfully, delivering huge amount of particle collision data at the highest collision energy ever registered in human history, first at 7 and 8 TeV in 2011 and 2012, in the so called LHC Run-1, then at 13 TeV from 2015 till now at LHC Run-2. A proton proton collider, LHC is a "top factory", producing much more $\mathrm{t\bar{t}}$ events than Tevatron. Combining with the advanced detector like Compact Muon Solenoid (CMS), properties of top quarks such as mass, cross section of $\mathrm{t\bar{t}}$ and single top, have been measured with highest accuracy to date.

This thesis present a measurement of one of the properties of top quark, called Forward-backward Asymmetry (A_{FB}) of $\mathrm{t\bar{t}}$ production. Pair production of top quark and anti-quark is the main source of top quarks in hadron colliders. There are two major production mechanism of $\mathrm{t\bar{t}}$ pairs, the first is via gluon-gluon (gg process) fusion, the second is via initial quark and anti-quark annihilation ($\mathrm{q\bar{q}}$ process). If a reference direction is chosen as the direction of initial quark, then the $q\bar{q} \to t\bar{t}$ process is predicted not forward-backward symmetric in $\mathrm{t\bar{t}}$ center of mass frame. Theoretical calculation using SM predict more top quark is produced in the forward hemisphere than the backward hemisphere. Equivalently, this effect can be observed as the excess of top quark over top anti-quark in the forward hemisphere, therefore it is also called

Charge Asymmetry in many literatures as well.

Forward-backward asymmetry of $\mathrm{t\bar{t}}$ production draw the attention initially as both CDF and D0 experiments[5,8] reported observing a significant deviation from the SM prediction[10,25,26] in 2011. This motivated a lot research in model building that explain the anomaly with beyond standard model (BSM) physics. As the time of writing the thesis, with the improvement of theoretical calculation and updated measurements using full data set recorded in Tevatron[6,7,9] , this anomaly has been reconciled. Regardless, as A_{FB} only originated from higher order perturbative calculation using SM, it provides a precise test of SM. In addition, it is sensitive to the interference of SM process with a heavy BSM resonance that is hard to detect directly. For these reasons, it is still of great scientific interest to measure this effect in LHC.

Measuring the top quark forward-backward asymmetry at the LHC is considerably more challenging than at the Tevatron. The $\mathrm{t\bar{t}}$ cross section at the Tevatron is dominated by the $\mathrm{q\bar{q}}$ process and the incident quark and anti-quark directions are reasonably well defined by the proton and antiproton beams. At the LHC, the production process is dominantly gg and the the quark content of the initial state is symmetric. Since there can be no asymmetry from the gg initial state, these two effects significantly complicate the extraction of the asymmetry in $q\bar{q} \to t\bar{t}$.

Measurements[2–4,23] done to date at LHC have focused on the determination of the so called charge asymmetry A_C that is based upon the number of positively and negatively charged leptons observed in top pair events at large lepton rapidity. This quantity is diluted by the symmetric gg initial states and uses only a fraction of the available information.

All of the measurements done to date have been "empirical" in the sense that the measured quantity does not depend upon a model of the $\mathrm{t\bar{t}}$ production mechanism although the interpretation of the measurements is model dependent. This thesis introduced a different approach. A simplified model for the production mechanism is adopted. This allows the use of a likelihood analysis to isolate the $\mathrm{q\bar{q}}$ subprocess from the gg and qg subprocesses and from other backgrounds. The adopted model is a leading order description of several possible BSM processes and is a reasonable approximation of the expected NLO QCD effects.

Using the template fit method proposed in this thesis, a measurement of inclusive A_{FB} in $\mathrm{t\bar{t}}$ production at LHC is performed and described in the thesis. The full 8 TeV data recorded by CMS is analyzed, and only the events in semileptonic decay of $\mathrm{t\bar{t}}$ are used for the measurement.

This thesis is organized as follows:

Chapter **??** and 2 give an overview of the theoretical and phenomenological foundation of SM, cross sections and top quark physics.

Chapter 3 introduces the experimental apparatus , including the LHC and the sub detectors of CMS.

Chapter 4 described the signal and background process modeling and the data sample analyzed in this thesis. An overview of Monte-Carlo (MC) simulation procedure is given first, then the specific processes and the technical set up for the MC is listed.

Chapter 5 first described the physical objects reconstruction algorithms used in CMS and this thesis. Then, the signal event selection and the result of the selection is discussed.

Finally, Chapter 6 contains the details of the A_{FB} measurements, which is the focus of this thesis and the original work of the author of this thesis as part of the team.

Acknowledgments

I'd like to thank..

Dedication

This thesis is dedicated to Ethan Feng

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Chapter 1

Theoretical Background

In this chapter, I will give a brief overview of the Standard Model (SM) of particle physics and the technical methods used to calculate experimental observables using Quantum Field Theory (QFT). First, an overview of the particle content and the interactions of the Standard Model is introduced. Then the theoretical formalism of QFT is briefly reviewed: the experimental and physical meaning of decay rates and cross sections; the connection between scattering amplitudes and cross sections; and Lagrangian densities and gauge invariance. Finally, the formalism of perturbative calculation and the Feynman Calculus is introduced. This chapter provide the context for all the discussions in following chapters.

Due to the technical complexity of this topic, I will give only important results and recipes without providing proofs or derivations. More detailed descriptions of this topic can be found in [?,?,?]

1.1 Standard Model

The Standard Model (SM) of particle physics is a description of nature built upon quantum field theory (QFT) and the principle of gauge symmetry that explains the fundamental building blocks of matter and their interactions. It has been proven extremely successful in explaining all observed experimental data. It has also made a number of predictions including the unseen W and Z bosons which were discovered in 1983. We will briefly summarize the particle content and the interactions of the SM, as a particle physicist's view of the universe.

Using the language of QFT, both matter and interactions are fields which are continuous in space and time, and elementary particles are the quanta of the corresponding fields. Particles are point-like, structureless objects that are fully described by their masses, spins, and various charges. The strengths of their interactions depend on the values of their charges. They are not static, but dynamic in nature, meaning that they can change into other particles, or be produced in matter-antimatter pairs from vacuum, or annihilate with their anti-partners. All these processes are described in the language of interaction vertices, where momentum, charge, spins, and some other quantities are conserved.

In the SM, the fundamental building blocks of matter are fermions, which are spin 1/2 particles. They are further divided into two groups, leptons and quarks. Both leptons and quarks are divided into three generations where each generation is similar in every way except for the masses of its members. Leptons include electrons, muons, taus and three corresponding neutrinos of the same flavor. Charged leptons carry electric charge Q=-1, whereas their corresponding neutrinos are neutral particles. The six quarks are also categorized into the three generations, the up (u) and down (d) quarks, the charm (c) and strange (s) quarks, top (t) and bottom (b) quarks. All up-type quarks (u,c,t) carry charge $Q = +2/3$, all bottom type quarks (d,s,b) carry charge $Q = -1/3$.

There are four fundamental forces in nature: the electromagnetic (EM) force which binds electrons and nuclei together; the weak force which is responsible for the beta decay of neutrons to protons; the strong force which binds quarks together to form protons and neutrons; and finally the gravitational force. Among these forces, the SM provides a theoretical frame work in which three of the four forces, EM, weak and strong interactions emerge naturally from the requirement of local gauge symmetry of the Lagrangian.

[remove or fix this sentence] At the energy scale where SM is valid, gravitational force is too small compare to the other two, so it is ignored for the study of particle physics at LHC.

Fig.1.1 shows the fundamental particles, arranged according to the forces that they experience as well as their generation among the three generations of fermions. It also shows their quantum numbers and experimentally measured masses.

Electromagnetic interactions are the most common interactions in our everyday life. All electrically charged particles like leptons, quarks, and W/Z bosons can inter-

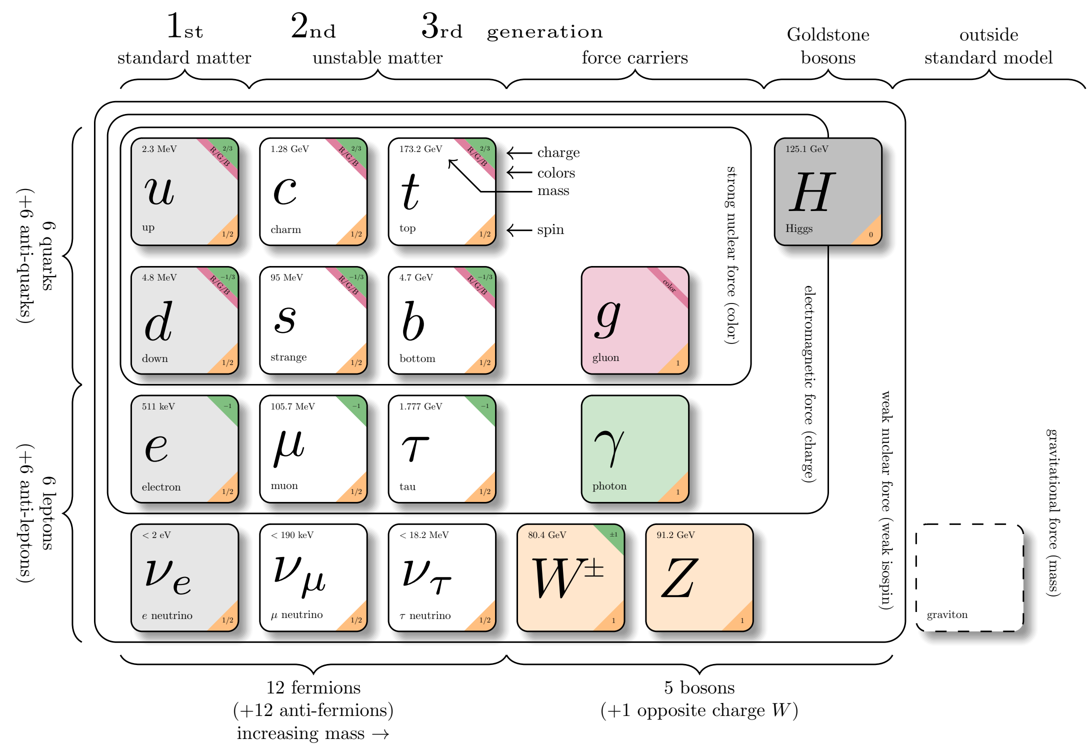


Figure 1.1: The table of all elementary particles discovered to date and their relationships in SM. cite[peskin]

act electromagnetically. It is achieved by an exchange force carrier, the photon, which is massless and electric charge neutral. Because the photon is massless, according to QFT, the range of EM force is infinite. Fig.? shows a typical interaction vertex for EM interactions. The strength of the EM interaction is characterized by the fine structure constant $\alpha_{EM} = \frac{e^2}{4\pi} = 1/137$

The weak interaction applies to all elementary particles that carry weak charges such as leptons, quarks, and W/Z bosons. It is the underlying mechanism that enables the radiative decay of sub-atomic particles, by inducing flavor changing processes. For example, an up-type quark can become a down-type quark via weak interaction, which is the process behind beta decay.

The force carriers of the weak interaction are the electric charged W^+W^- bosons of mass 80 GeV and the electric charge neutral Z boson of mass 91 GeV. At energy scales much less than the W mass, the large mass of the force carrier suppresses the strength of the weak interaction such that it is about 3 to 4 orders of magnitude smaller than the strength of the EM interaction and hence "weak". At energy scales comparable to masses of the W/Z bosons, which in quantum mechanics is equivalent to very short distances (10^{-18} m), it becomes comparable in strength to the EM interaction.

The weak interaction is the only interaction that mediates flavor changing processes (via the coupling to the charged W bosons). An up-type quark can change to a down-type quark, and an electron can change to a neutrino. The flavor changing coupling can happen both in the same generation and across generations. For example, a u quark can become a d or s quark via coupling to the $ensuremathW^+$, although it is more likely to become a d quark. In the SM, the coupling strength between different flavors of quarks is described by Cabibo-Kobayashi-Maskawa (CKM) , which is a 3 by 3 unitary matrix, each element of the matrix shows the coupling strength between up and down-type quarks, as shown below.

$$CKM = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

The current measured magnitudes of CKM elements are given below [ref], and we give only the rough central value for illustrative purposes:

$$|CKM| = \begin{bmatrix} 0.97 & 0.22 & 0.003 \\ 0.22 & 0.97 & 0.04 \\ 0.008 & 0.04 & 0.9991 \end{bmatrix}$$

In the CKM matrix, the diagonal elements represent the coupling between quarks in the same generation, while the off-diagonal terms represent the flavor changing couplings between different generations. Notice that the diagonal elements are close to one, and off-diagonal elements are negligible/small between first/second and third generation quarks. This indicate top quark couples almost exclusively to the bottom quark, which is a signature of top quark decay.

Finally, the strong force acts between any particles that are color charged, namely quarks and gluons. It is mediated by massless, spin 1 gauge bosons called gluons. The strong interaction is described by a gauge theory called Quantum Chromodynamics (QCD). In QCD, there are three fields associated with each flavor of quark and we label them with different colors: red, green, blue. The names of the colors are just conventional and have nothing to do with actual colors. The theory of QCD is invariant under local SU(3) gauge transformations on the quark fields. The gauge invariance introduces a 3×3 matrix gauge field, corresponds to eight gluons, each one is associated with a color and an anti-color.

One unique property of QCD is called asymptotic freedom, which states that at sufficiently high energy, the strong interaction is no longer strong, and quarks and gluons behave like free particles, just like leptons or photons. Another related phenomena of QCD is called quark confinement: quarks and gluons cannot exist as isolated, free particles, so called "bare" states. Both asymptotic freedom and quark confinement share the same origin, namely the running coupling constant. Because of QCD is a SU(3) gauge theory, the coupling constant of strong interaction α_s, which reflects the strength of strong interaction, increases when the exchanged momentum at interacting vertex decreases.

1.2 Decay rates and cross sections

In scattering experiments where two beams of particles collide with each other, the cross section, denoted by σ, is a quantity that characterizes the intrinsic underlying interactions of the colliding particles independently of the beam intensities.

Roughly speaking, the cross section describes the probability of observing a particular process. It has the dimensions of area, and an intuitive interpretation of cross section is that it is the area of the target particle presented to an incoming point-like beam particle in a fixed target scattering experiment.

The number of events of a process observed during a time period, can be calculated in the following way:

$$N_{exp} = \sigma_{exp} \times \int \mathcal{L}(t)dt \tag{1.1}$$

Where $\mathcal{L}(t)$ is instantaneous luminosity, which measures the intensity of colliding beams. In the LHC, where both beams include bunches of colliding particles the instantaneous luminosity can be expressed as

$$\mathcal{L} = f_{coll}\frac{n^2}{4\pi\sigma_x\sigma_y} \tag{1.2}$$

where each bunch contains n particles, the RMS horizontal and vertical sizes of the beams are σ_x and σ_y, and each bunch is collided with frequency f_{coll}. It is common to use another quantity, integrated luminosity, $\mathcal{L}_{int} = \int \mathcal{L}(t)dt$, which represents the total number of collisions done over time, and is usually measured in the units of pb^{-1} or fb^{-1} where b is an abbreviation for barn which is defined as $10^{-28}m^2$.

It is often interesting to know not just the total number of observed events of a process, which is given by $\mathcal{L}_{int}\sigma_{exp}$, but also the distribution of the events in final state variables. To do this, we also introduce another observable, called the differential cross section usually denoted by $d\sigma$. In the special case of a two particle collision with a two particle final state (the $2 \to 2$ process), a type of differential cross section of particular interest is the angular one:

$$\mathcal{L}_{int}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\mathrm{d}N}{\mathrm{d}\Omega} \tag{1.3}$$

where $d\Omega = \sin\theta d\theta d\phi$ is the solid angle of one of the outgoing final state particles. In another words, $d\sigma/d\Omega$ is the angular distribution of the final state particle.

There are two types of cross section, the inclusive (total) and exclusive ones. Inclusive means the total cross section regardless of the specific final states (some times are called channels) that are observed. Exclusive ones are the cross section of observing a specific channel. So by definition, $\sigma_{\text{tot}} = \sum_i^n \sigma_i$.

Another observable commonly used in particle physics is the decay rate of an unstable particle, denoted by Γ, which represents the probability per unit time that the particle will decay into final states of 2 or more daughter particles. Assuming that the initial number of particles is N(0), the number of remaining particles after time t is:

$$\mathrm{N}(t) = \mathrm{N}(0) \exp^{-\Gamma t} \tag{1.4}$$

For a particle that can decay to many different decay modes, the total decay rate is the sum of the rates for all decay modes:

$$\Gamma_{tot} = \sum_{i=1}^{n} \Gamma_i \tag{1.5}$$

And the branching ratio of decay mode is defined simply as $\mathrm{Br}_i = \Gamma_i/\Gamma_{tot}$. The branching ratio is another observable that can be measured experimentally.

In scattering experiments, if the initial particles can form an intermediate bound state, then the cross section near the mass of the bound state exhibits an enhancement known as a resonance. The cross section will have a peak of the form described by

Breit-Wigner formula

$$\sigma \propto \frac{1}{(E - E_0)^2 + \Gamma^2/4} \tag{1.6}$$

where the width of the resonance Γ is also the decay rate of the unstable resonance.

1.3 Lagrangian Density and Gauge Invariance

In Quantum Field Theory, both the equations of motion and the interactions between particles can be fully described by choosing a Largrangian density function (simply denoted by Lagrangian), $\mathcal{L}$.

The Lagrangian is a function of fields ($\phi(x^\mu)$) and their space time derivatives ($\partial_\mu \phi$). The fields are themselves continuous functions of space and time , $x^\mu = (t, x_1, x_2, x_3)$, which explicitly puts space and time on an equal footing as required by special relativity.

All elementary particles are the quanta of the underlying fields. Depending on the spin of the particle, different types of fields satisfy different equations of motion. Scalar fields are associated with spin-0 particles (Higgs boson in SM), denoted by ϕ. Spinor fields are associated with spin-1/2 particles (fermions, such as leptons or quarks), denoted by ψ. Vector fields are associated with spin-1 particles (all gauge bosons, such as photon or gluons), denoted by A^μ. The forms of Lagrangian in QFT is almost the same as classical field theory, the difference is that in QFT, the fields incorporate creation and annihilation operators.

The equations of motion for free fields can be derived by using the principle of least action, which states that the motion of free particles between two space-time points x_1^μ, x_2^μ ,must follow the path of least action. Action is defined as the space-time integral:

$$S = \int \mathcal{L}(\phi, \partial_\mu \phi) \mathrm{d}^4 x \tag{1.7}$$

The path of least action is equivalent to the condition $\delta S = 0$ which leads to the Euler-Lagrange equation of motion for the field,

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)} \right) - \frac{\mathcal{L}}{\partial \phi} = 0 \tag{1.8}$$

QFT is a local theory, which means it only has a localized Lagrangian density, where all interactions among fields happen at the a point in space-time. The interaction terms of matter fields and gauge boson fields in the Standard Model are introduced as a consequence of enforcing non-abelian local gauge invariance, which was first proposed by Yang and Mills in 1950s.

For example, electromagnetic interactions can be introduced by enforcing local U(1) abelian gauge invariance on the Lagrangian density. Starting from the Lagrangian of free fermion field:

$$\mathcal{L} = i\bar{\psi}\partial_\mu \gamma^\mu \psi - m\bar{\psi}\psi \tag{1.9}$$

where ψ is the spinor field, and γ^μ are 4×4 matrices. This Lagrangian is invariant only under global U(1) transformation $\psi \to \exp^{i\theta}\psi$. In order to promote the global U(1) transformation to local ones, where $\psi \to \exp^{i\theta(x)}\psi$, the derivative ∂_μ need to be replaced by a specially designed covariant derivative:

$$\mathcal{D}_\mu = \partial_\mu + iqA_\mu \tag{1.10}$$

such that under the local gauge transformation $\psi \to \exp^{-iq\lambda(x)}$, the newly introduced vector field A_μ transforms according to :

$$A_\mu \to A_\mu + \partial_\mu \lambda \tag{1.11}$$

Then the following Lagrangian will become invariant under local gauge transformations:

$$\mathcal{L} = i\bar{\psi}\mathcal{D}_\mu \gamma^\mu \psi - m\bar{\psi}\psi \tag{1.12}$$

Expanding the above Lagrangian:

$$\mathcal{L} = [i\bar{\psi}\partial_\mu \gamma^\mu \psi - m\bar{\psi}\psi] - (q\bar{\psi}\gamma^\mu \psi)A_\mu \tag{1.13}$$

We find that the coupling of matter field ψ with the gauge boson field A_μ, the quantization of which is photons, naturally emerge from the term $(q\bar{\psi}\gamma^\mu\psi)A_\mu$ where q is the electric charge.

The same procedure can be expanded to describe the unified electro-weak interaction, by enforcing SU$(2)_L \otimes$U(1) local gauge invariance. The gauge bosons introduced in the covariant derivatives are $ensuremathW^+ ensuremathW^-$,Z and photon. Eight gluons are introduced by enforcing the invariance of SU(3) color group transformations.

1.4 From Matrix Element to Cross Sections

To relate the dynamics described by Lagrangian to the experimentally observable cross section, we need to first introduce the concept of S-matrix S and its matrix element M.

The S-matrix is a unitary operator that relates the incoming particle states (initial states) and the outgoing final states of a scattering experiment. We define the initial two particle state as $|\boldsymbol{k}_A\boldsymbol{k}_B\rangle_{in}$, and outgoing many particle final state as $|\boldsymbol{p}_1\boldsymbol{p}_2\rangle_{out}$, where $\boldsymbol{k}$ and $\boldsymbol{p}$ are 4-momentum of initial and final states. The cross section is proportional to the transition probability from incoming state to outgoing state, which can be calculated according to quantum mechanics as follows:

$$P = |_{\text{out}}\langle \boldsymbol{p}_1\boldsymbol{p}_2\cdots|\boldsymbol{k}_A\boldsymbol{k}_B\rangle_{\text{in}}|^2 \tag{1.14}$$

S matrix is defined as an operator that contains all the information about time evolution and interaction between initial and final states:

$$_{\text{out}}\langle \boldsymbol{p}_1\boldsymbol{p}_2\cdots|\boldsymbol{k}_A\boldsymbol{k}_B\rangle_{\text{in}} \equiv \langle \boldsymbol{p}_1\boldsymbol{p}_2\cdots|\, S\,|\boldsymbol{k}_A\boldsymbol{k}_B\rangle \tag{1.15}$$

Since the scattering process can be separated into the overlapping (interacting) and non-overlapping parts of two particles, it can be written as $S = 1 + iT$. And matrix element $\mathcal{M}$ can be defined to contain only the information of interaction, separate from all the kinematics, such as conservation of momentum:

$$\langle \boldsymbol{p}_1 \boldsymbol{p}_2 \cdots | \, iT \, | \boldsymbol{k}_A \boldsymbol{k}_B \rangle = (2\pi)^4 \delta^(4)(\boldsymbol{k}_A + \boldsymbol{k}_B - \sum \pm p_f)\dot{i}\mathcal{M}(\pm k_A, \pm k_B \rightarrow \boldsymbol{p}_f) \quad (1.16)$$

The matrix element can be calculated using perturbation theory based on the Lagrangian by using a set of rules called the Feynman calculus. The cross section is related to matrix element. In the simplest case of $2 \rightarrow 2$ scattering, the differential cross section in center of mass frame can be calculated with the following form:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{CM} = \frac{1}{2E_A 2E_B |v_A - v_B|} \frac{|\boldsymbol{p}_1|}{(2\pi)^2 4E_{cm}} |\mathcal{M}(p_A, p_B \rightarrow p_1, p_2)|^2 \quad (1.17)$$

1.5 Feynman Calculus and Perturbation Theory

As described in previous section, the observed cross section is related to the matrix element $\mathcal{M}$. It can be calculated perturbatively in terms of the order of the coupling constant, usually denoted by α, by following the Feynman rules which are derived from the Lagrangian of the theory.

The building blocks of this formalism, the Feynman Calculus, are the Feynman Rules, which describe the propagation of free fields and their interactions at vertices. An example of QED Feynman rules are given below in Fig.1.2,1.3

It can be shown that the scattering matrix element $i\mathcal{M}$ can be calculated by summing over all connected Feynman diagrams evaluated according the Feynman

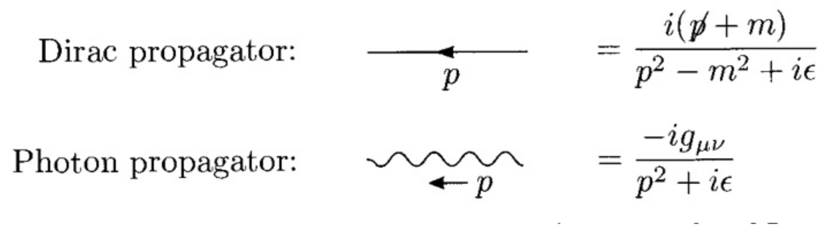


Figure 1.2: The Feynman diagram of fermion and photon propagator. cite[peskin]

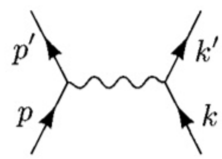
Figure 1.3: The Feynman diagram of QED vertex, represent the electromagnetic interaction by exchanging a photon. cite[peskin]

rules. In the calculation of each diagram, momentum conservation is imposed at all vertices, and if there is loop in the diagram, the undetermined momentum in the loop must be integrated out.

The matrix element can be calculated perturbatively , order by order, in terms of the power of interaction coefficient. In QED, the order is represented by the power of fine structure constant defined as $\alpha_{\mathrm{EM}} = e^2/4\pi \approx 1/137$. The rationale of this approach follows from the small size of the coupling constant, which implies that the contribution of each higher order in the calculation is significantly smaller than that of the previous order.

We call the leading order (LO) diagrams the ones containing the lowest power of α_{EM} of all connected diagrams. LO diagrams are also often called tree-level diagrams. One example of an LO diagram and its corresponding matrix element, for the scattering of two fermions is shown below in Fig.[1.4]

$$i\mathcal{M} =$$



$$= (-ie)^2 \bar{u}(p')\gamma^\mu u(p) \frac{-ig_{\mu\nu}}{(p'-p)^2} \bar{u}(k')\gamma^\nu u(k).$$

Figure 1.4: The Feynman diagram of LO scattering of two fermions. cite[peskin]

In the Feynman diagram shown in Fig.1.4, the arrows label the direction of momentum flow for the matter fields (the direction of anti-matter momentum is the reverse of the arrow). The momenta of the initial and final states are labeled as p, k and p', k'. The matrix element corresponds to this diagram can be seen as following from the individual Feynman rules mentioned above.

1.6 Higher Order Corrections and Renormalization

In higher order diagrams containing loops, the undetermined momentum in the intermediate virtual process (loop) must be integrated over all values. These integrals often become infinite as the momentum in the loop goes to infinity. One example of loop diagram of the same process of fermion scattering is shown below in Fig.1.5, which is called the vacuum polarization correction, where the virtual photon splits into a fermion/anti-fermion pair. It can be shown that this diagram is divergent as $\ln q$ where q is the momentum transfer that is carried by photon.

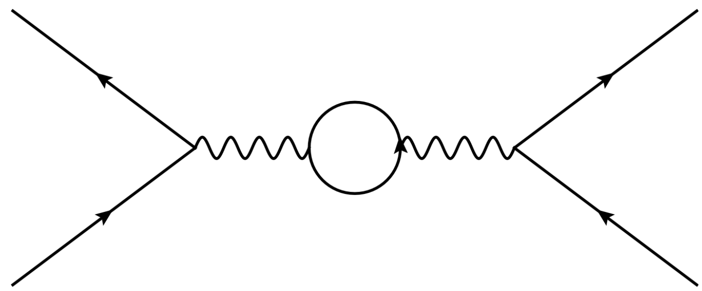


Figure 1.5: The Feynman diagram of loop correction of femion scattering.

In order to make the matrix element from this diagram finite, a special procedure called Renormalization is applied. This procedure involves a redefinition of the coupling constant to absorb the divergent terms, and the new coupling constant that actually depends on the momentum transfer q. This is called running coupling constant, and is given in Eq.1.18 for the case of vacuum polarization correction below:

$$\alpha(q^2) = \alpha(0)\left[1 + \frac{\alpha(0)}{3\pi} f(\frac{-q^2}{m^2})\right] \tag{1.18}$$

where $f(x)\ \ln x$, and $q^2 < 0$ for the momentum being exchanged. The coupling constant increases at larger momentum scales, which is equivalent to smaller distances of the interaction. In another words, the effective charge of the observed particle changes with the distance being probed.

The higher order corrections to the LO calculation together with renormalization procedure, introduce a momentum scale called renormalization scale μ_R. Calculations including higher-order contributions to the matrix element are usually functions of this scale through their dependence on renormalized quantities, such as coupling constants. In practice the renormalization scale is usually chosen as the typical momentum transfer of the process, Q, or the invariant mass of the produced final state particles.

In contrast to QED, the running coupling constant of QCD, $\alpha_s\mu_R$ decreases as exchanged momentum increases. So in sufficiently high energy regimes, perturbation calculations can provide accurate predictions of scattering processes involving the strong interaction, while at lower energy scales non-perturbative effects are quite important. Because the strong interaction becomes strong at the scales of hadron masses, no bare quark and gluons can be observed directly; they are observed experimentally as highly collimated group of hadrons, called "jets".

This completes our brief review of the Standard Model. The next chapter focuses on the specific phenomenology of top quark physics, which is the main topic of this thesis.

Chapter 2

Top physics Phenomenology at the LHC

In the Standard Model of particle physics, top quark is the up-type quark in the third generation of fermions. It has spin 1/2, electric charge $Q = 2/3$ and forms a weak isospin doublet with the bottom quark. It is also charged under the SU(3) group, being a color triplet with three colors.

As a result, top quark is affected by all three SM forces: the electromagnetic force, the weak force and the strong force. It couples to the respective gauge bosons via the following vertices described in Fig.2.5-Fig.2.6 .

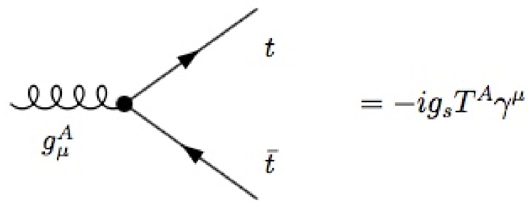


Figure 2.1: Top quark coupling to gluon via strong interaction. [cite 1709.10508]

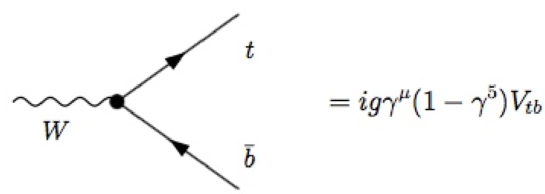


Figure 2.2: Top quark coupling to W boson and bottom quark via weak interaction.

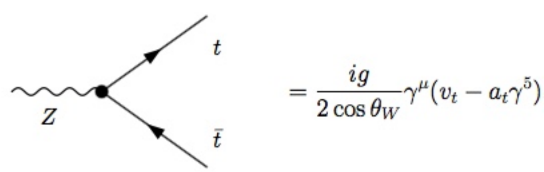


Figure 2.3: Top quark coupling to Z boson (right), via weak interaction.

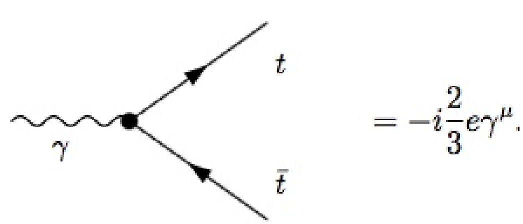


Figure 2.4: Top quark coupling to photon via electromagnetic interaction.

Top quark is special among all known six quarks due to its large mass. First discovered at the Fermilab Tevatron collider in 1995 [cite], it ihas a mass that is presently measured to be about 173 GeV, almost as heavy as tungsten atom. It is the only fundamental fermion that is heavier than W boson, which ihas a mass of about 80 GeV. Due to the large mass difference between top quark and W boson, the phase space for top decay is very large, causing the top quark to decay before being able to form any hadronic bound state. This provide an opportunity for the careful study of QCD as the top quark can be treated as a quasi-free quark during the production and decay processes.

Another reason for the importance of top quark physics is due to the large coupling of top quarks and the newly discovered Higgs boson. As the Yukawa coupling between fermions and Higgs bosons is proportional to the mass of fermion, the top quark has the largest coupling to the Higgs boson. The production of Higgs bosons at the LHC often involves $t\bar{t}H$ coupling, in both the dominant production mechanism of gluon-gluon fusion process (Fig.?) and in the associated production of Higgs and $\mathrm{t\bar{t}}$ (Fig.?). Therefore the study of top quark mass and its coupling to the Higgs are critical in testing the validity of Higgs mechanism, which is thought be be responsible for origin of mass via spontaneous symmetry breaking.

The Large Hadron Collider, which combines a much higher center of mass energy and a much higher luminosity than the Tevatron, is indeed a top factory, opening the door to more precise measurements of the properties of top quarks.

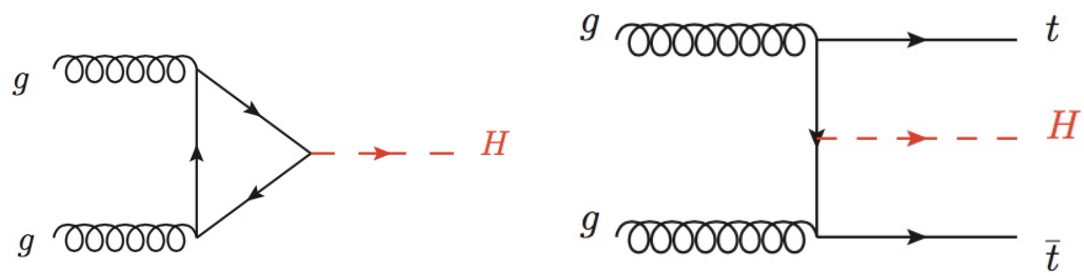


Figure 2.5: Major higgs production mechanism in LHC. The left figure is via gluon gluon fusion, while right is via $\mathrm{t\bar{t}}$ fusion. [cite 1709.10508]

Many properties of top quark have been carefully studied at the LHC, including the mass of top quark, the cross section of top anti-top pair production, and the spin correlations of top anti-top pair production. A good summary of latest results of top property measurements can be found in the literature. [cite review of LHC top measurement papers]

Of many properties of top quark, in this thesis we exclusively focus on one particular property of top pair production, namely the "Forward-Backward Asymmetry" (A_{FB}). It is the spatial asymmetry of top quark pair production with respect to the direction of incoming initial quark, as shown in Fig.[?]. At parton level it is defined as

$$A_{\mathrm{FB}} = \frac{N_{\mathrm{tbart}}(c* > 0) - N_{\mathrm{t\bar{t}}}(c* < 0)}{N_{\mathrm{tbart}}(c* > 0) + N_{\mathrm{t\bar{t}}}(c* < 0)} \tag{2.1}$$

where $c* \equiv \cos(\theta*)$ and $\theta*$ is the production angle of top quark in $t\bar{t}$ center of mass frame. This quantity is interesting because according to the SM, A_{FB} is zero at LO

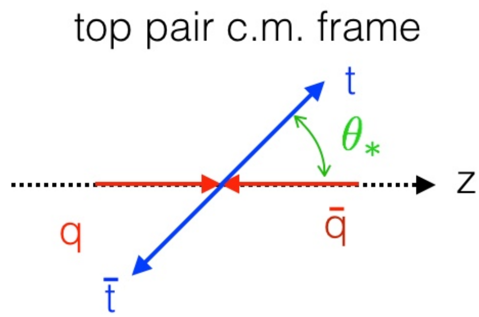


Figure 2.6: Top quark coupling to photon via electromagnetic interaction.

of in perturbative QCD calculation, and becomes non-zero from NLO contributions. A good measurement of A_{FB} provides a precision test of the SM and is sensitive to contributions from possible non Standard Model contributions.

In this chapter we will first review the production of top quark pairs in Chapter 2.1-Chapter 2.1.3. Then, we review the decay of top quarks. Finally, we review the status of forward-backward asymmetry of top quark pair production, which is the main topic this thesis.

2.1 Top Quark Pair Production

2.1.1 Leading Order

In hadron colliders, top anti-top pairs are mostly produced via strong interactions. In the leading order of perturbative QCD (order of α_s^2), there are two production mechanisms. The first one is via quark anti-quark annihilation, which we denote as $q\bar{q}$ initiated top pair production. (we use $q\bar{q}$ process for simplicity sometime in the later chapters of this thesis). The Feynman diagram of this process is shown in Fig.?. The differential cross section is,

$$\frac{d\sigma}{dc_*}(q\bar{q}; M^2) = \frac{\pi\alpha_s^2}{9M^2}\beta\left[1 + \beta^2 c_*^2 + \left(1 - \beta^2\right)\right] \tag{2.2}$$

where: M is the invariant mass of $t\bar{t}$ pair, $\beta = \sqrt{1 - 4m_t^2/M^2}$ is the top quark velocity in the $\mathrm{t\bar{t}}$ center of mass (cm) frame, θ^* is the production angle between the initial state quark direction and the top quark direction in the $t\bar{t}$ cm frame, $c_* \equiv \cos\theta^*$, and $\alpha_s \equiv g_s^2/4\pi$ is the strong interaction strength constant which is about 0.12 at the scale of Z boson mass.

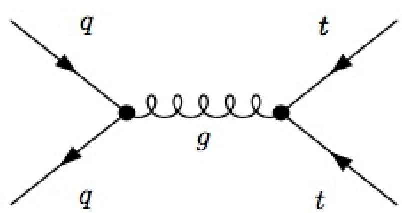


Figure 2.7: Feynman diagram for leading order parton level $q\bar{q} \to t\bar{t}$ process via strong interaction. [cite 1709.10508]

The second process of top pair production combines the s, t, u channels of the gluon-gluon initiated process (simply denoted as gg process in this thesis), as described by the Feynman diagram in Fig.? The parton level differential cross section of this process in LO reads:

$$\frac{d\sigma}{dc_*}(gg;M^2) = \frac{\pi\alpha_s^2}{48M^2}\beta\left[\frac{16}{1-\beta^2c_*^2}-9\right]\left\{\frac{1+\beta^2c_*^2}{2}+(1-\beta^2)-\frac{(1-\beta^2)^2}{1-\beta^2c_*^2}\right\} \quad (2.3)$$

The t and u channel dominated gg process has a distribution that is more peaked in the forward and backward directions, i.e. more likely in the phase space with higher $c*$, compare with $q\bar{q}$ process. This feature is crucial to motivate our template fit based measurement that is described in Chapter.?, which relies on the discrimination of the $q\bar{q}$ and gg production mechanisms.

Note that according to Eq.2.2, the LO calculation of the $q\bar{q} \rightarrow t\bar{t}$ process does not produce a non-zero A_{FB}, as the differential cross section is even in $c*$. The same is true for the LO calculation of $gg \rightarrow t\bar{t}$

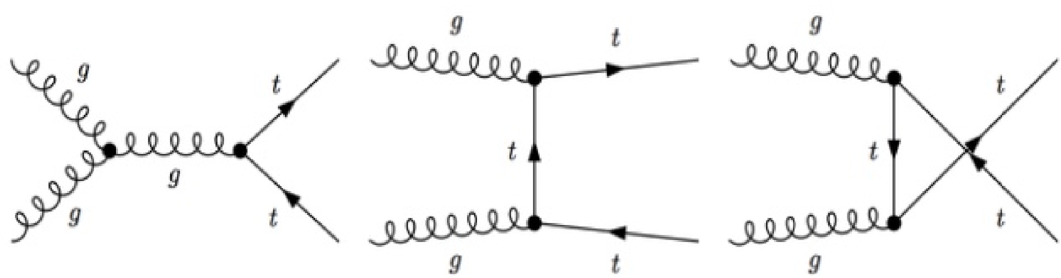


Figure 2.8: Feynman diagram for leading order parton level $gg \rightarrow t\bar{t}$ process via strong interaction. The s,t,u channels are shown in left,middle,right figures respectively.

2.1.2 Next to Leading Order Corrections

The higher order corrections to top pair production are important due to the sizable value of strong interaction coefficient $\alpha_s \sim 0.1$ at the energy scale of this process. As the energy scale of top pair production is set by the large mass of top quark (173 GeV) the perturbative QCD calculation is able to give accurate predictions.

Currently, Next-to-Leading-Order calculations are regarded as the standard for event generation and simulation of top-quark production by the LHC experiments. These are implemented in several event generators. The generators used in this thesis are Powheg-box [cite] and aMC@NLO [cite]. The impact of the NLO contributions to the total cross section compared with the LO contributions can be as large as 30% [cite]. The NLO corrections also have sizable effects on the shapes of many top quark kinematic distributions.

More importantly, NLO processes are the lowest higher-order processes that generate a non-zero forward-backward asymmetry via the SM. As a result, we will limit our discussion of higher-order QCD effects in top quark pair production to the NLO processes that contribute to A_{FB}.

At parton level, the dominant sources of non-zero A_{FB} are the NLO corrections to the process of $q\bar{q} \to t\bar{t}$. The asymmetry originates from the interference of virtual radiation of gluon (box diagram) in Fig.(c) and Born process (LO) of $q\bar{q} \to t\bar{t}$ in Fig.(d). [cite Kuhn and Rodrigo 98']. In order to avoid the infrared divergences when the momenta of the virtually radiated gluon in Fig. (c) go to zero, it has to be summed with the interference between initial state and final state real gluon emission of $q\bar{q} \to t\bar{t}$, which are described by Fig. (a) and Fig (b) . The inclusive asymmetry from this source is positive, between 6% and 8% in most of the kinematic regions that can be probed in Tevatron or LHC. [cite Kuhn 2011]

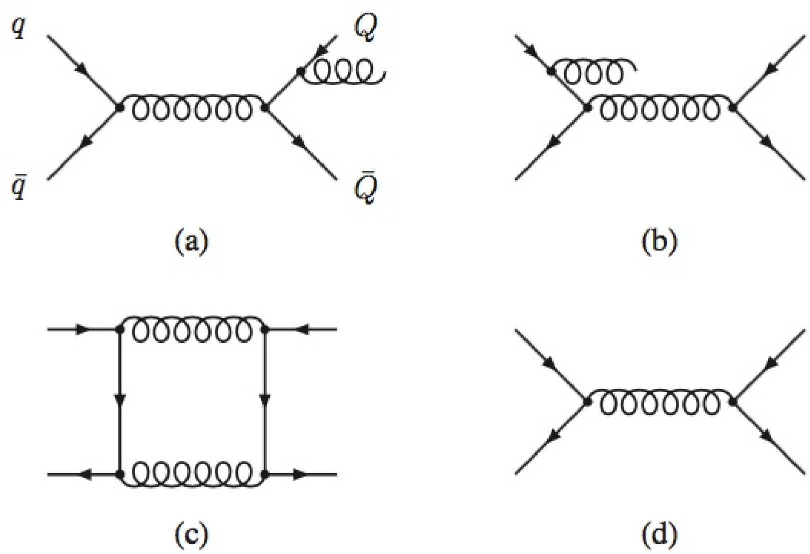


Figure 2.9: Feynman diagram of next-to-leading order $\mathrm{t\bar{t}}$ production that contributes to A_{FB}. In the figure, q indicates light quark, Q represent heavy flavor quark, in our case, top quark. [cite Kuhn]

Another non-negligible source of A_{FB} is from the interference of QCD induced $t\bar{t}$ production and electromagnetic (QED) induced $t\bar{t}$ production. The color singlet configuration of QCD box diagram, Fig.? , interferes with the s-channel $t\bar{t}$ production via photon, which is also color singlet.

Because some of the QCD contributions to A_{FB} originate from NLO terms involving real gluon radiation, this thesis actually studies the A_{FB} observed in $t\bar{t}+\mathrm{jet}$ production, where jet refers to the hadronized products of an extra quark or gluon. As a consequence of the additional jet allowed, another process that is predicted to produce non-zero A_{FB} should be mentioned, the so-called "flavor excitation" in the $g+q \to t+\bar{t}+q$ channel. It originates from the interference terms of the amplitudes for the quark-gluon scattering. Like radiative corrections for $q\bar{q} \to t\bar{t}$, the matrix element of this calculation has the order of α_s^3, and the relevant Feynman diagrams are shown in Fig.?. The parton level A_{FB} originating from $g+q \to t+\bar{t}+q$ is much smaller than that from $q\bar{q} \to t\bar{t}$ process.

In the energy scale studied in this thesis, where the partonic center of mass energy $\sqrt{\hat{s}}$ is below 1 TeV, the contributions of the order α^3 corrections to the q$\bar{\mathrm{q}}$ process, the interference of QCD-QED, and the $g+q \to t+\bar{t}+q$ process to the partonic level A_{FB} are about 7%, 1% and 0.1%, respectively. In addition, the differential asymmetry defined in Eq.? is approximately a linear function of $\cos\theta_*$ for both q$\bar{\mathrm{q}}$ and QCD-QED interference terms, while it is approximately quadratic for $g+q \to t+\bar{t}+q$ terms. For both reasons, we attempt to measure the A_{FB} originating from the $q\bar{q} \to t\bar{t}$ process from our data and correct the measured value for the $g+q \to t+\bar{t}+q$ contributions using MC simulation.

There is one subtlety when we use NLO MC simulated events to estimate the A_{FB} and compare that value with the analytic calculations of.[?] In,[?] the symmetric part of

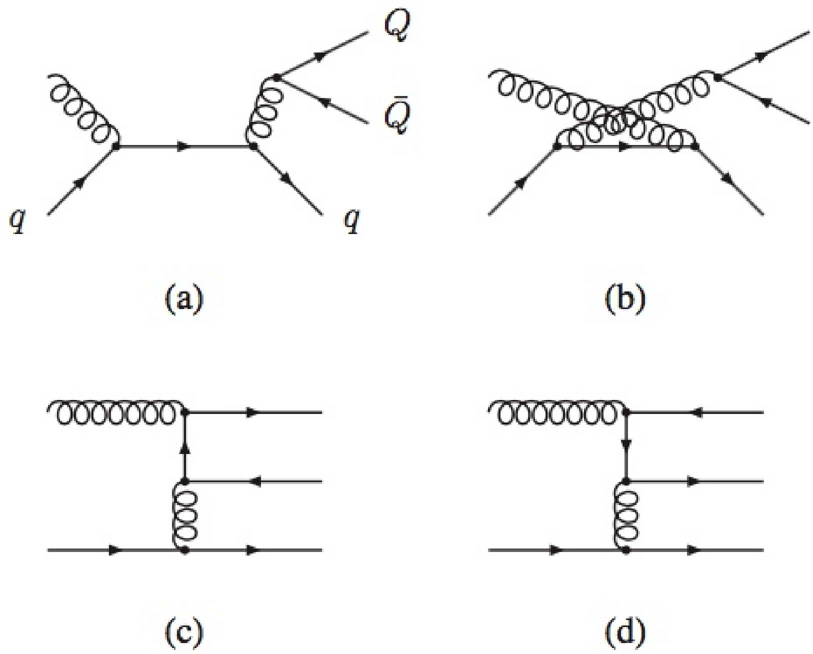


Figure 2.10: Feynman diagram of next-to-leading order $\mathrm{t\bar{t}}+q$ production via quark gluon initial states, that contributes to A_{FB}. In the figure, q indicates light quark, Q represent heavy flavor quark, in our case, top quark. [cite Kuhn]

the cross section is calculated at LO (α_s^2), while the direct counting result from the NLO MCs use the NLO cross section for the symmetric part of the $q\bar{q} \to t\bar{t}$ process. Given that the NLO corrections increase the total cross section of this process by up to 30%, this means the A_{FB} derived by direct counting from the NLO MCs is only 0.7 times the value from theoretical prediction given in.[?]

2.1.3 Top Quark Production in Hadron Colliders

In previous sections, we have described the parton level production of top anti-top pairs according to the SM. In reality, quarks are never observed as isolated free particles. Because of the strong interaction, it is the colorless bound states of quarks: mesons (quark-antiquark pairs) such as pions and bayons (three quarks) that are actually observed in both the initial and final states of any scattering experiments. Because of the coupling constant of the strong interaction is very large at the low mass scales of the hadrons, detailed calculations of particle processes are not possible using perturbation theory. However, because of the asymptotic freedom property of QCD, it can be shown that the phase space and kinematic distributions of scattering involve strong interactions can be described by a hard process in which large momentum transfer happens. An intuitive understanding is during the hadronization any process with large momentum transfer is suppressed as it corresponds to small coupling constant, so the hadronization products are are produced only at small center-of-mass energies with respect to each other and they are nearly collinear with the original quasi-free particles involved in the hard scattering process.

Another result of asymptotic freedom in QCD is the factorization theorem, which says the cross section for the scattering of hadrons can be calculated by convolving the parton distribution functions (PDF) that describe the distributions of momentum fractions carried by the partons that form the scattered hadron, with the cross section for hard scattering process. We some times call the hard scattering process the parton level process. So the total cross sections for $\mathrm{t\bar{t}}$ production in proton-proton or proton anti-proton collider can be represented in the following way:

$$\sigma_{p_1 p_2 \to \mathrm{t\bar{t}}} = \sum_{(i,j)\in(q,\bar{q},g)} \int_0^1 \int_0^1 (\sigma_{ij\to\mathrm{t\bar{t}}}) D_i^{p_1}(x_1, Q) D_j^{p_2}(x_2, Q) dx_1 dx_2 \tag{2.4}$$

where p_1, p_2 can be either proton or anti-proton depending on the type of collider. $D_i^{p_1}(x, Q)$ is the PDF, which gives the differential probability that a parton, such as an up-quark, shares the fraction x of the momentum of its parent hadron of type p_1 (proton or anti-proton). Note that the PDF also depends on the energy scale Q of the hard process. Similarly, differential cross sections in hadron collisions can also be factorized by the convolution of the PDFs and parton level differential cross sections.

The PDF are determined experimentally by fitting data from hadron scattering and deep inelastic scattering experiments. One example of a proton PDF at the energy scale of $\mathrm{t\bar{t}}$ production is shown in Fig.? below. It shows that the valence quarks in the proton (consisting of two up-quarks and one down-quark), the up- and down-quarks, tend to carry larger fractions of the proton momentum than the fractions carried by sea quarks, such as $\bar{u}$ and $\bar{d}$ quarks, and gluons.

The parton distribution functions have major consequences for the dominant production mechanisms of top quarks at the LHC and the Tevatron. The kinematic constraint of $\mathrm{t\bar{t}}$ production requires that the center-of-mass energy of the initial partons (which is also the invariant mass of produced $\mathrm{t\bar{t}}$ pairs) $\sqrt{\hat{s}} = M_{\mathrm{t\bar{t}}} = \sqrt{x_1 x_2 s}$ (s is the proton-proton or proton-antiproton center-of-mass energy), to be at least two times the mass of top quarks, which is about 345 GeV. Such a large energy requirement indicate that both partons need to carry sufficiently large fractions of the energies of the collided hadrons to produce $\mathrm{t\bar{t}}$ pairs.

In Tevatron which is a proton anti-proton collider, the dominant parton level production mechanism of $\mathrm{t\bar{t}}$ is via $\mathrm{q\bar{q}}$ initial states (about 90%). This is because both the initial quark and anti-quark could be valence quarks from proton or anti-proton in the collision, thus are more likely than initial state gluons to carry sufficient momentum for $\mathrm{t\bar{t}}$ production. In contrast, the majority of $\mathrm{t\bar{t}}$ pairs in LHC is produced via gg fusion process, as LHC is a proton-proton collider and it is unlikely for an anti-quark to carry sufficient momentum. Therefore, the $q\bar{q} \to t\bar{t}$ subprocess is only about 10% of the total $t\bar{t}$ cross section at the LHC at 8 TeV.

The consequence is that the $\mathrm{t\bar{t}}$ A_{FB} at the LHC is much smaller than that at the Tevatron due to the dilution by the forward-backward symmetric $gg \to t\bar{t}$ process. Another challenge is that at the Tevatron because of the valence antiquarks in antiproton beam, initial quark is almost always along the same direction of initial proton, so we can choose the direction of initial proton as the positive direction when we determine the production angle $\cos\theta_{*}$. In contrast, in LHC the initial beam configuration is forward-backward symmetric. This makes the inference of quark direction at parton level more difficult. The solution for this problem follows from the observation that the quark in the $q\bar{q} \to t\bar{t}$ process likely carries more momentum than anti-quark. So the direction of direction of $\mathrm{q\bar{q}}$ c.m system is usually the initial quark direction, especially in the case where the difference of momentum fraction of initial quarks, $|x_f| = |x_1 - x_2|$ is larger, i.e. the $t\bar{t}$ c.m. system has higher boost in longitudinal direction.

2.2 Top Decay

The top quark decays via weak interaction almost exclusively to a W boson and a bottom quark due to the form of CKM matrix, where $|v_{tb} \sim 1$. In addition, because of the mass of top quark 173 GeV is much larger than the mass of W boson, the top quark decay width is so large that the top quark decays happens in a shorter time than the hadronization time. Therefore, top quark decay can be calculated with perturbative QCD very accurately.

The final states of $\mathrm{t\bar{t}}$ events can be categorized based on the decay mode of the two W bosons. W bosons decay weakly to a quark anti-quark pair (u,d,c,s type),which is called hadronic decay, or to a lepton-neutrino pair (leptonic decay). Therefore, there are three different experimental decay topologies for $\mathrm{t\bar{t}}$ pairs:

- All-hadronic: Both W bosons decay hadronically, $\mathrm{t\bar{t}} \to b\bar{b}jjjj$

  The most abundant decay mode, which is about 44% of all $t\bar{t}$ events, as shown in Fig.2.11. It is not as clean as the other two channels, with large W+jets and QCD multijet backgrounds.

- Semileptonic: One of the W bosons decays leptonically and the other decays hadronically , $t\bar{t} \to b\bar{b}l\nu jj$. The Feynman diagram is shown in Fig.2.12

We only consider the case where lepton is electron or muon, and ignore the case where lepton is tau, because tau will quickly decay which is complicated to reconstruct.

This channel is optimal for studying A_{FB} for several reasons: It is relatively clean due to the requirement of a electron or muon and two bottom quarks; it is relatively abundant, about 30% of all $t\bar{t}$ events, providing sufficient statistics for the measurement; It has only one neutrino, making it relatively easy to correctly reconstruct the momentum of top and anti-top from their decay products.

- Dileptonic: Both W bosons decay leptonically, $t\bar{t} \to b\bar{b}ll\nu\nu$

  This is the cleanest channel, due to the requirement of two leptons. The problem is the relative small abundance (about 4%), and existence of two neutrinos makes reconstruction of top anti-top momentum challenging, thus not suitable for our purpose.

As mentioned in Section.2.1.2, we allow an extra hard gluon from the ISR or FSR radiation processes associated with $t\bar{t}$ production. As a result, the final state studied in this thesis is l+4/5jets+MET, where MET means missing transverse energy which corresponds to the transverse momentum of the unobserved neutrino.

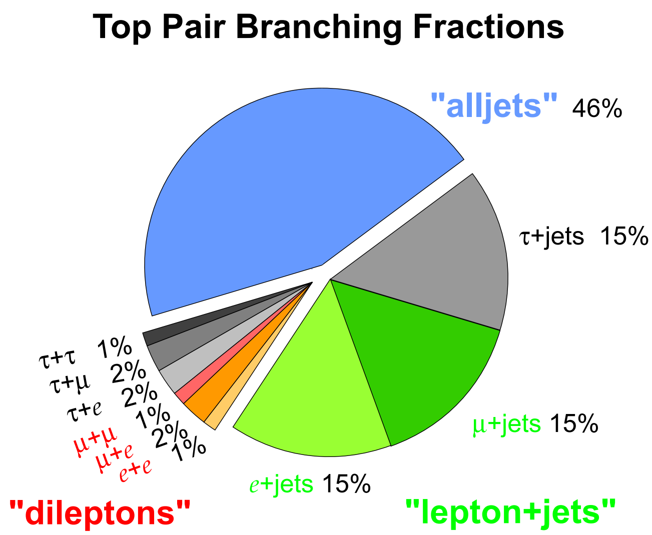


Figure 2.11: The branching fractions of all channels of $t\bar{t}$ productions.

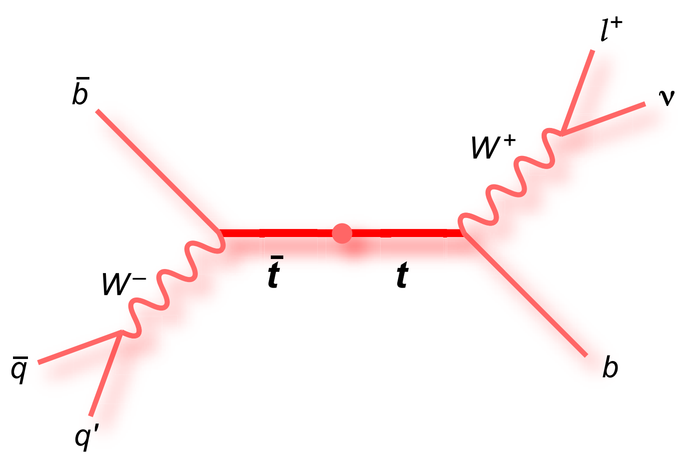


Figure 2.12: The Feynman diagram of semileptonic decay of $t\bar{t}$ pairs. There is another decay process with $W^- \to l^-\bar{\nu}$ not shown here.

2.3 Forward Backward Asymmetry

In this section I will give an overview of the status of current AFB and A_C measurement in Tevatron and LHC.

Chapter 3

Experimental Setup

3.1 The Large Hadron Collider

3.2 The Compact Muon Solenoid

3.2.1 Coordinate Conventions

3.2.2 The Magnet

3.2.3 Inner Tracker

3.2.3.1 Pixel Detector

3.2.3.2 Strip Detector

3.2.4 Electromagnetic Calorimeter

3.2.5 Hadronic Calorimeter

3.2.6 Muon System

3.2.6.1 Muon Drift Tubes

3.2.6.2 Cathode Strip Chambers

Chapter 4

Process Modeling and Software Setup

In LHC, huge amount of collision events are produced. Among them, only a very small fraction of events are those that of interest for most physics analysis. The majority of events produced in LHC is soft QCD process. As shown in Fig.4.1, in LHC at 8 TeV, the cross section of $\mathrm{t\bar{t}}$ production process, which is the signal process in this thesis, is about 10 orders of magnitudes smaller than the total production cross section of LHC.

This thesis measures the A_{FB} originated from $q\bar{q} \to t\bar{t}$ process, as well as relative ratio of $q\bar{q} \to t\bar{t}$ production among all production mechanisms of $\mathrm{t\bar{t}}$ in LHC. In order to achieve an accurate measurements with low statistical uncertainties, we want to apply selection on the collected events that strikes a balance between increasing signal

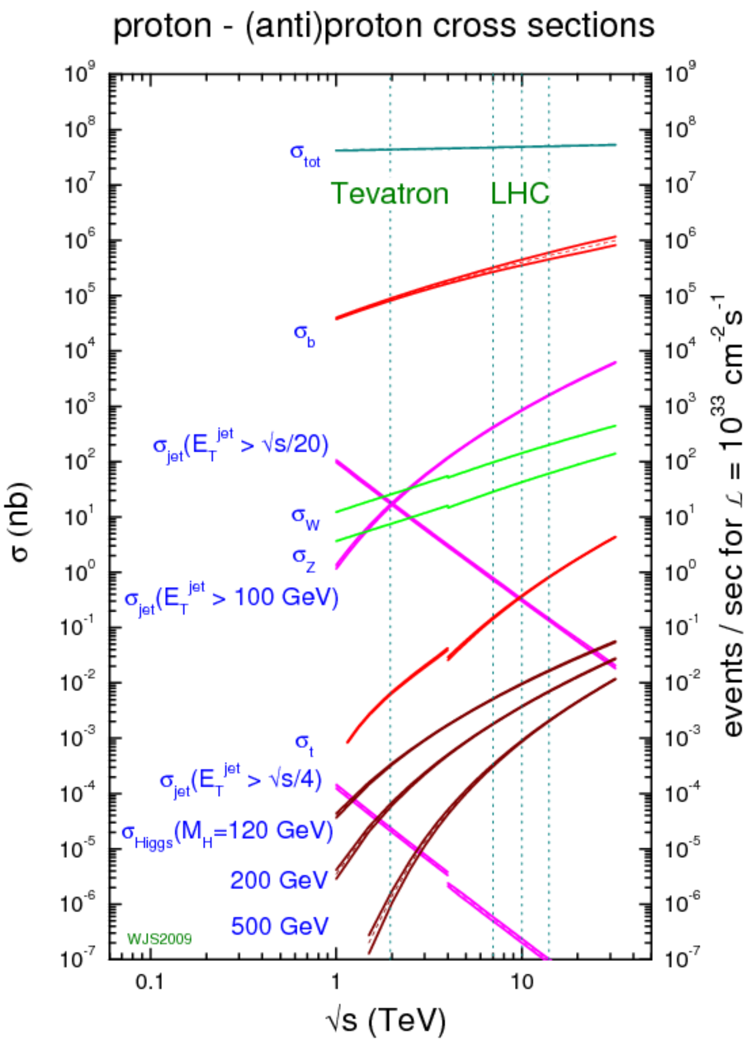


Figure 4.1: Cross sections for various physcis processes in hadron coliders, corresponding to collision energy, taken from.[30] Three different energy for LHC marked in the figure corresponds to 7,10 and 14 TeV.

background ratio and still maintain a reasonable signal efficiency so there are sufficient amount of events left post selection.

The selection criteria is designed based on the topology of our signal events, as well as the features of major background processes. Our signal is semileptonic $t\bar{t}$ events, described in Fig.4.2, with a final state of one high p_{T} electron or muon plus four or five energetic jets, two of them are originated from bottom quarks. The detailed selection critiria is given in Section.5.2.

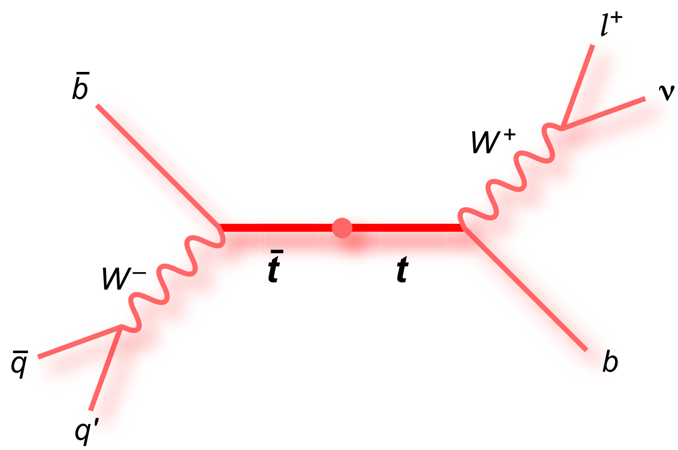


Figure 4.2: The diagram of semileptonic decay of $t\bar{t}$ pairs. There is another decay process with $W^- \to l^-\bar{\nu}$ not shown here.

Even after selection, there are still various processes that form the irreducible background of the measurement. In this chapter, the origin and modeling of the signal and irreducible background processes are discussed. In addition, the software set up for the analysis, including simulation, data sample preparation, and fitting, is provided.

4.1 Signal and background process modeling

4.1.1 Monte-Carlo Simulation

Most of the signal and background processes are modeled by MC simulation. The simulation process is usually in several steps.

The first step is to generate events based on the hard scattering process at parton level, using dedicated Monte-Carlo event generator. The generation of hard process is based on the Matrix Element calculated using QFT, as described in Section.1.4. The ME generator can generate events with a few hard radiated partons due to computational complexities. The products of this step are referred to the parton-level or generator-level particles, and the information about these particles, such as particle type, charge, momentum is referred as generator truth in later chapters of the thesis.

The additional initial state/ final state radiated gluons are produced using a different event generator in the second step, which is denoted as Parton Showering (PS) process. A special matching procedure is performed between the particles generated in ME step and particles in PS step to avoid duplicates of additional partons.

The third step is the fragmentation/hadronization step, which takes the partons generated in PS step and form stable hadrons. As hadronization is non-perturbative, a phenomenological model called Lund String Model is adopted for this purpose. The decay of stable hadrons are simulated by taking the well know fraction ratio.

The last step of the simulation chain is to simulate the propagation of all the stable particles in CMS detector, and the detector response in all sub detectors of CMS. This step is performed using the dedicated detector simulation software.

The entire simulation chain is demonstrated in Fig.4.3. All the signal and background process simulations follow the same procedures described in this section, with different choices of generators in ME or PS steps.

All MC simulated events are produced by the SUMMER12 central MC production campaign by CMS.

4.1.2 Signal process modeling

The signal process in this thesis is semileptonic $t\bar{t}$ production. Specifically, we look at the $t\bar{t}$ production processes with one of the W decays to electron or muon, and another W decays to a pair of light flavor jets. The process where one of the W decays to tau lepton is not treated as signal process, due to the complexity of tau further decay process and poor reconstruction of taus in CMS.

The signal process is modeled using the inclusive $t\bar{t}$ events generated with aMC@NLO ME generator,[12] which is an NLO event generator. The parton showering is done using Pythia PS generator.[31] Due to the matching scheme used in aMC@NLO, the generated events are weighted, with some events having negative weights to account

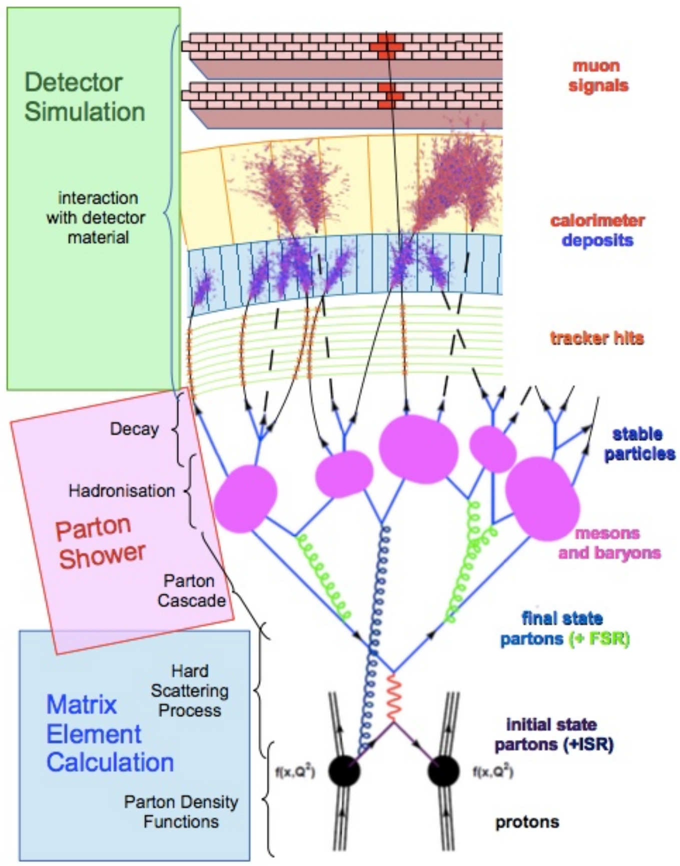


Figure 4.3: An illustration of entire Monte-Carlo Simulation chain in CMS.[21]

for the duplication of Pythia generated events.[?]

An alternative version of signal sample is also considered, generated using POWHEG ME generator and use Pythia for parton showering. POWHEG is another NLO generator[11] that has the advantage of easy interface with Pythia for parton showering, and all positive weights. We use Powheg signal sample for studying the sensitivity of measurement with respect to the choice of signal modeling in this thesis. Another relevance of POWHEG sample in this thesis is that we use the generator level information of POWHEG generated $t\bar{t}$ events in the feasibility studies of the analysis method.

In order to get the semileptonic $t\bar{t}$ events from the inclusive $t\bar{t}$ MC sample, the generator truth information is used to select true semileptonic decay events, where one of the W boson decays leptonically, another decays hadronically.

4.1.3 Background process modeling

The requirement of a high quality lepton and two b-jets, together with requirements on minimum transverse momentum for all the final state particles, can effectively reduce vast majorities of background events, especially the dominant QCD multijet process. Still, there are several processes have non-negligible contribution in the final events that are used for the later analysis. These processes are called irreducible backgrounds, and need detailed and careful modeling. In most cases, the background processes are modeled by dedicated MC simulations. In the case of QCD multijet background, a data driven approach is taken as it is unfeasible to model this process purely with MC.

Non semileptonic $t\bar{t}$

One of the major irreducible background is fully hadronic or fully dileptonic $t\bar{t}$ events. The hadronic $t\bar{t}$ final states have two b-jets and four light flavor jets. With one of the light flavor jet mis-identified as electron (or muon, though less likely), some of the hadronic $t\bar{t}$ events can pass all selections. The fully leptonic $t\bar{t}$ event is consist of two high p_{T} leptons and two b-jets and large missing energy from the two neutrinos of W decays. With one of the lepton not being identified, combining with additional high p_{T} jets either from ISR/FSR radiation during the $t\bar{t}$ production or from QCD multijets process, this process can fake signal events too. Another process that can fake signal is the case where one of W decays to tau, that further decays to hadrons, and another W decays to electron or muon.

The reason why we categorize these process as background instead of signal despite the fact that these are true $t\bar{t}$ production process is that the later top quark kinematic reconstruction procedure is designed for semileptonic $t\bar{t}$ only. As the result, any non semileptonic $t\bar{t}$ event will be poorly reconstructed.

The modeling of non semileptonic $t\bar{t}$ background is from the same inclusive $t\bar{t}$ sample used in signal process modeling, and select the events that is not semi-leptonic decay of $t\bar{t}$ using the generator truth embedded in the simulation information.

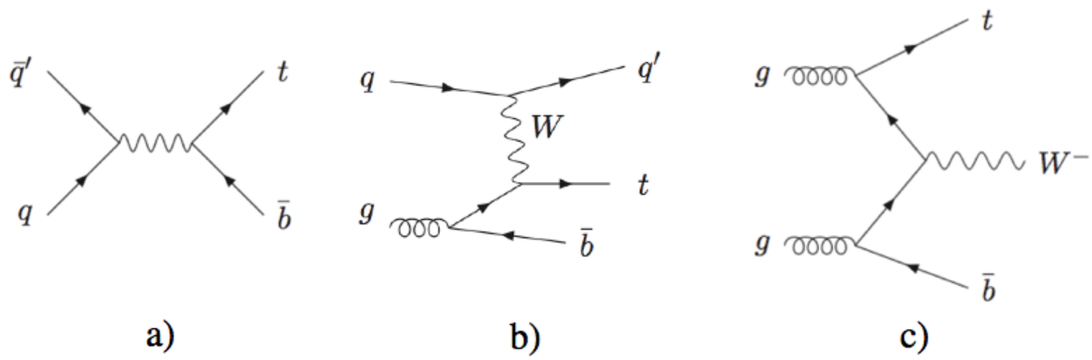


Figure 4.4: The Feynman diagrams of s,t and tW channel of single top production, from left to right.[27]

Single top production

A major background in this analysis, single top production events can be very similar topologically to the signal process. The representing Feynman diagrams for single top production in s,t and tW channels are shown in Fig.4.4.

The modeling of this background is via MC simulation using POWHEG as ME generator and interface with Pythia for parton showering.

W+Jets

The production of W boson with several associated jets is another non-negligible background. Although the kinematic distribution and final states from W+Jets process is very different from the $t\bar{t}$ process, due to the large production cross section of this process it is still possible for some events to pass all selections.

This process is modeled by using MadGraph event generator,[13] a popular leading order ME event generator, interfaced with Pythia for parton showering. Note here for the MC samples used for modeling this process, the additional jets produced associated with W boson is handled by the ME generator up to 4 additional jets, and beyond 4 jets production the extra jets are handled in PS step, due to the computational complexities introduced by the large combinatorics by adding more jets. For this reason, as well as other known limitations of the simulation of W+Jets process, the normalization and potentially kinematic distribution predicted by the simulation is not accurate enough.

Two measures are taken in order to mitigate the poor modeling of the W+Jets process. First in the event selection, two b-tagged jets are required, which significantly reduced the fraction of W+Jets background to the level of about 1%. The second measure is to determine the normalization of this process via a template fit, together with the measurement of A_{FB} that is described in Section.6.1.2.

Data Driven QCD Multijet Background

QCD Multijet process has enormous total cross sections and extremely low selection efficiency in our analysis. As a result, we cannot rely on MC simulated events to produce background templates for this process. Instead, we use a data driven approach by selecting the Data events that are in the side-band region of the phase space. The side band region is defined by inverting the selection criterion for electrons, including both RelIso and electron ID. Therefore the side band region is completely orthogonal to signal region, and suppose to be mostly dominated by QCD Multijet events.

There are still contamination of other background events and signal events in side band region. We take the Data events in sideband region with events from other processes subtracted. The rest of events are assumed to be entirely consist of QCD multijet process. We assume the shape of kinematic distributions of QCD events in sideband region to be the same as that in signal region, but with different normalization due to very different selection efficiency.

In order to estimate the normalization of QCD events in signal region based on the total number of events in sideband region, we follow the ABCD method. This method involves define more side band regions that are correlated in the same fashions as the signal region and sideband region defined above.

Our choice of selection criteria for ABCD(EF) regions are defined in Fig.[4.5]. Control plots are shown in Fig.[4.6]. Based on ABCD method, we compute conversion factor as defined in Table.[4.1], and apply the conversion factor to get an estimate of number of events for QCD Multijet process in signal region. Note that in order to calculate conversion factors, the expected number of "background" contaminated events are subtracted from number of data events in each region.

Based on the conversion factor calculated from ABCD method, and the number of observed events in C region, we expect 547 events from QCD multijet process, and we assigned a conservative uncertainty of 20% in the nuisance parameter R_{QCD} in our template fit.

The data events in region C (with contamination removed) are then reconstructed as $t\bar{t}$ final states, and become the QCD template in e+$jets$ channel. Since the template fit method depends mostly on the difference in distribution of signal and background processes, the expected QCD event rate is not very crucial, as we choose to determine the proper event rate in template fit. So the number of QCD events we estimated in this section is merely a reasonable initial value for the template fit.

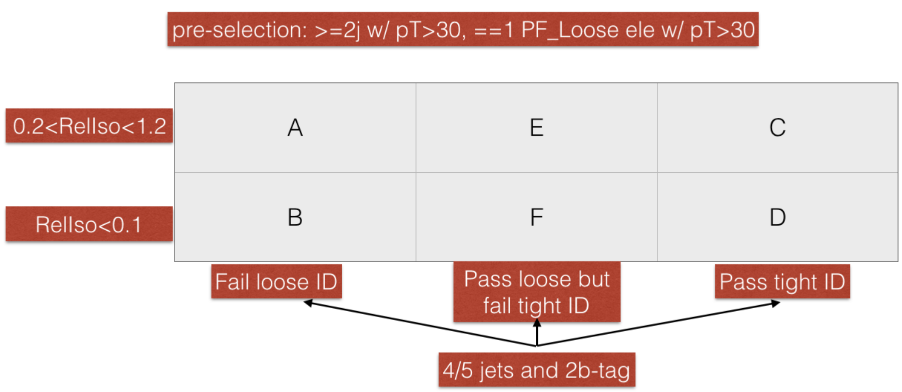


Figure 4.5: The selection criterion for different regions of side-band and signal region.

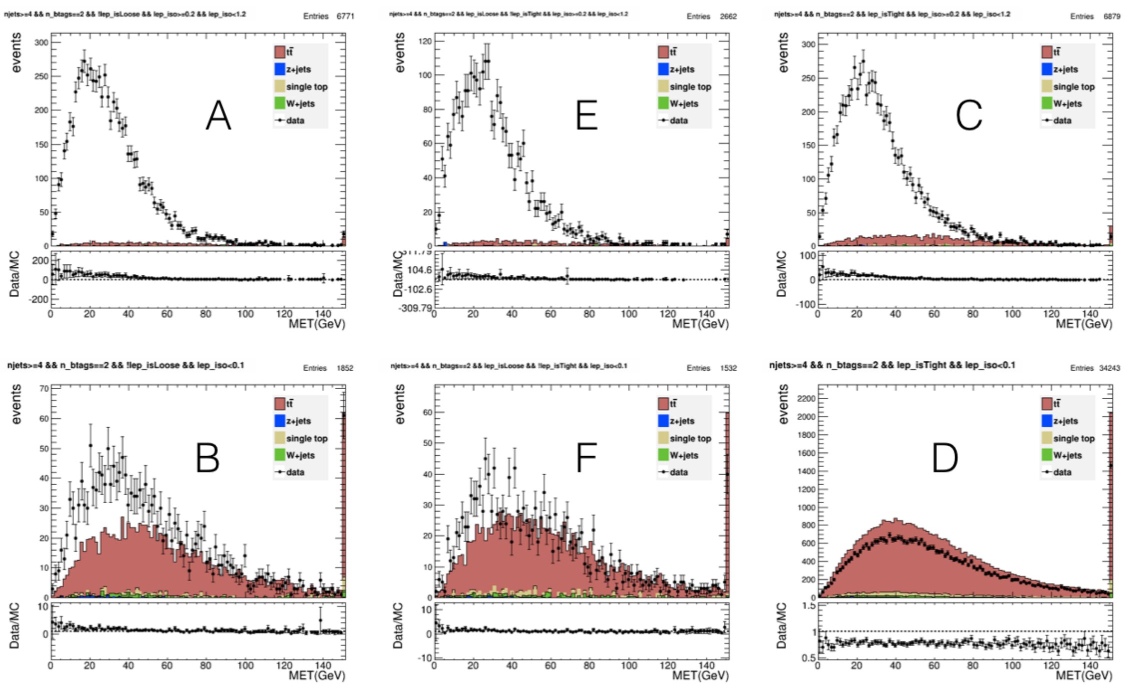


Figure 4.6: The missing transverse energy for $e+jets$ events in ABCD(EF) regions. The MC events are in solid color, and data events are in solid dots with error bars. The number of data events in each region is labeled as number of entries in upper right corner of each individual figure.

Method	predicted QCD events	$\sigma_{N_{QCD}}$	R_{QCD}	$\sigma_{R_{QCD}}$
N_{QCD} in D = B/A*C	547	52	1.3%	0.12%
N_{QCD} in D = F/E*C	435	129	0.98%	0.293%

Table 4.1: Expected number of QCD events in signal region based on the observed data events in side band C region and the conversion factor calculated from A/B and/or E/F regions. $\sigma_{N_{QCD}}$ and $\sigma_{R_{QCD}}$ are corresponding uncertainties assuming the number of observed events in each region follows Poisson distributions.

4.2 Data and MC Samples

4.2.1 Software

The reconstruction and the analysis of the data used in this study can be divided into three stages. The first stage involves the selection and storage of lepton and jet particle flow objects from AOD to B2G PATuples. Simulated events also include generator level information. This stage is done by B2G group using CMSSW 5.3.X release and TLBSM 53x version 3 code.[?] In the second stage, lepton ID tags, b-tagging discriminant information, and PDF weights (simulation only) are added. The CMSSW 5.3.24-based JHU Ntuplizer, developed for several B2G analyses, is used to generate EDM Ntuples. In the third stage, the final event selection, top quark reconstruction, and template fit are performed. The third stage is independent of CMSSW although the CMSSW 7.2.0 environment is used to access ROOT version 5.34.18cms12. The template fit is performed using Theta package.[28]

4.2.2 Data

The full 2012 LHC run dataset recorded by CMS detector, listed in Table 4.2, is used. It represents proton proton collision at center of mass energy of 8 TeV with integrated luminosity of $19.7 \pm 0.5 fb^{-1}$. To synchronize the trigger efficiency for Data and MC simulations, the following offline HLT requirements are applied to both Data and MC.

- electron+jets channel: `HLT_Ele27_WP80_v*`

- muon+jets channel: `HLT_IsoMu24_eta2p1_v*`

Only lumi-sections included in list of certified good runs provided in the following JSON file are included in the analysis.

- `Cert_190456-208686_8TeV_22Jan2013ReReco_Collisions12_JSON.txt`

Table 4.2: Single Electron/Muon Datasets

Dataset	**Integrated Luminosity** (pb^{-1})
/SingleMu/Run2012A-22Jan2013-v1/AOD	888
/SingleMu/Run2012B-22Jan2013-v1/AOD	4442
/SingleMu/Run2012C-22Jan2013-v1/AOD	7110
/SingleMu/Run2012D-22Jan2013-v1/AOD	7308
/SingleElectron/Run2012A-22Jan2013-v1/AOD	888
/SingleElectron/Run2012B-22Jan2013-v1/AOD	4442
/SingleElectron/Run2012C-22Jan2013-v1/AOD	7110
/SingleElectron/Run2012D-22Jan2013-v1/AOD	7308
Total Analyzed Integrated Luminosity	19748

4.2.3 Monte Carlo Simulation

This analysis requires large samples of fully simulated events to generate the different parts of the likelihood functions. Because the likelihood functions are built by reweighting Standard Model $t\bar{t}$ events, no special simulated samples are required. The samples used to model the signal and background functions, including the choice of generator and parton distribution functions, are listed in Table 4.3. All MC samples were generated in the official CMS Summer12 MC production campaign. More details about the simulated samples used can be found on the B2G Twiki.[?]

In order to build templates of likelihood functions all MC samples are normalized to the corresponding integrated luminosity of data. This is done given the number of simulated events generated and total cross sections of each individual process listed in Table 4.4. In addition, they are corrected using various scale factors to account for known discrepancies between data and simulation, as discussed below in Section 6.5.

Table 4.3: Monte Carlo Simulation Information I

Simulated Process	**MC Dataset**
$t\bar{t}$	TT_8TeV-mcatnlo
$\mathrm{t\bar{t}}$ (alternative)	TT_CT10_TuneZ2star_8TeV-powheg-tauola
W+1 Jet	W1JetsToLNu_TuneZ2Star_8TeV-madgraph
W+2 Jets	W2JetsToLNu_TuneZ2Star_8TeV-madgraph
W+3 Jets	W3JetsToLNu_TuneZ2Star_8TeV-madgraph
W+4 Jets	W4JetsToLNu_TuneZ2Star_8TeV-madgraph
Z/γ+1 Jet	DY1JetsToLL_M-50_TuneZ2Star_8TeV-madgraph
Z/γ+2 Jets	DY2JetsToLL_M-50_TuneZ2Star_8TeV-madgraph
Z/γ+3 Jets	DY3JetsToLL_M-50_TuneZ2Star_8TeV-madgraph
Z/γ+4 Jets	DY4JetsToLL_M-50_TuneZ2Star_8TeV-madgraph
t (s-channel)	T_s-channel_TuneZ2star_8TeV-powheg-tauola
t (t-channel)	T_t-channel_TuneZ2star_8TeV-powheg-tauola
t (tW-channel)	T_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola
$\bar{t}$ (s-channel)	Tbar_s-channel_TuneZ2star_8TeV-powheg-tauola
$\bar{t}$ (t-channel)	Tbar_t-channel_TuneZ2star_8TeV-powheg-tauola
$\bar{t}$ (tW-channel)	Tbar_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola

Simulated Process	**Matrix Element Generator**	$N^{Events}_{Generated}$	σ (pb)
$t\bar{t}$	aMC@NLO	32852589	245.8
$\mathrm{t\bar{t}}$ (alternative)	POWHEG	21560109	245.8
W+1 Jet	MADGRAPH	23038253	6662.8
W+2 Jets	MADGRAPH	33993463	2159.2
W+3 Jets	MADGRAPH	15507852	640.4
W+4 Jets	MADGRAPH	13326400	264.0
Z/γ+1 Jet	MADGRAPH	23994669	660.6
Z/γ+2 Jets	MADGRAPH	2345857	215.1
Z/γ+3 Jets	MADGRAPH	10655325	65.79
Z/γ+4 Jets	MADGRAPH	5843425	28.59
Z/γ+4 Jets	MADGRAPH	5843425	28.59
t (s-channel)	POWHEG	259176	3.79
t (t-channel)	POWHEG	3748155	56.4
t (tW-channel)	POWHEG	495559	11.1
$\bar{t}$ (s-channel)	POWHEG	139604	1.76
$\bar{t}$ (t-channel)	POWHEG	1930185	30.7
$\bar{t}$ (tW-channel)	POWHEG	491463	11.1

Table 4.4: Generator information and number of simulated events from Summer12 production of CMS.

Chapter 5

Physical Object Reconstruction and Event Selection

In this chapter, the reconstruction of physical objects such as leptons and jets out of sub-detector response is first introduced, following by the specific definition of physical objects used in the analysis of this thesis. Finally, the sequential $t\bar{t}$ signal event selection and the post selection control plots are provided.

5.1 Reconstruction and Selection of Physical Objects

In this thesis, the fundamental building blocks of $t\bar{t}$ events are physics objects, such as electrons, muons, jets and missing transverse energy (MET) which representing neutrinos. In CMS, and LHC in general, these objects are reconstructed from digital signals from all relevant sub detectors, including trackers, calorimeters and muon trackers, using Particle-Flow (PF) algorithm,[1] together with jet clustering algorithms.

The list of reconstructed objects, called PF candidates, are the starting point of further event selection, that applies specific criteria on the quality and kinematic property on the PF candidates, to keep as much signal events as possible while reduce the size of background events. The PF candidates after the selections are assigned as final states of $\mathrm{t\bar{t}}$ events, in this thesis, lepton and 4/5 jets. Finally the top and anti-top quarks are reconstructed from the final states, by performing the kinematic reconstruction that choose the best combination to make a plausible pair of top quarks. As the sensitivity of the measurement on A_{FB} depends on an accurate reconstruction of $\mathrm{t\bar{t}}$ pairs, it is critical to understand the reconstruction of each individual pieces in this picture.

5.1.1 Overview of event reconstruction

The particle-flow algorithm reconstruct all stable particles, including electrons, muons, photons, charged hadrons and neutral hadrons, by combing the information of CMS sub-detectors optimally according to carefully designed metrics. The list of reconstructed particles are then used to construct jets, which is the hadronisation products of partons, and MET, which is the imbalance of transverse momentum of all PF candidates. In addition, the PF candidates are also used to calculate PF based relative isolation ($RelIso$) of leptons, which is the relative proportion of momentum of lepton candidate out of PF among all PF candidates within a certain distance from the lepton. This isolation variable is an important discriminating variable for rejecting fake leptons.

PF algorithm can apply on both data and MC simulation, and the PF candidates out of MC is used for modeling the distribution of signal and background when possible. Additionally, the PF candidates are directly comparable to the particles from MC generator (before further feed into CMS detector simulator).

Fundamental Elements

The fundamental building blocks of particle reconstruction are charged particle tracks, calorimeter clusters and muon tracks. A brief overview of the techniques of reconstruction of these elements is given below.

Tracks are reconstructed from the hits in the layers of innermost pixel tracker and the silicone strip tracker outside the pixel tracker, using an iterative algorithm.[17] The tracking software is called Combinatorial Track Finder (CTF), based on the technique of combinatorial kalman filter, that allows pattern recognition and track finding at the same time.

Starting from the collection of hits in tracker systems, as many as six iteration of track finding is performed. The initial iterations reconstruct tracks that are easiest to find, and with very tight criteria, leading to reconstruction of high p_T and from primary interaction vertex. The hits that belongs to previous reconstructed tracks are removed. Later iterations will start with looser seeding criteria, and will reconstruct the tracks usually from secondary vertices. The efficiency of charged hadron tracks in central region of the detector is above 90%, with a resolution in measured p_T of about 1.5%.

Calorimeter clusters are used for measuring the energy deposit of both charged particles, such as electrons or charged hadrons and neutral particles, such as photon and neutral hadrons. It is critical in terms of detecting the energy and direction of neutral particles, as they don't leave any tracks in tracker system. In addition, they are used to identify and reconstruct electrons together with the Bremsstrahlung photons. The clustering algorithm used in PF also need to separate the energy deposit of neutral particles from charged particles.

The clustering algorithm first identify cluster seeds which are cells in calorimeters with maximal energy, then topological clusters are formed around the seed by aggregating the adjacent cells that has energy deposit beyond a certain threshold. The clustering algorithm is performed separately in all sub-detectors, including ECAL, HCAL and PS calorimeters. The reconstructed energy clusters are later used for charge particle reconstruction by combining the tracking information.

Particle-Flow Algortithms

After the input elements are gathered, PF algorithm is applied to reconstruct particles. The PF algorithm can be separated into two stages. The first stage to link several elements in various CMS sub-detectors, called a block, and treating the block as detector response from one single particles. This process can avoid the double counting the same particle in several detectors, as well as improving the accuracy of particle identification. For example, a charged hadron, like pions, will leave hits in tracker which are reconstructed as tracks, and create energy deposit in ECAL and HCAL, which are individually grouped as clusters. The link algorithm is performed for each pair of detector elements, and if the pair of elements are marginally consistent with the hypothesis of coming from the same stable particle, the link will be established. For example, a link between a track and ECAL or HCAL clusters is established if the extrapolated position of the track in the corresponding calorimetry is within the boundary the linked cluster. In addition to forming links, a link distance between the extrapolated track position and the cluster position is computed to quantify the consistency of the link.

The second stage is particle reconstruction and identification from the linked blocks. Different types of particles are reconstructed and identified as part of the block, in an ordered of muon, electron, neutral hadrons, charged hadrons,and photons. The successful reconstruction of each particle relies on consistency of the combination of elements in the block that is used for the reconstruction. If more than one combination of elements are possible, the optimal combination is selected based on the distance computed in the linking stage. Any element, such as tracks and calorimeters clusters , once identified for reconstruction of a particle, is removed afterwards, and remaining elements in a block is used for reconstruction of other particles.

5.1.2 Muons

Muon Reconstruction

Muons are the particles that are reconstructed best in CMS due to the superior inner tracker, muon system and the strong magnetic field from the superconducting solenoid. Muons are reconstructed based on the tracker tracks in the inner tracker and muon tracks in the muon system. There are two types of muons depends on the reconstruction algorithm: tracker muons and global muons.[16]

Global muons are reconstructed first by finding matching tracker tracks and muon tracks, by propagate both tracks into a common region. Once matching tracks are found, the hits belong to the found tracks are fitted again using a Kalman-filter technique, to establish a better global muon with higher momentum resolution than standalone fit for both systems.

Tracker muons are reconstructed inside-out, meaning that the tracker tracks are propagated all the way to the muon system, taking into account of the magnetic field, energy loss and scattering in the materials in between. Any tracks with matching muon system hits in at least one segment of muon system are considered as tracker muons.

The muon reconstruction efficiency in CMS is very high, with 99% of muons within muon system geometric acceptance and having sufficient high p_T reconstructed as either tracker muons or global muons. Most of the track muons and global muons are reconstructed from the same tracks, and are merged into a single muon candidate. Once muon candidates are reconstructed, in actual down stream physics analysis, a further selection on the muon candidates is applied to achieve a balance of efficiency of low fake muon or cosmic muon rate.

Muon Selection

For the muon+jets channel, both data and simulation are required to pass additional offline high level trigger `HLT_IsoMu24_eta2p1_v*`. This trigger selects events with at least one isolated muon of $p_T > 24$ GeV and $|\eta| < 2.1$. Additionally, real and simulated events are required to have exactly one global muon candidate with $p_T > 26$ GeV and $|\eta| < 2.1$. In order to improve the quality of selected muon, it is also required to satisfy the Muon POG "tight" criteria for 2012 data.[?] The selected muon must have global track fit quality $\chi^2/ndf < 10$. It must have at least one muon chamber hit included in the global-muon track fit, with muon segments in at least two muon stations. In addition, the muons must have at least one hit in pixel detector and have at least 5 hits in the inner tracker. In order to assure the muons are from primary collisions, the tracker tracks must have transverse and longitudinal impact parameters with respect to the primary vertex smaller than 2 mm and 5 mm, respectively. Additionally, each muon candidate is required to satisfy a particle flow based isolation (`RelIso`) requirement $\mathrm{PF_{iso}}/p_T < 0.12$ where the isolation is of the "combined relative" type with $\Delta\beta$ corrections applied to reduce pileup effects and is computed within a cone size of 0.4.

5.1.3 Electrons

Electron Reconstruction

Unlike muons, electrons are reconstructed by combining the tracks from inner tracker and cluster of energy deposit in ECAL.

Because of radiative energy loss of electron via interaction with materials in tracking system, the standard Kalman filter fitting used in PF is not sufficient to reconstruct electron tracks well enough. Electron tracks are reconstructed first using the same tracking algorithm for all charged particles in PF, described in 5.1.1. This first pass using KF usually works for the case of small bremsstrahlung. For the case of non-negligible bremsstrahlung, KF will fail reconstructing the correct track by missing hits or reconstruct tracks with bad quality (large χ_{KF}). In this case, a second pass of fitting is performed, using a dedicated Gaussian sum fitter (GSF).

As part of PF algorithm, ECAL clusters are reconstructed based on GSF tracks.

The goal of clustering algorithm is to cluster all the crystals in ECAL that have energy deposit from the electron and the its bremsstrahlung photon, so the energy of electron can be accurately measured. The clusters from the electron itself are identified by extrapolating the GSF tracks to the ECAL and finding the matching ECAL crystals; the clusters from the photon are identified by drawing a tangent line from the GSF tracks in each layer of the tracker, and extend the lines to ECAL and finding the matching crystals. The reason is that bremsstrahlung happens mostly in the material dense region of the detector before the electron reaches the ECAL, which is the tracker layers.

Finally electron candidates are reconstructed by associating tracks and ECAL clusters, so both momentum and energy is measured. The charge of electron is mostly from the curvature of the tracks.

Electron Identification

In order to identify signal electrons which are from prompt decay of the mother particles originated form primary vertices, and separate them from background sources, a further selection procedure is needed to identify good quality electrons. The main sources of background are the following: electron pairs from photon conversion, jets misidentified as electrons, electrons from semileptonic decay of b and c quarks. Two different type of electron ID algorithms are widely used in physics analysis , one is cut-bases, which is a sequential selection on a set of discriminant; another one is a

MVA based approach, which use boosted decision tree to combine many variables to maximize the discriminating power of separating signal and background electron candidates. In this thesis, we use the cut-based selection, which is simpler, more transparent and more robust.

Among the discriminating variables used for electron ID, one is especially important, the relative isolation RelIso of electrons. The requirement of isolation is especially effective in reducing the background of jets misidentified as electrons or the electron within a jet , which is originated from the decay of b or c quarks. For both cases, there are a significant amount of charged particles around the electron candidate. Therefore,$\mathrm{RelIso}_{\mathrm{PF}}$ that quantifies the total energy surrounding the electron candidate, is defined as follows, based on the PF candidates:

$$\mathrm{RelIso}_{\mathrm{PF}} = \frac{\sum p_{\mathrm{T}}^{\mathrm{charged}} + \max\left[0, \sum p_{\mathrm{T}}^{\mathrm{neutralhad}} + \sum p_{\mathrm{T}}^{\gamma} - p_{\mathrm{T}}^{\mathrm{PU}}\right]}{p_{\mathrm{T}}^{\mathrm{electron}}} \tag{5.1}$$

Electron Selection

For electron+jets channel, both data and simulation events are required to pass offline trigger `HLT_Ele27_WP80`. This trigger select events with at least one electron with $p_T > 27$GeV. To further select top pair events it is required to have exactly one particle flow electron with $p_T > 30$GeV and $|\eta| < 2.5$. Electrons with a supercluster in the eta range of 1.4442 and 1.5660, corresponding to the transition region between barrel and end-cap calorimeter are not selected. To insure the selected electron is from primary colision it is required to be associated with tracks that has impact parameter with respect to beam spot smaller than 0.02 cm, and has longitudinal distance from primary vertex smaller than 0.1 cm. In addition, a cut based electron ID is applied and the selected electron is required to satisfy "tight" criteria.[?] Additionally, each electron candidate is required to satisfy a particle flow isolation smaller than 0.1 , with a cone size of 0.3 .

In order to reject electrons originated from the conversion of photons, a vertex fit conversion method is used and the electron selected is required to pass this conversion veto. In addition, the GSF track associated with the selected electron is required to have no missing hits in inner tracking system.

5.1.4 Veto Leptons

Finally, to suppress signal from dileptonic top events, any event with a second veto muon or veto electron is not selected.

The veto muon is defined as having particle flow muon ID, being a global muon, with $p_T > 10GeV$, $|\eta| < 2.5$ and $RelIso(R = 0.4) < 0.2$.

The veto electron is defined as an electron with $p_T > 20$GeV, $|\eta| < 2.5$ and $RelIso(R = 0.3) < 0.15$. In addtion, the veto electrons are required to pass cut based electron ID with "Loose" working point as defined in EGamma POG Twiki.[?]

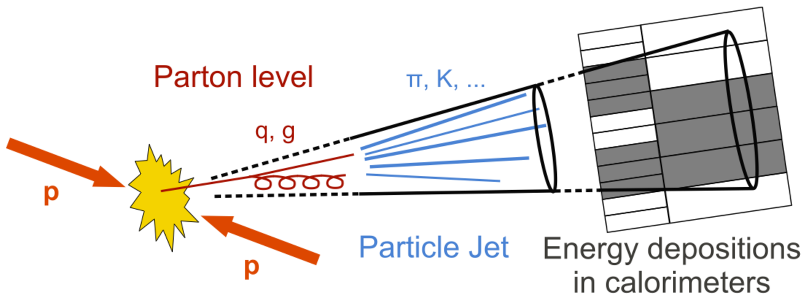


Figure 5.1: A Schematic over view of jets, and the relationship to partons in hadron coliders.[24]

5.1.5 Jets

Jets are observable objects in hadron colliders that are formed by grouping collimated bunches of stable hadrons originated from partons (quarks and gluons). As a direct result of QCD and asymptotic freedom discuss in , no isolated , so called bare quarks or gluons exist. Rather, they undergo hadronization process, forming stable particles, and observed as parton showers in tracker and calorimeters. The shower of stable particles are clustered using jet clustering algorithms to form jets with a certain cone size. These jets are the product of reverse engineering of the hadronization process, and are studied using the parton level calculations, as demonstrate in the Fig.5.1.

Jets Reconstruction

Jets used in the analysis of this thesis are reconstructed from stable hadrons out of PF algorithm in CMS. Due to the complexity of this topic, only a very brief summary is provided below, more details are provided in.[14,19]

There are many different jet clustering algorithms, but they should all satisfy the following requirements:

- Collinear-safe: the clustered jets should be stable under the splitting a single particle into several particles of low angular separation. This is required by the common process of collinear gluon radiation.

- Infrared-safe: clustering algorithm should be stable by adding or removing low energy radiation. It means detector noise or additional PU hadrons will not significantly alter the result of jet clustering

In this thesis, and most of the analysis in CMS, the anti-kT (AK) algorithm is used for jet clustering. This algorithm cluster jet from stable particles by recursively combine soft (carries small transverse momentum) particles with hard ones. It belongs to a general type of clustering algorithms called sequential recombination algorithms, including kT algorithm and Cambridge-Aachen Algorithms.

The AK algorithms starts from defining a momentum weighted distance measure between any pair of particles (or intermediate jet, called pseudo-jet) i,j, defined as follows:

$$d_{ij} = \min(1/k_{T,i}^2, 1/k_{T,j}^2)\frac{\Delta R_{ij}^2}{R^2}, \tag{5.2}$$

$$d_{iB} = 1/k_{T,i}^2 \tag{5.3}$$

where $k_{T,i}$ are transverse momentum of i'th particle, $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ are commonly used distance measure in LHC , and R is the desired cone size of the clustered jet. In this thesis, we use the jets clustered with $R = 0.5$, and denote them as $AK5$ jets.

In each iteration, every pairwise distance d_{ij} , and the beam distance d_{iB} are calculated. If the smallest of all the distances calculated is a pairwise distance d_{ij}, the pair of particles are merged by summing their four momentums. If the smallest one is d_{iB}, then the i'th particle (or pseudo-jet) is called a new jet, and it is removed from the list of particles/pseudo-jets. This combination process is repeated until all jets are identified.

What this algorithm actually does is to merge soft particles into a hard particle/pseudo-jet that is within the cone centered around the hard pseudo-jet of size R. Two hard jets will be merged into a new jet only when there distance is within R, otherwise they are kept as separate jets, per the construction of d_iB. One example of the result of AK algorithm is shown in Fig.? , using a cone size of $R = 1$, on the parton level simulated event. It shows the clusted jets are indeed clustered per the design of the algorithm.

Jets Selection

The hadronic jets used in this analysis are reconstructed using the anti-kT algorithm with cone size 0.5. Jet energy corrections have being applied using the JEC

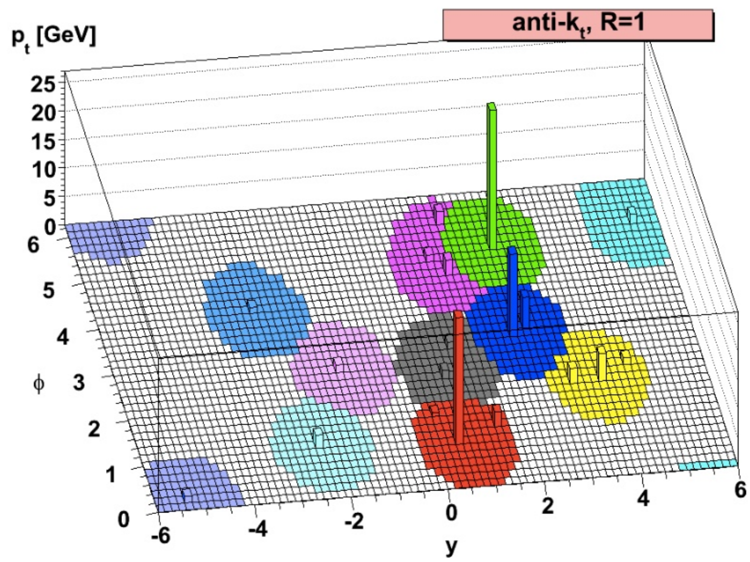


Figure 5.2: An example of AK clustering algorithm, based on simulation, taken from.[14] Cone size is $R = 1$. Each colored cone is a clustered jet. The histogram shows the p_T of underlying partons.

from `Winter14(5_3_X)` as recommended by JetMET POG[?].[?] The list of JEC txt files used is as follows:

- `START53_V27_L1FastJet_AK5PFchs.txt`
- `START53_V27_L2Relative_AK5PFchs.txt`
- `START53_V27_L3Absolute_AK5PFchs.txt`
- `Winter14_V5_DATA_L1FastJet_AK5PFchs.txt`
- `Winter14_V5_DATA_L2Relative_AK5PFchs.txt`
- `Winter14_V5_DATA_L3Absolute_AK5PFchs.txt`
- `Winter14_V5_DATA_L2L3Residual_AK5PFchs.txt`

All jets are required to have reconstructed pseudorapidities in the region $|\eta| < 2.5$. The selected jets in each event are required to have transverse momenta larger than 30GeV. Events with more than 5 selected jets or less than 4 selected jets are excluded.

In addition to these kinematic requirements, we also require that at least two jets be identified as a b-jet. The b-jet identification is based upon the Combined Secondary Vertex (CSV) tagging algorithm[?] and requires that the CSV discriminator be larger than 0.679.

5.2 Event Selection

The event selection for this analysis follows the Top PAG Run-1 selection recommendations.[18] To select top pair events in the lepton + jet channel, the candidate event is required to have a high p_T electron or muon and four or five high p_T jets. In order to reduce background events such as `W+jets` two of the jets must be tagged as b-jets. This analysis is based upon particle flow objects discussed in previous section.

5.2.1 Cut-flow

The selection criteria are applied sequentially to both data and MC. The numbers of real and simulated events passing each step are summarized in Table 5.1. The final entry in the table lists the number selected events for which the kinematic reconstruction [as described in section 6.2.1] is successful. Only in the last step, the MC event rates have been corrected using scale factors to account for efficiency differences between data and MC for the lepton ID, trigger, and btagging requirements. Total number of events in simulation has been normalized to the integrated luminosity corresponding to the data using the total cross sections for each individual process as listed in Table 4.4.

The effectiveness of the selection criteria is illustrated in Figs. 5.3. The plot shows the normalized abundances of simulated $t\bar{t}$ and background events as functions of reconstructed $t\bar{t}$ mass before the application of the criteria. The sample is dominated

	e+jets		μ+jets	
Selection Step	N_{Data}	N_{MC}	N_{Data}	N_{MC}
trigger	268293848	29318762	123122494	32845362
lepton	64361692	20186742	32845362	25208917
dilepton veto	62447916	19446044	74041500	24085598
$N_{jets} \geqslant 4$	254892	227859	222279	246025
$N_{btags} \geqslant 2$	56015	62788	55730	67974
$N_{jets} \leqslant 5$ and kin Reco	42923	47199	45321	51061

Table 5.1: Event yields after HLT trigger applied, contains one good lepton, not containing another lepton, has at least four selected jets, has at least two of the jets tagged as b jets, has no more than 5 selected jets while successfully being reconstructed. MC corrections such as trigger efficiency, pileup re-weighting etc have been applied in the last step of the cut flow. All MC events have been normalized to the same integrated luminosity as Data.

by background from W+jets production. The plot on the right shows the same distributions after the application of the selection criteria. Clearly the signal $t\bar{t}$ is greatly enhanced with respect to the backgrounds.

Note that in the last step we merged several background processes into a single template called *other backgrounds*, which includes single top production, Drell-Yan, and $t\bar{t}$ events that are not e+jets or mu+jets. On the other hand, we separate W+Jets and QCD process from other backgrounds. The motivation is that the processes included in our defined "other backgrounds" are well modeled by MC simulations. By merging them together into one template we essentially fix the relative compositions among those processes according to the expected values given by MC. In contrast, according to many existing analysis the W+Jets are not very well modeled in the MC simulations we used that are generated using matrix element calculated in leading order. For data driven QCD the uncertainty of normalization is fairly large as discussed in section [4.1.3]. So we separate W+Jets process and QCD process from other backgrounds in the templates and later simultaneously fit for the normalization during the template fit.

After applying the selection criteria and reconstruction algorithm to the simulated data sets, semi-leptonic top pair events comprise 90% of the resulting sample. The relative fractions of events from signal and various backgrounds are listed in Table 5.2. The dominant background is ”other backgrounds”.

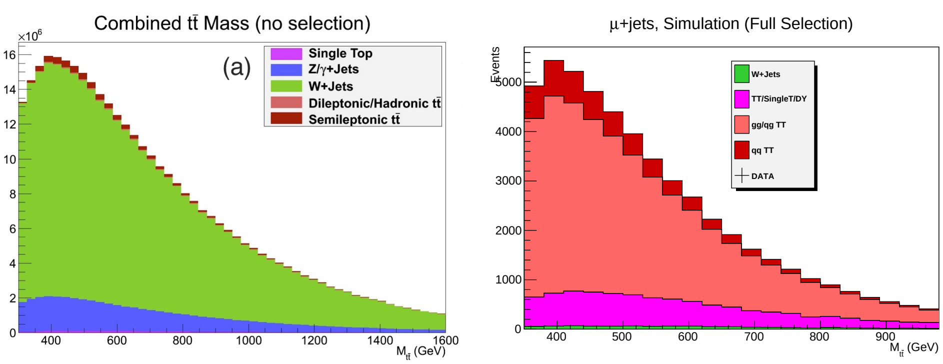


Figure 5.3: The $t\bar{t}$ invariant mass distributions of normalized signal and background Monte Carlo samples before event selection (a) and after event selection (b).

	e+jets		μ+jets	
Process	N_{MC}	Fraction	N_{MC}	Fraction
$q\bar{q} \to t\bar{t}$	5173	11.0	5510	10.8
$gg/qg \to t\bar{t}$	33824	71.7	36126	70.8
other backgrounds	6914	14.7	8530	16.7
W+Jets	764	1.6	894	1.8
QCD	522	1.1	NA	NA
Total	47199	100	51061	100

Table 5.2: Expected number of events and relative event composition after event selection and reconstruction, by counting of MC templates. Fractions are in terms of percent. Data driven QCD process is included in e+jets channel only. The normalization of QCD follows the discussion of section [ref].

5.2.2 Control Plots

A set of control plots that compare MC and data distributions of several kinematic observables are shown in this section. All the plots are from events that passed all selection cuts, but before any further reconstruction quality cuts are made.

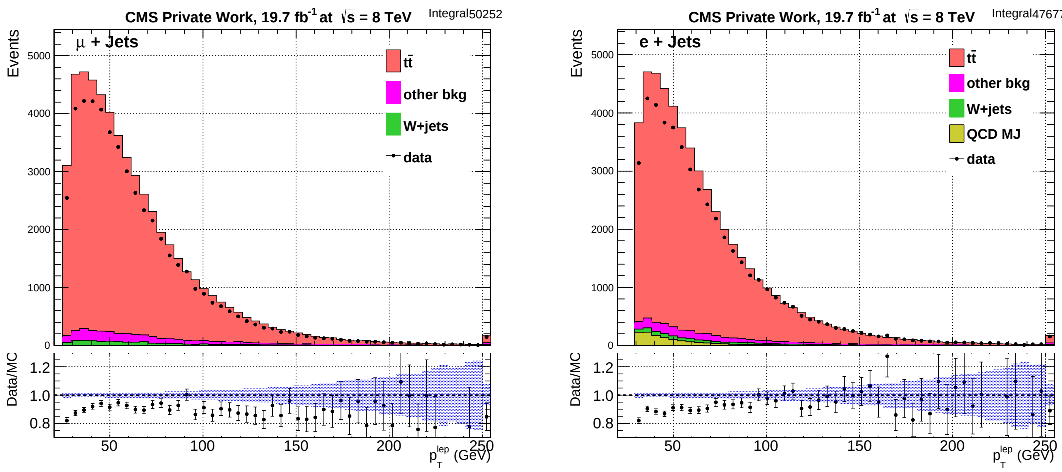


Figure 5.4: The e/μ p_T distributions of normalized signal and background Monte Carlo samples after event selection, for mu+jets channel (a) and e+jets(b).

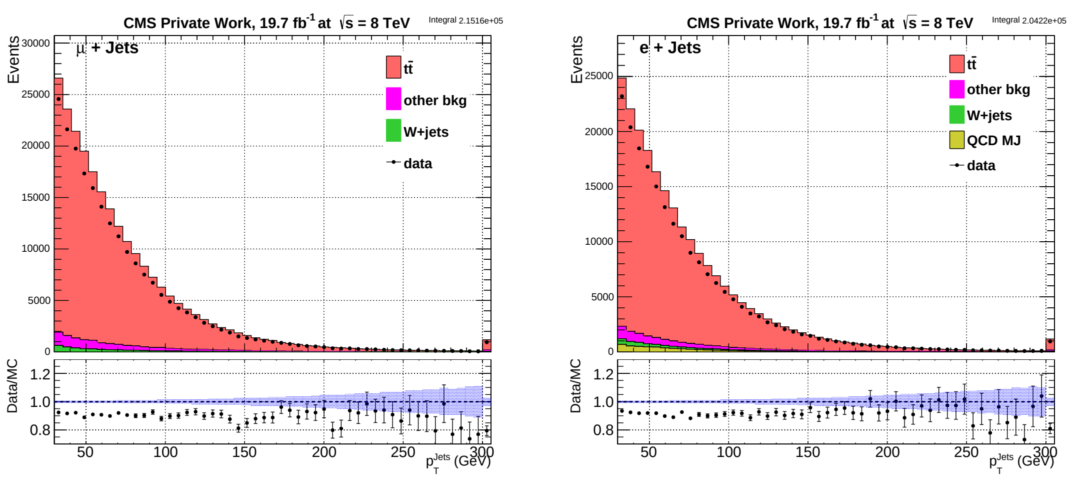


Figure 5.5: The jets p_T distributions of normalized signal and background Monte Carlo samples after event selection, for mu+jets channel (a) and e+jets(b).

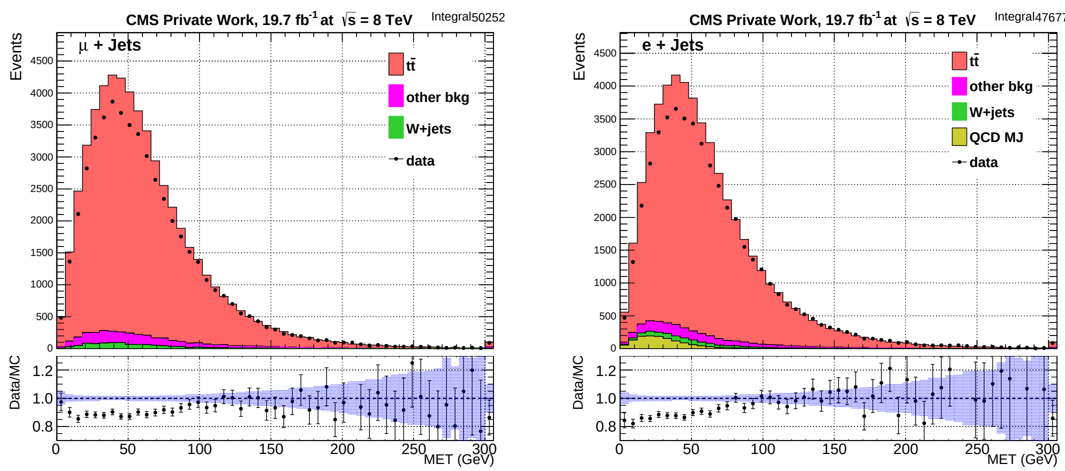


Figure 5.6: The MET distributions of normalized signal and background Monte Carlo samples after event selection, for mu+jets channel (a) and e+jets(b).

Chapter 6

Measurement of $\mathrm{t\bar{t}}$ Forawd-backward Asymmetry

In this chapter, we first introduce the empirical motivation and theoretical formulation of the template based A_{FB} measurement. Next, the method and result of kinematic reconstruction of $\mathrm{t\bar{t}}$ pairs from the momentum of observed final states is provided. Then, we describe the details of the actual implementation of the template fit based on the maximal likelihood method. Afterwards, the systematic uncertainties in this measurement as well as the study of the sensitivity is described. Finally, the measurement result and discussion is provided.

6.1 Analysis Method for Template Based AFB Measurement

6.1.1 Motivation

The likelihood approach is based upon the observation that the angular distributions resulting from the s-channel dominated $q\bar{q}$ subprocess and from the t-channel dominated gg subprocess are quite distinct. Additionally, the gluon structure functions are "softer", more peaked a low x, than are the quark structure functions. Therefore, highly boosted $t\bar{t}$ pairs, those produced at large x_{F} or rapidity, are more likely to be $q\bar{q}$-produced and the boost direction is most likely to be the direction of the incident quark. To define the variables, we let x_1 and x_2 be the momentum fractions of the incident partons ordered so that the net boost is positive, $x_{\mathrm{F}} = x_1 - x_2 > 0$. The invariant mass of the $t\bar{t}$ pair, M, is then related to the momentum fractions, $M^2 = x_1 x_2 s$, where s is the square of the pp center-of-mass energy. The differential cross section for $t\bar{t}$ production is composed of three parts,

$$\begin{aligned}\frac{d^3\sigma}{dx_{\mathrm{F}}dMdc_*} =& \frac{2M}{s\sqrt{x_{\mathrm{F}}^2 + 4M^2/s}}\left\{\frac{d\sigma}{dc_*}(q\bar{q};M^2)\left[D_q(x_1)D_{\bar{q}}(x_2) + D_q(x_2)D_{\bar{q}}(x_1)\right]\right.\\ &\left.+\frac{d\sigma}{dc_*}(gg;M^2)D_g(x_1)D_g(x_2)\right\} + \frac{d^3\sigma}{dx_{\mathrm{F}}dMdc_*}(\text{background}) \qquad (6.1)\end{aligned}$$

where $x_{1,2} = \pm x_{\mathrm{F}} + \sqrt{x_{\mathrm{F}}^2 + 4M^2/s}$, $c_* \equiv \cos\theta^*$ and θ^* is angle between the initial state quark direction and the top direction in the $t\bar{t}$ cm frame , and where the tree-level cross sections for $q\bar{q},\ gg \to t\bar{t}$ are

$$\frac{d\sigma}{dc_*}(q\bar{q};M^2) = \frac{\pi\alpha_s^2}{9M^2}\beta\left[1+\beta^2c_*^2+\left(1-\beta^2\right)\right] \tag{6.2}$$

and

$$\frac{d\sigma}{dc_*}(gg;M^2) = \frac{\pi\alpha_s^2}{48M^2}\beta\left[\frac{16}{1-\beta^2c_*^2}-9\right]\left\{\frac{1+\beta^2c_*^2}{2}+(1-\beta^2)-\frac{(1-\beta^2)^2}{1-\beta^2c_*^2}\right\} \tag{6.3}$$

and where the top quark velocity in the cm-frame is $\beta = \sqrt{1-4m_t^2/M^2}$. The gg subprocess produces a more forward-peaked cross section which provides the primary discriminant in the separation of the gg and qq subprocesses.

This study will consider events that can have extra jets which implies that the $t\bar{t}$ pairs can have non-zero transverse momenta . This is accommodated in NLO descriptions by using the Collins-Soper (CS) definition[20] of the production angle and by allowing the cross section to develop a (CS frame dependent) term corresponding to longitudinal gluon polarization,

$$\frac{d\sigma}{dc_*}(q\bar{q};M^2) = K\frac{\pi\alpha_s^2}{9M^2}\beta\left[1+\beta^2c_*^2+\left(1-\beta^2\right)+\alpha\left(1-\beta^2c_*^2\right)\right] \tag{6.4}$$

where K is a normalization parameter and the average longitudinal polarization α is determined from a fit to a sample of generated events.

An asymmetric $q\bar{q}$ subprocess could be caused by several kinds of new physics that interfere with or augment the tree-level process.[15,22] Most of these can be characterized in leading order by a small generalization of the tree-level cross section,

$$\frac{d\sigma}{dc_*}(q\bar{q}; M^2) = R\frac{\pi\alpha_s^2}{9M^2}\beta\Big\{1 + \beta^2 c_*^2 + \left(1-\beta^2\right) + \alpha\left(1-\beta^2 c_*^2\right) \\ + 2\left[1 + \frac{1}{3}\beta^2 + (1-\beta^2) + \alpha\left(1 - \frac{1}{3}\beta^2\right)\right] A_{\mathrm{FB}}^{(1)} c_*\Big\} \quad (6.5)$$

Note that the asymmetry is characterized by the slope of the linear term in c_* and is labelled with the superscript (1). Next-to-leading-order QCD corrections are expected[25] to produce an asymmetry of approximately 8%. A comparison of the ratio of the c_*-odd and even terms for the full NLO calculation and for the simple linear model given in equation 6.5 with $A_{\mathrm{FB}}^{(1)} = 0.08$ is shown in Fig. 6.1. The black curves show the NLO calculation for three different values of M. The red curves show the linear model for the same values of M. It is clear that the linear model is fairly accurate at lower masses and is still a reasonable approximation at larger masses. A test of this hypothesis was performed by fitting the full NLO angular distribution generated by Powheg to the form given in equation 6.5 and by comparing the resulting linearized asymmetry with the asymmetry determined from counting the forward and backward top events. The results are listed in Table 6.1 for the full sample and for the 4-jet and 5-jet subsamples. Excellent agreement is observed.

The distributions in (M, c_*, x_F) for the gg and $q\bar{q}$ initial states can be visualized by considering a sample of $t\bar{t}(j)$ events generated with Powheg for pp collisions at $\sqrt{s} = 8$ TeV. Because an extra jet is allowed, there is also a substantial contribution from the process $qg \to t\bar{t}q$ which is larger in magnitude than the $q\bar{q}$ subprocess. The

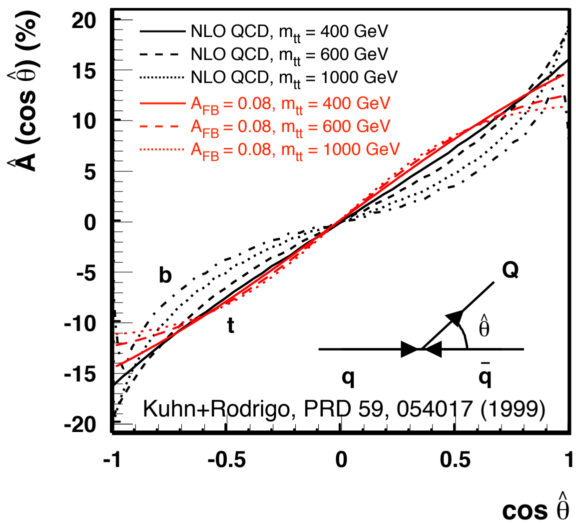


Figure 6.1: The ratio of the c_*-odd and even terms for the full NLO calculation and for the simple linear model given in equation 6.5 with $A_{\mathrm{FB}}^{(1)} = 0.08$. The black curves show the NLO calculation for three different values of M: 400 GeV (solid), 600 GeV (dashes), and 1000 GeV (dots). The black dash-dot curve corresponds to b quarks and should be ignored. The red curves show the linear model with $A_{\mathrm{FB}}^{(1)} = 0.08$ for the same masses.

mass, $\cos\theta^*$, and x_F distributions for the three subprocesses are shown in Fig. 6.2. Note that the gg and qg distributions are quite similar. Because the asymmetry for qg events is expected to be smaller than for $q\bar{q}$ events events[25] (see also Table 6.4), the gg and qg subprocesses are combined into a single distribution function for the purpose of this work. The $q\bar{q}$ mass distribution is somewhat narrower than the others. The $q\bar{q}$ angular distribution is much flatter than the others due to t-channel pole that dominates the gg and qg cross sections. Of key importance, the x_F distribution of the $q\bar{q}$ events has a longer tail that helps to discriminate them and to correctly identify

Table 6.1: The $q\bar{q} \to t\bar{t}$ forward-backward asymmetry as determined from a sample of Powheg NLO generated events by counting and by fitting to the linearized function.

Sample	A_{FB} (counting)	$A_{FB}^{(1)}$ (fitting)
All events	$+0.0356 \pm 0.0015$	$+0.0352 \pm 0.0013$
4 jets only	$+0.0903 \pm 0.0018$	$+0.0900 \pm 0.0016$
5 jets only	-0.0698 ± 0.0026	-0.0720 ± 0.0023

the incident quark direction. The result of taking the longitudinal direction of the $t\bar{t}$ pair in the lab frame as the quark direction is shown in Fig. 6.2(d). Defining N_C as the number of correct assignments and N_I as the number of incorrect assignments, the dilution factor $D = (N_C - N_I)/(N_C + N_I)$ is plotted vs x_F. Note that it becomes large in the $q\bar{q}$ enriched region at large x_F.

Because there can be "feed-down" from QCD processes that produce $t\bar{t}$ with more than one extra jet, we define the gg label to include events produced from the gg, qg, qq, $\bar{q}\bar{q}$, and $q_i\bar{q}_j$ (flavor $i \neq$ flavor j) subprocesses.

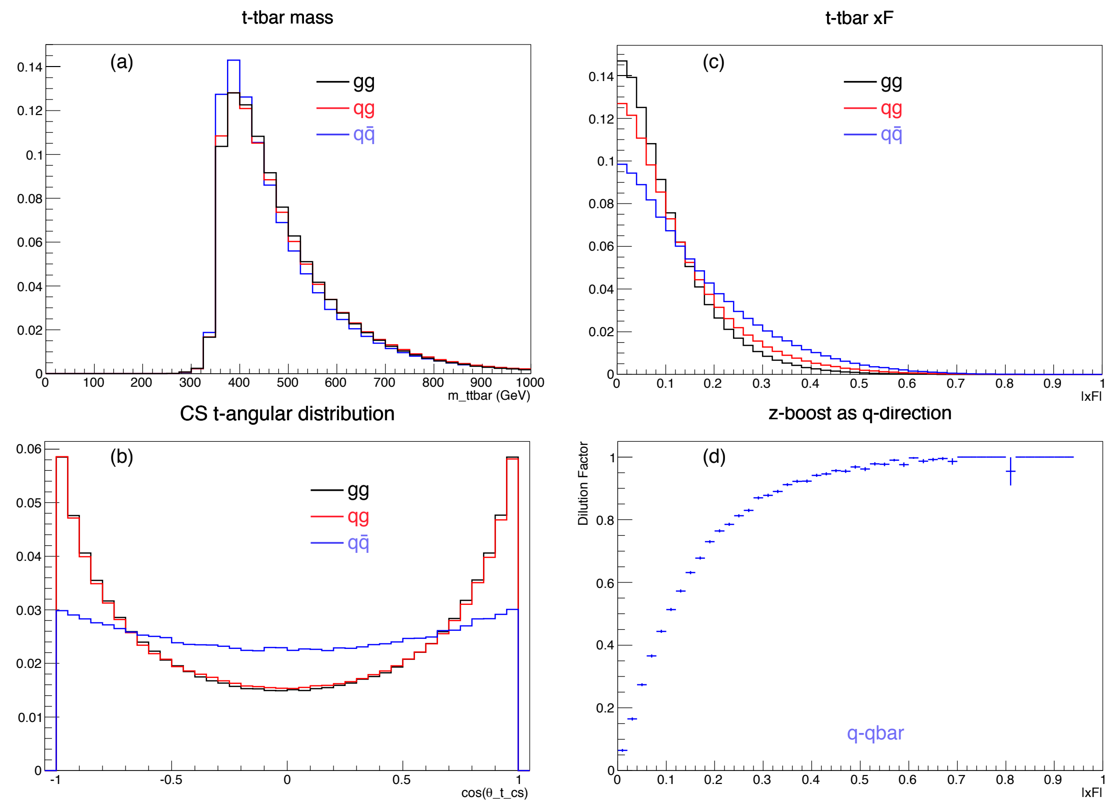


Figure 6.2: The mass (a), $\cos\theta^*$ (b), and $|x_F|$ (c) distributions for the subprocesses $gg/qg/q\bar{q} \to t\bar{t}(j)$. The result of taking the longitudinal direction of the $t\bar{t}$ pair in the lab frame as the quark direction is shown in panel (d). Defining N_C as the number of correct assignments and N_I as the number of incorrect assignments, the dilution factor $D = (N_C - N_I)/(N_C + N_I)$ is plotted vs x_F. Note that it becomes large in the $q\bar{q}$ enriched region at large $|x_F|$.

6.1.2 Analysis Scheme

It is possible to reconstruct the three key variables x_{r}, M_{r}, and c_{r} from lepton and 4(5)-jet final states. The sign of the lepton tags the top vs antitop direction. The direction of the pair along the beam axis can be taken as the likely quark direction for $q\bar{q}$. Integrating over the pair pt (necessary only for the 5-jet cases), the data can be represented as a set of triplets in the reconstructed variables. The distribution function of the reconstructed variables can be expressed as a convolution of the cross section defined in equation 6.1 (with the $q\bar{q}$ cross section given by equation 6.5),

$$f(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}) = C \int dx_{\mathrm{F}} dM dc_* R(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}; x_{\mathrm{F}}, M, c_*) \varepsilon(x_{\mathrm{F}}, M, c_*) \frac{d^3\sigma}{dx_{\mathrm{F}} dM dc_*} \quad (6.6)$$

where C is a normalization constant, R is a "resolution function" that incorporates real detector resolution and parton shower effects, and ε is an efficiency function. The key point is that the linearity of the c_*-odd term in equation 6.5 is not disturbed by the convolution and the linear coefficient $A_{FB}^{(1)}$ is unaffected. The linearity of the problem also allows the fitting function to be represented by a set of nine **parameter-independent** 3D histograms or templates. These histograms can be constructed by appropriate weighting and re-weighting of a large sample fully digitized and reconstructed events from a simulation. The $gg(qg) \to t\bar{t}(X)$ and background distributions $f_{gg}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}})$ and $f^j_{\mathrm{bk}}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}})$ can be extracted directly from fully simulated samples by binning in the reconstructed variables. The various parts of the $q\bar{q}$ distribution can be constructed by re-weighting simulated data using generator-level variables to generate the weights and binning in reconstructed variables.

To illustrate the re-weighting procedure, let's assume that we have a sample of fully simulated and reconstructed $q\bar{q} \to t\bar{t}$ events. For simplicity, let's assume that $\xi, \delta = 0$ in equation 6.5. If the simulation is tree-level, it generates the symmetric cross section [1] given in equation 6.4 and we can create one 3D histogram or template simply by binning the events in the reconstructed variables. We call this symmetric distribution $f_{\mathrm{qs}}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}, Q)$ and normalize it by the total number of events. We can generate the asymmetric distribution by applying the following weight to each simulated event using generator-level quantities,

$$w_{\mathrm{a}}(M^2, c_*) = 2\frac{1+\frac{1}{3}\beta^2+(1-\beta^2)+\alpha(1-\frac{1}{3}\beta^2)}{1+\beta^2c_*^2+(1-\beta^2)+\alpha\left(1-\beta^2c_*^2\right)}c_* \tag{6.7}$$

and then binning the weighted events in the reconstructed quantities to produce the asymmetric distribution $f_{\mathrm{qa}}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}, Q)$ with the same normalization as used for the symmetric distribution. A simple three parameter likelihood fit to the real data would follow from the following four histograms,

$$\begin{aligned} f(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}) = &\sum_j R_{\mathrm{bk}}^j f_{\mathrm{bk}}^j(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}) + \left(1-\sum_j R_{\mathrm{bk}}^j\right)\Big\{(1-R_{q\bar{q}})\, f_{gg}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}) \\ &+ R_{q\bar{q}}\left[f_{\mathrm{qs}}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}) + A_{\mathrm{FB}}^{(1)} f_{\mathrm{qa}}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}})\right]\Big\} \end{aligned} \tag{6.8}$$

[1]Due to the symmetrized weighting described below, NLO simulations generating asymmetric distributions can also be used.

where the background fractions R^j_{bk}, $q\bar{q}$ fraction $R_{q\bar{q}}$, and asymmetry $A^{(1)}_{\mathrm{FB}}$ are allowed to float. Note that the backgrounds can be summed into a single distribution and represented by a single parameter or they can be subdivided into several parts represented by several fraction parameters. This analysis should be done in bins or slices of M_{r} so that it is really a series of 3-parameter fits and extracts $A^{(1)}_{\mathrm{FB}}(M)$. Due to the limited statistics available in the 2012 data, mass binning of the parameters has not yet been implemented. Note that this technique automatically accounts for resolution, dilution, migration, and acceptance effects so long as they are correctly modeled in the simulation.

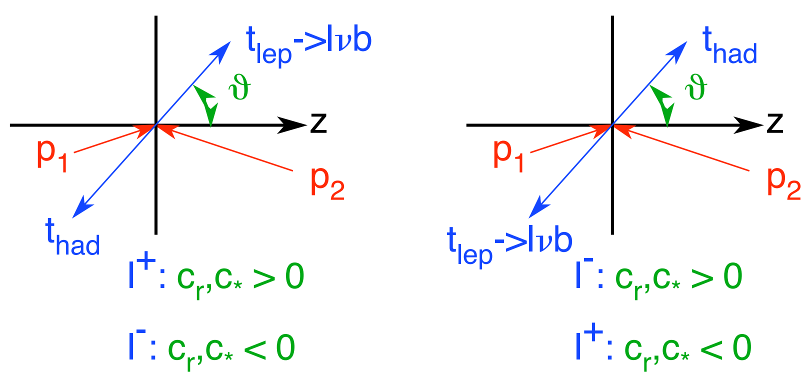


Figure 6.3: The $t\bar{t}$ center-of-mass frame where system is presumed to be boosted in the direction of the proton with momentum vector $\vec{p}_1$ which determines the positive direction using the Collins-Soper definition of the production angle.

The acceptance for the moving $t\bar{t}$ pairs has a small subtlety that can be exploited to help distinguish the signal from the backgrounds. The $t\bar{t}$ center-of-mass frame is shown in Fig. 6.3. The system is presumed to be boosted in the direction of the proton with momentum vector $\vec{p}_1$ and it determines the positive direction using the Collins-Soper definition of the production angle. It is possible that the leptonically decaying t or $\bar{t}$ is produced in the "forward" direction as shown on the left-hand side of the figure. If the leptonic top decays to a positively (negatively) charged lepton, the sign of c_* and c_r are positive (negative). Assuming that the detector locally accepts and reconstructs positive and negative charges with the same efficiency and resolution, the acceptance and resolution for the two cases are the same. Similarly, the leptonically decaying t or $\bar{t}$ can be produced in the "backward" direction as shown on the right-hand side of the figure. Again, the sign of the lepton determines two cases that have the same efficiency and resolution. However, the efficiency and resolution for the left and right cases are not in general the same. A non-zero value of $A_{\mathrm{FB}}^{(1)}$ when combined with the acceptance difference would produce an asymmetry in the number of positively and negatively charged leptons observed in the sample. The approach described above merges the two $c > 0$ and the two $c < 0$ cases to create truly symmetric and antisymmetric functions and cannot describe this effect. It is, however, possible to split the problem by lepton charge instead. This modifies equation 6.8 as follows,

$$
\begin{aligned}
f(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}, Q) = \sum_j R_{\mathrm{bk}}^j f_{\mathrm{bk}}^j(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}) + \left(1 - \sum_j R_{\mathrm{bk}}^j\right) \Big\{ (1 - R_{q\bar{q}})\, f_{gg}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}, Q) \\
+ R_{q\bar{q}} \left[f_{\mathrm{qs}}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}, Q) + A_{\mathrm{FB}}^{(1)} f_{\mathrm{qa}}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}, Q) \right] \Big\} \qquad (6.9)
\end{aligned}
$$

where the functions are built using the lepton charge Q information. Because we desire to symmetrize and anti-symmetrize the $q\bar{q}$ fitting functions, the CP symmetries shown in Fig. 6.3 can be exploited to use each simulated event twice. For each simulated event with lepton charge Q, generated angle c_*, and reconstructed angle c_r, the distribution functions for the coordinate $(x_\mathrm{r}, M_\mathrm{r}, c_\mathrm{r}, Q)$ and $(x_\mathrm{r}, M_\mathrm{r}, -c_\mathrm{r}, -Q)$ can be accumulated where the weights for the latter point assume a generated angle of $-c_*$. The new distributions functions don't have definite symmetry until they are combined over lepton charge Q. Due to the double-weighting, **the charge-summed distribution functions have definite symmetry (or antisymmetry) even if the original unweighted simulation was not $\mathbf{c_*}$-symmetric.** The function f_{gg} describes the distribution of gg and qg events. The gg events are used symmetrically with 0.5 event accumulated in each of the $(c_\mathrm{r}, Q)/(-c_\mathrm{r}, -Q)$ bin pairs. The qg events are not symmetrized so that the final distribution function reflects their expected FB asymmetry. The advantage of this formulation is that it can describe a charge asymmetry arising from the combination of a non-zero $A_\mathrm{FB}^{(1)}$ and an asymmetric acceptance. More importantly, it accommodates the charge-asymmetric background which has significant contributions from W+jet events and single top events. The accepted charge ratios of fully simulated and reconstructed semi-muonic top pair candidates from various signal and background processes are listed in Table 6.2. It is clear that including charge information increases the background discrimination power of the fitting procedure.

Table 6.2: The sample fractions and lepton charge ratios for various signal and background processes from samples of fully simulated and reconstructed Powheg and MadGraph5 semi-muonic events. The samples and selection criteria are described in Sections 4.2-??.

Process	Generator	Sample Fraction	$N(\mu^+)/N(\mu^-)$
$q\bar{q} \to t\bar{t}(\mathrm{j}) \to \mu + 4(5)\mathrm{j}$	Powheg	0.062	1.000±0.014
$gg(qg) \to t\bar{t}(\mathrm{j}) \to \mu + 4(5)\mathrm{j}$	Powheg	0.731	0.998±0.004
$pp \to t\bar{t}(\mathrm{j}) \to$ hadronic/dileptonic	Powheg	0.106	1.018±0.011
$W +$ jets	Madgraph5	0.037	1.408±0.026
single top	Powheg	0.056	1.260±0.019
$Z/\gamma +$ jets	MadGraph5	0.009	1.045±0.039

6.2 Kinematic Reconstruction of t-tbar events

6.2.1 Method

Real and simulated events containing a charged lepton and four or five jets are reconstructed by minimizing a likelihood estimator that is a function of the neutrino longitudinal momentum p^z_ν and five momentum scaling factors λ_j. For each final state particle assignment hypothesis, the 4-vectors of the charged particles are each momentum-scaled,

$$
\begin{aligned}
&\boldsymbol{p_\ell} = (\lambda_1|\vec{p}_\ell|, \lambda_1\vec{p}_\ell) & & \boldsymbol{p_{b\ell}} = \left(\sqrt{m_b^2 + \lambda_2^2|\vec{p}_{b\ell}|^2}, \lambda_2\vec{p}_{b\ell}\right) \\
&\boldsymbol{p_{h1}} = (\lambda_3|\vec{p}_{h1}|, \lambda_3\vec{p}_{h1}) \quad \boldsymbol{p_{h2}} = (\lambda_4|\vec{p}_{h2}|, \lambda_4\vec{p}_{h2}) & & \boldsymbol{p_{bh}} = \left(\sqrt{m_b^2 + \lambda_5^2|\vec{p}_{bh}|^2}, \lambda_5\vec{p}_{bh}\right)
\end{aligned}
\tag{6.10}
$$

and the neutrino is constructed from the missing transverse momentum after scaling

$$
\begin{aligned}
\vec{p}^{\perp}_{\nu} &= -\left[\lambda_1\vec{p}^{\perp}_{\ell} + \lambda_2\vec{p}^{\perp}_{b\ell} + \lambda_3\vec{p}^{\perp}_{h1} + \lambda_4\vec{p}^{\perp}_{h2} + \lambda_5\vec{p}^{\perp}_{bh} + \vec{p}^{\perp}_{\text{recoil}}\right] \\
\boldsymbol{p_\nu} &= \left(\sqrt{(p^z_\nu)^2 + |p^{\perp}_\nu|^2}, \vec{p}^{\perp}\nu, p^z_\nu\right)
\end{aligned}
\tag{6.11}
$$

where $\vec{p}^{\perp}_{\text{recoil}}$ is the total transverse momentum of the event after the removal of the five particles. The six scaled and reconstructed four-vectors are used to calculate the following four invariant masses to be used in the likelihood function,

$$
\begin{aligned}
q^2_W[\ell] &= (\boldsymbol{p_\ell} + \boldsymbol{p_\nu})^2 & q^2_t[\ell] &= (\boldsymbol{p_\ell} + \boldsymbol{p_\nu} + \boldsymbol{p_{b\ell}})^2 \\
q^2_W[h] &= (\boldsymbol{p_{h1}} + \boldsymbol{p_{h2}})^2 & q^2_t[h] &= (\boldsymbol{p_{h1}} + \boldsymbol{p_{h2}} + \boldsymbol{p_{bh}})^2
\end{aligned}
\tag{6.12}
$$

where the invariant masses of the hadronic W boson (top quark) are functions of the parameters $\lambda_3, \lambda_4(, \lambda_5)$ and the invariant masses of the leptonic states depend upon all six parameters. These are combined in a likelihood function that constrains and tests the consistency of the masses with the hypothesis, the consistency of the momentum scaling factors with unity, and the consistency of the b-jet identification with the measured b-tag discriminators d_j,

$$\chi^2 = -2 \sum_{i=\ell,\mathrm{h}} \ln \left\{ \frac{C}{(q_t^2[i] - m_t^2)^2 + m_t^2 \Gamma_t^2} \cdot \frac{(m_t^2 - q_W^2[i])^2 (2m_t^2 + q_W^2[i])}{(q_W^2[i] - m_W^2)^2 + m_W^2 \Gamma_W^2} \right\} + \sum_{j=1}^{5} \frac{(\lambda_j - 1)^2}{\sigma_j^2} \\ - 2 \ln \left\{ g_b(d_{b\ell}) g_b(d_{bh}) g_q(d_{h1}) g_q(d_{h2}) \right\} \tag{6.13}$$

where C is a constant normalization parameter, σ_j is the fractional momentum resolution for particle j (assumed to be 0.1 for jets and 0.03 for muons), $g_b(d)$ are discriminator distribution functions for b-jets from t decays, and $g_q(d)$ is the discriminator distribution function for light quark jets from W decays. In events with an extra jet, a discriminator distribution function $g_{other}(d)$ for jets produced in association with $t\bar{t}$ pairs is also used. These discriminator distribution functions are pictured in Fig. 6.4 to illustrate the distinction they provide.

The minimization procedure is started assuming that all momentum scaling factors are unity, $\lambda_j = 1$. With this assumption, the leptonic W mass constraint has, in general, two solutions for p_ν^z. To avoid local minima, both solutions are used as starting points for the minimization procedure and the resulting fit with the smallest χ^2 is kept. This function was designed to constrain the top masses with simple

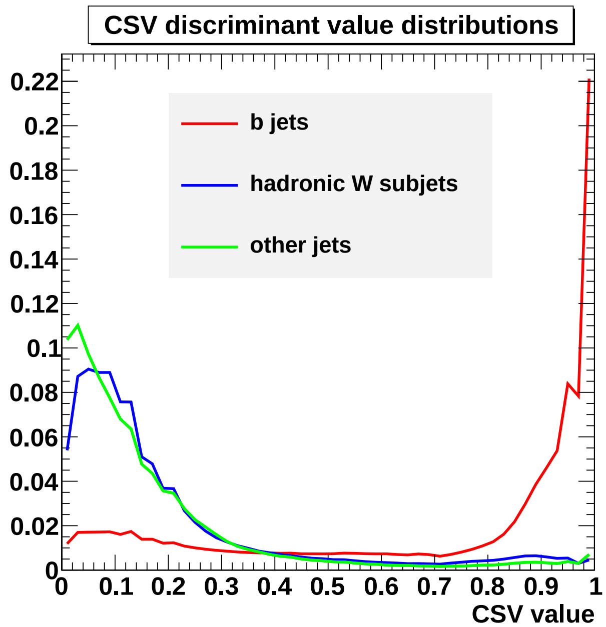


Figure 6.4: The CSV discriminator distribution functions used in the kinematic fit to distinguish b jets [red] from hadronic W subjets [blue] and incidental extra jets [green].

Lorentzian functions that include widths and the W masses to the slightly modified and correlated Lorentzian shapes expected for $t \to Wb$ decays. In actual fact, the presence of the momentum scaling factors allows the best fit masses to converge to m_t and m_W in all cases. In both data and simulation, we use the accepted value of the W mass, $m_W = 80.4$ GeV. We assume $m_t = 172.5$ GeV and $m_t = 173.3$ GeV in simulation and data respectively.

The fitting procedure is performed on all possible jet orderings for each of the topologies used in the analysis and the configuration with the smallest value of χ^2 is retained.

6.2.2 Performance of kinematic reconstruction

Based on the reconstructed top and anti-top momentum, the kinematic observables that are used for the A_{FB} measurement , (x_{r}, M_{r}, c_{r}) can be constructed. The same set of variables can be constructed from the momentum of generated $\mathrm{t\bar{t}}$ pairs, using the generator truth information included in the simulation. To evaluate the performance of the kinematic reconstruction, we compare the distribution of reconstructed kinematic variables with the generated ones, using the full set of simulated $\mathrm{t\bar{t}}$ events. Note that generated x_{F}, M are defined for all $\mathrm{t\bar{t}}$ process regardless of its production mechanism, whereas generated c_* is only well defined for $q\bar{q} \to t\bar{t}$ process. As a result, the comparison of generated and reconstructed c_* is based on $q\bar{q} \to t\bar{t}$ simulated events, while x_{F}, M is based on all semileptonic $\mathrm{t\bar{t}}$ events.

The sensitivity and correctness of A_{FB} measurement in this thesis relies on two performance metrics of kinematic reconstruction. The first metric is the resolution of reconstructed kinematic observables, which can be evaluated by plotting the residual, for example, $c_{\mathrm{r}} - c_*$. A smaller variance of residual indicate a more accurate reconstruction of $\mathrm{t\bar{t}}$ momentums. The second metric is the linearity of reconstructed versus generated observables. This can be checked by either the mean of the residuals, or the 2D plot.

The reconstruction of the kinematic variables works reasonably well. The correlations of the generated variables (x_{F}, M, c_*) and the reconstructed variables (x_{r}, M_{r}, c_{r}) are shown in Fig.6.5. Linear behavior with unit slopes is observed over the range of available statistics. The c_* versus c_r also shows evidence of quark direction sign error as expected from Fig. 6.2(d).

We also further check the effectiveness of top quark pairs reconstruction by plotting the residual of x_F, $M_{t\bar{t}}$, c_*, shown in Fig.6.6

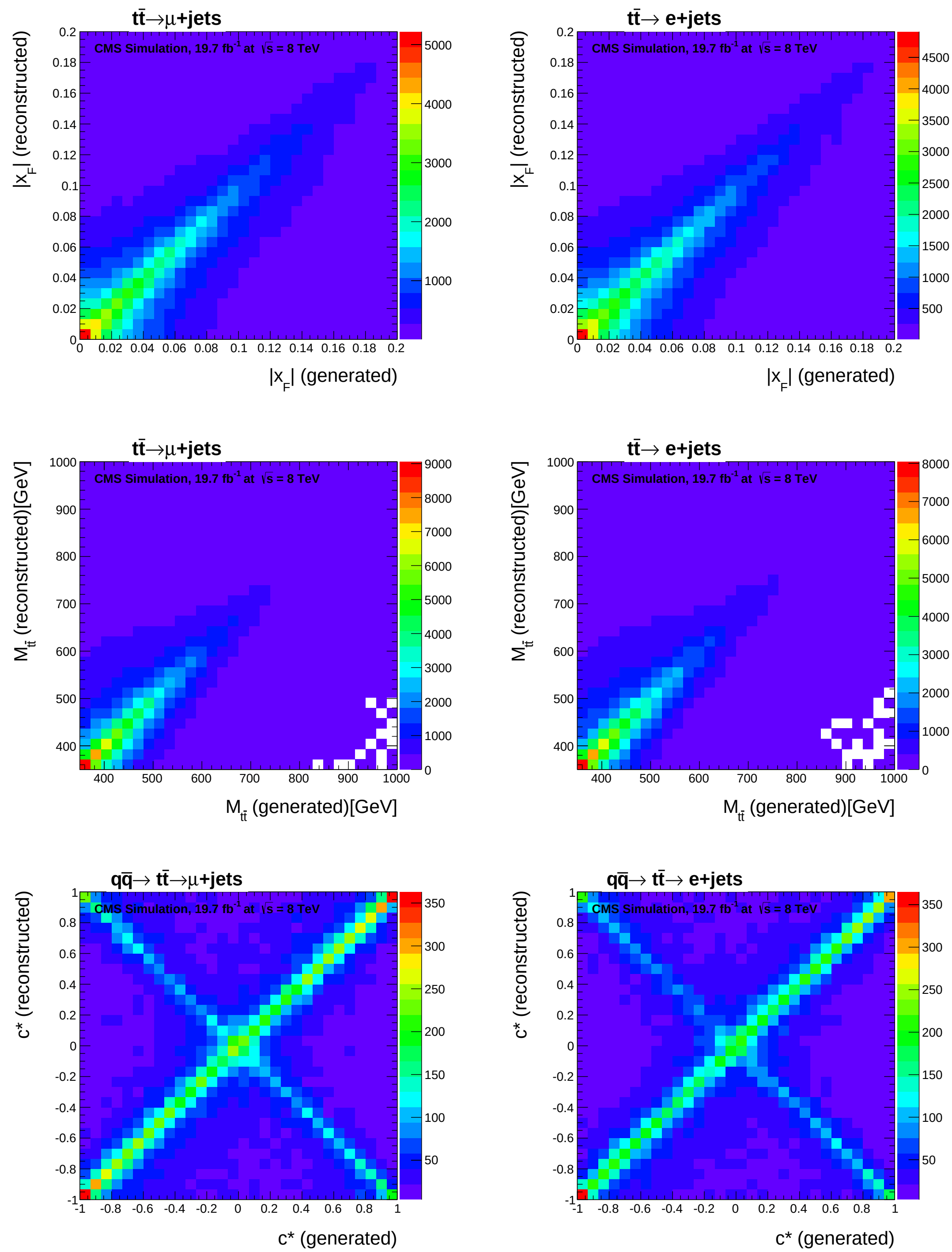


Figure 6.5: The correlations of the generated/reconstructed variable pairs x_F/x_r , M/M_r and c_*/c_r for a sample of simulated $t\bar{t}$ events. The figures at the left are from μ+jets channel, at right are e+jets channel.

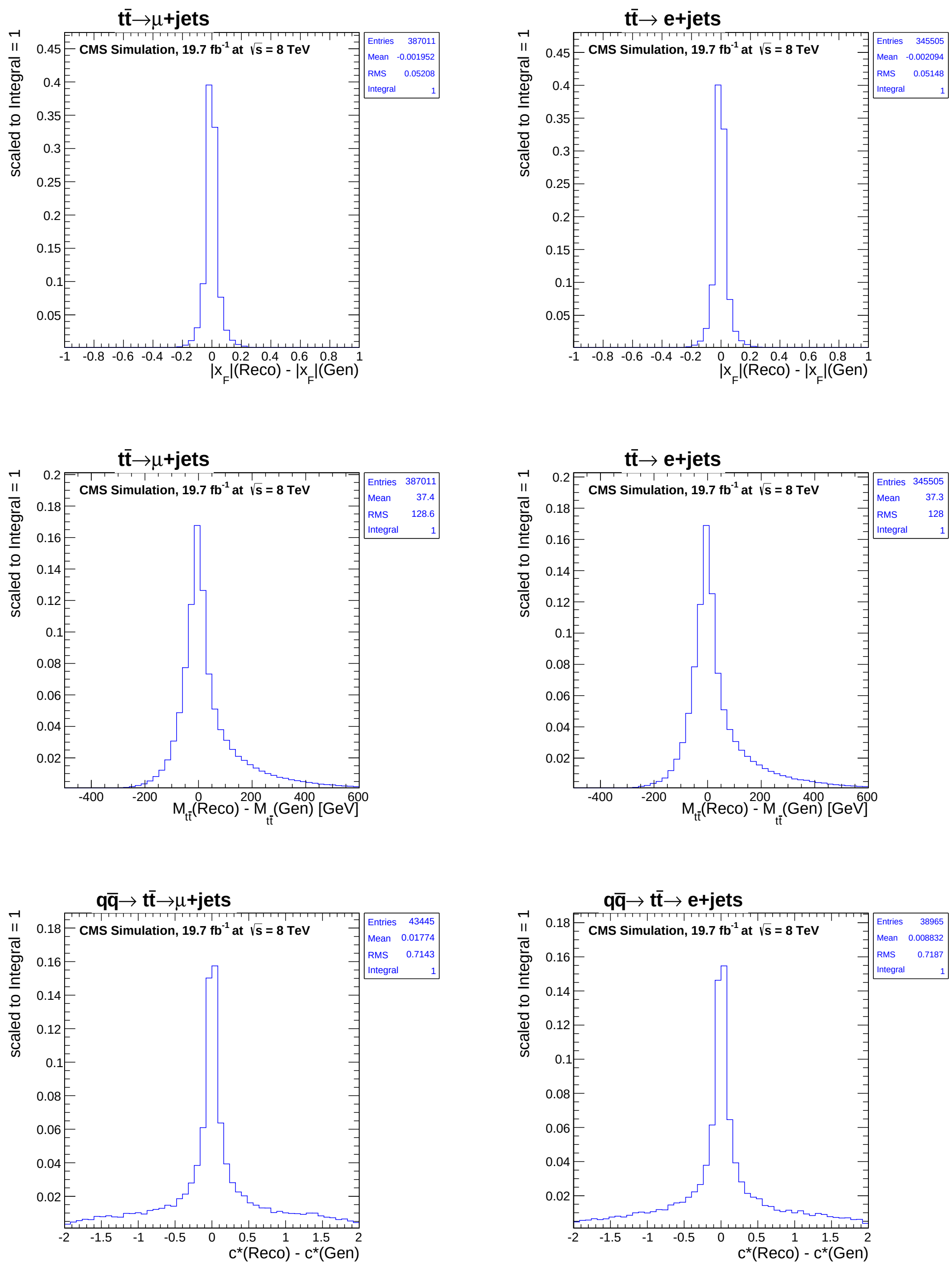


Figure 6.6: The residual of the generated/reconstructed variable pairs x_F/x_{r} , M/M_{r} and c_*/c_{r} for a sample of simulated $t\bar{t}$ events. The figures at the left are from μ+jets channel, at right are e+jets channel.

6.3 Template Fitter

The main goal for this analysis is to simultaneously measure Forward-backward asymmetry (A_{FB}) and fraction of $q\bar{q}$ initiated $t\bar{t}$ events, $R_{q\bar{q}}$. We perform the parameter estimation by doing binned maximal likelihood fit using the 3 dimensional templates as described in Eq.[6.8].

6.3.1 Overview of Fitting Procedure

Here we give a general overview of the theoretical set up of fitter that we use.

6.3.2 THETA Package

We use THETA Package for template fit.[cite] The main idea is assume data event rates follow Poisson distribution for every bin in the phase space spanned by $cos_{\theta}*, M_{t\bar{t}}$ and $|x_F|$. The statistical model is then a product of independent Poisson distributions:

$$p(\boldsymbol{n}^{Data}|\boldsymbol{\theta}) = \prod_i Poisson(n_i^{Data}|\lambda_i(\boldsymbol{\theta})) \tag{6.14}$$

where $\boldsymbol{n}^{Data} = (n_1, n_2, ..., n_i)$ represent the number of events in each bin. λ_i is the expected number of events in bin i, which is given by the sum of signal and background events in that bin:

$$\lambda_i(\boldsymbol{\theta}) = n(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}|\boldsymbol{\theta}) = \sum_j n^j_{\mathrm{bk}}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}|\boldsymbol{\theta}) + n_{gg}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}|\boldsymbol{\theta}) + n_{\mathrm{q\bar{q}}}(x_{\mathrm{r}}, M_{\mathrm{r}}, c_{\mathrm{r}}|\boldsymbol{\theta}) \tag{6.15}$$

Here $\boldsymbol{\theta}$ represents all parameters, including the parameters of interest and nuisance parameters. There are two types of nuisance parameters in the fit. First type is the one that controls relative compositions of individual background processes, including R_{WJets},R_{other} and R_{QCD}, which are defined in Equation. 6.9. The second type of nuisance parameters are introduced for evaluation of systematic uncertainties, summarized in Section. 6.5

We measure parameters of interest together with nuisance parameters by maximizing total likelihood given data distributions. In Formula. 6.16 expected number of events for bin i is the sum of signal and background templates (histograms). Depend on the choice of $\boldsymbol{\theta}$ the templates have different shapes and normalization. The way the templates change is modeled by template morphing. For every parameter, for instance A_{FB}, three versions of templates are provided, corresponding to $A_{FB} = -1, 0, +1$. Note for this parameter, A_{FB} templates are only provided for $n_{q\bar{q}}$ as it is the only process that depend on A_{FB} in our model. Then during the fit, for each value of A_{FB}, the corresponding likelihood which is a function of A_{FB} is calculated given expected number of events for every bin. For simplicity, let's focus on the i'th bin, denote as $n_{q\bar{q}}(A_{FB})$. This number is derived from interpolation of three set of numbers for the same bin, $n_{q\bar{q}}(A_{FB} = -1, 0, +1)$. In Theta, the interpolation is cubic for $|\theta| < 1$ and linear for $|\theta| > 1$.

There is another way to model the change of expected number of events by introducing a parameter representing event rate. In our case, we introduce a nuisance parameter c_{lumi} for the integrated luminosity. This parameter models the global normalization for all processes. Now the expected number of events for every bin looks like this:

$$\lambda_i(\theta) = n(x_\mathrm{r}, M_\mathrm{r}, c_\mathrm{r}|\theta) = c_{lumi}\left[\sum_j n_{\mathrm{bkg_j}}(x_\mathrm{r}, M_\mathrm{r}, c_\mathrm{r}|\theta) + n_{gg}(x_\mathrm{r}, M_\mathrm{r}, c_\mathrm{r}|\theta) + n_{\mathrm{q\bar{q}}}(x_\mathrm{r}, M_\mathrm{r}, c_\mathrm{r}|\theta)\right] \tag{6.16}$$

Finally, the likelihood also include the proper prior distribution for all parameters. Denote the prior distribution for parameter θ_j to be $\pi(\theta_j)$, the likelihood given data distribution become:

$$L(\boldsymbol{n}^{Data}|\boldsymbol{\theta}) = \prod_i Poisson(n_i^{Data}|\lambda_i(\boldsymbol{\theta}))\prod_j \pi(\theta_j) \tag{6.17}$$

And the measured parameter values $\hat{\boldsymbol{\theta}}$ is taken as the maximal likelihood estimator.

$$\hat{\boldsymbol{\theta}} = argmax_{\boldsymbol{\theta}} L(\boldsymbol{n}^{Data}|\boldsymbol{\theta}) \tag{6.18}$$

In practice we choose to minimize the negative log-likelihood (NLL) below:

$$NLL(\boldsymbol{n}^{Data}|\boldsymbol{\theta}) = -\left[\sum_i Poisson(n_i^{Data}|\lambda_i(\boldsymbol{\theta}) + \sum_j \pi(\theta_j)\right] \tag{6.19}$$

6.3.3 Template binning

Since we perform a binned likelihood fit based on 3 dimensional templates, we studied the optimal binning for our templates. On one hand we chose the binning such that every bin has sufficient number of events, on the other hand there are more bins in regions of phase space where signal and background distributions are more statistically distinguishable.

In addition we choose to limit the phase space of events in the region where $M_{t\bar{t}} < 980\,GeV$ for two reasons. First reason is the MC templates beyond this kinematic region have much fewer events passed all selections, resulting a poor modeling of expected data distributions. Second reason is events with $M_{t\bar{t}} > 980\,GeV$ tend to be boosted, causing decay products of top/anti-top quarks, especially hadronic decay side, to be merged into fewer jets. Because our kinematic re-construction algorithm assumed fully resolved event topology, this causes a poorly reconstructed $t/\bar{t}$ momentum.

In the end, the templates are constructed from un-binned simulated events with the following binning:

- $c*$: [-1.0,1.0], every 0.1
- $M_{t\bar{t}}$: [350,980], every 30 GeV
- $|x_F|$: [0,0.02,0.04,0.06,0.08,0.1,0.12,0.14,0.16,0.18,0.2,0.22,0.26,0.3,0.6]

The Fig.[6.7] and Fig.[6.8] shows the projections of templates in all three dimensions for signal and background processes. The clear distinction of various process can be seen which suggest the potential statistical power of the template fit.

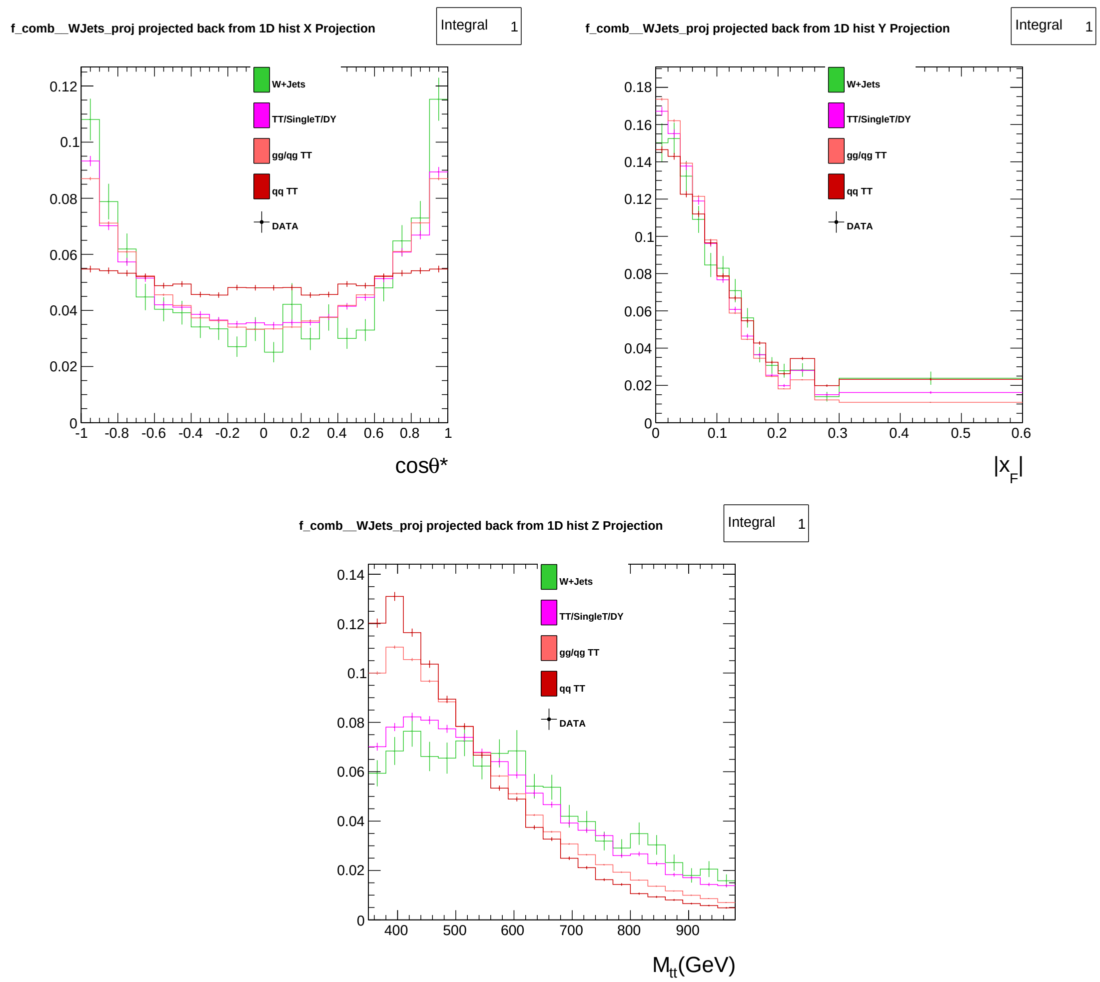


Figure 6.7: The profile of templates of all processes projected to each of the three dimensions for $\mu + jets$ channel.

Although the original templates are 3 dimensional so all three kinematic variables are fully correlated, we unrolled the templates into 1 dimension with arbitrary order of bins so we can use Theta to do the template fit for us. The Fig.[6.9] shows the unrolled 1D distribution for the combined simulated events for $\mu + jets$ with $Q > 0$ for illustration purpose. Note this 1-D template is the one that actually feed into template fit, and the number of events in each bin corresponds to λ_i in Eq.[6.17], which is the expected number of observations.

6.3.4 Template building

The key ingredients in the template fit method is to produce up and down templates, which are histograms that contains information about expected number of events in every bin, corresponding to θ_j^{up} and θ_j^{down}. Together with nominal templates, $\lambda_i(\theta)$ can be inferred by interpolating from these three sets of templates.

In order to build templates that is consistent with the fitting framework described above, we reformulate our statistical model from probability distribution to the distribution of expected number of events. So we change Eq. [6.9] to the following:

$$F(\boldsymbol{x}; Q|\boldsymbol{\theta}) = \sum_j F_{bkg_j}(\boldsymbol{x}; Q|\boldsymbol{\theta}) + F_{gg}(\boldsymbol{x}; Q|\boldsymbol{\theta}) + F_{q\bar{q}}(\boldsymbol{x}; Q|\boldsymbol{\theta}) \tag{6.20}$$

Here $\boldsymbol{x} = (|x_F|, M_{t\bar{t}}, c*)$ is the triple of reconstructed kinematic variables of top quark, Q is the charge of the lepton in the event as we fit $Q = \pm 1$ events separately. All $F(\boldsymbol{x}; Q|\boldsymbol{\theta})$ are from fully selected and reconstructed events from MC simulation (except for data driven templates) and are normalized to the same integrated luminosity as Data.

So here we list all relevant information about producing up/down templates for all parameters. We start from our parameters of interest, A_{FB} and $R_{q\bar{q}}$. For A_{FB}, based on Eq.[4,ref], we build our templates from $q\bar{q} \to t\bar{t}$ templates by first symmetrize over production angle $c*$ and then re-weight based on the value of A_{FB}.

$$F_{q\bar{q}}(\boldsymbol{x}; Q|A_{FB}) = F_{qs}(\boldsymbol{x}; Q) + A_{FB} F_{qa}(\boldsymbol{x}; Q) \tag{6.21}$$

Where F_{qs} is the symmetrized $q\bar{q}$ templates which is produced from the original $q\bar{q}$ MC templates, $F_{q\bar{q}}$, following the description of Section. 6.1.2

$$F_{qs}(|x_F|, M_{t\bar{t}}, c*; Q) = \frac{1}{2}\left[F_{q\bar{q}}(|x_F|, M_{t\bar{t}}, c_*; Q) + F_{q\bar{q}}(|x_F|, M_{t\bar{t}}, -c_*; -Q)\right] \tag{6.22}$$

In Fig.6.10 we show the $F_{q\bar{q}}(c^*|A_{FB})$ templates corresponding to $A_{FB} = -1.0, 0, +1.0$ for both channels.

Note here F_{gg} is the template consist of both $gg \to t\bar{t}$ and non-gg initiated $t\bar{t}$ events. The gg initiated events are symmetric in c_*, by performing the same procedure that is applied to build $F_{q\bar{q}}$. In comparison, non-gg initiated part of F_{gg} is not symmetrized in order to preserve the intrinsic forward-backward asymmetry in qg initiated $t\bar{t}$ events. This guarantees the A_{FB} fit from data only reflects the asymmetry in $q\bar{q} \to t\bar{t}$ process, as desired.

Next, we produce the up/down templates representing the relative abundance of $q\bar{q} \to t\bar{t}$ in all signal $t\bar{t}$ events, denote as $R_{q\bar{q}}$ in Eq.[6.9]. Per the design of Theta Framework, instead of using $R_{q\bar{q}}$ as parameter directly, we introduced a different parameter, $SF_{q\bar{q}}$ which is a scale factor on the normalization of $q\bar{q}$ templates. The nominal value of $SF_{q\bar{q}} = 1$. We then have templates of $F_{q\bar{q}}$ and F_{gg} as follows:

$$F_{q\bar{q}}(\boldsymbol{x}; Q|SF_{q\bar{q}}) = SF_{q\bar{q}} * F_{qs}(\boldsymbol{x}; Q) \tag{6.23}$$

$$F_{gg}(\boldsymbol{x}; Q|SF_{q\bar{q}}) = \frac{N_{t\bar{t}} - SF_{q\bar{q}} N_{q\bar{q}}}{N_{t\bar{t}} - N_{q\bar{q}}} F_{gg}(\boldsymbol{x}; Q) \tag{6.24}$$

Where $N_{t\bar{t}}$ and $N_{q\bar{q}}$ are nominal number of events in signal $t\bar{t}$ process and gg process. The above equations implicitly constrain $N_{t\bar{t}}$ to be a constant for any value of $SF_{q\bar{q}}$, which is implied in the original formalism of our statistical model in Eq.[6.9]. Note here in Eq.[6.23] we scale symmetric $q\bar{q}$ templates rather than the one with non-zero A_{FB} as in Eq.[6.21] to get the up/down templates for $SF_{q\bar{q}}$. This because we want to model the change of distribution shape and normalization due to A_{FB} and $SF_{q\bar{q}}$ separately, although they are correlated in predicting the expected number of events for every bin.

In addition, we note here $F_{q\bar{q}}$ and F_{gg} are the only templates depend on $SF_{q\bar{q}}$, and it has no effect on F_{bkg}. $SF_{q\bar{q}}$ is directly measured from the fitting, and $R_{q\bar{q}}$ is related to $SF_{q\bar{q}}$ via the following equation:

$$R_{q\bar{q}} = SF_{q\bar{q}} \, R^0_{q\bar{q}} = \frac{N^{fit}_{q\bar{q}}}{N^{fit}_{t\bar{t}}} \tag{6.25}$$

In our analysis we use the post-fit counts, $N^{fit}_{q\bar{q}}$ and $N^{fit}_{t\bar{t}}$ to calculate the fit $R_{q\bar{q}}$.

Similarly, we introduce a scale factor for each background process, SF_{bkg_j} that corresponds to R_{bkg_j} defined in Eq.[6.9]. The corresponding templates are defined as follows:

$$F_{bkg_j}(\boldsymbol{x}; Q|SF_{bkg}) = SF_{bkg_j} \, F_{bkg_j}(\boldsymbol{x}; Q) \tag{6.26}$$

$$F_{gg}(\boldsymbol{x};Q|SF_{bkg_j}) = \frac{N_{t\bar{t}} - (SF_{bkg_j} - 1)\, N_{bkg_j}}{N_{t\bar{t}}}\, F_{gg}(\boldsymbol{x};Q) \tag{6.27}$$

$$F_{q\bar{q}}(\boldsymbol{x};Q|SF_{bkg_j}) = \frac{N_{t\bar{t}} - (SF_{bkg_j} - 1)\, N_{bkg_j}}{N_{t\bar{t}}}\, F_{q\bar{q}}(\boldsymbol{x};Q) \tag{6.28}$$

From now on, we will use R_{bkg_j} exclusively, instead of usng SF_{bkg_j}, for simplicity and consistency with the original formalism of our model described in Section.[6.1.2].

Finally, the up/down templates associated with systematic uncertainties are produced by applying alternative re-weighting factors $w_{\pm}$ on MC templates, which correspond to $\pm 1\sigma$ variation from nominal templates.

In Fig.6.12 we show $F_{gg}(\boldsymbol{x}|SF_{other\_bkg})$ and $F_{other\_bkg}(\boldsymbol{x}|SF_{other\_bkg})$ templates for μ+jets channel with $SF_{other\_bkg} = 0.2, 1.0, 1.8$, in three projected directions of templates. It shows for the "up" templates, that is $SF_{other\_bkg} = 1.8$ (the normalization of *other_bkg* process being 1.8 times the nominal value), the total events of gg/qg process become fewer than its nominal value, while *other_bkg* template is scaled up by 1.8 times, as we expected.

6.3.5 Lepton channel combination

In this analysis, we divide observed data into four parts (in Theta, they are called "Observable"), depending on lepton type of final states (e or μ) and type of lepton charge type (positive or negative), and fit each of the four parts individually.

However, in our model, the parameters A_{FB} and $R_{q\bar{q}}$ are independent with final states. As a result, we perform the simultaneous template fit in Theta to find the best A_{FB} and $R_{q\bar{q}}$ that fit the data.

The basic idea of combined fit is very simple. Instead of minimizing negative log likelihood as defined in Eq.[6.19] for all four observable, we minimize the sum of the NLL, as defined below:

$$NLL_{total}(\boldsymbol{n}^{Data}) = \sum_{Q=\pm 1} NLL(\boldsymbol{n}^{Data}; e, Q|A_{FB}, R_{q\bar{q}}, \boldsymbol{\theta}_e) + \sum_{Q=\pm 1} NLL(\boldsymbol{n}^{Data}; \mu, Q|A_{FB}, R_{q\bar{q}}, \boldsymbol{\theta}_\mu) \tag{6.29}$$

Note that fit takes into the correlations of all four observable via template morphing. We build the up/down templates for each parameter θ_i that reflect the proper correlation. For example, change in A_{FB} will and only will affect the distribution of $q\bar{q} \rightarrow t\bar{t}$ process for all four both $e + jets$ and $\mu + jets$ final states. It will not affect distributions of any other processes. The correlation between $e\mu$ channels can be seen from Fig.[6.10].

Unlike the common parameter A_{FB} and $R_{q\bar{q}}$, we model the normalization of background processes , such as R_{WJets}, R_{other_bkg} and R_{QCD}, separately for $e + jets$ and $mu + jets$ channels. So we introduce two nuisance parameters for each type of background process, one for $e + jets$ channel, another for $\mu + jets$ channel. For instance, we introduce R_{WJets_el} and R_{WJets_μ} and build two sets of un-correlated templates, as shown in Fig.[??]

A final note is on the set of templates for same lepton type, but different charge type , such as $F_{q\bar{q}}(\boldsymbol{x}; e, Q > 0|A_{FB})$ and $F_{q\bar{q}}(\boldsymbol{x}; e, Q < 0|A_{FB})$. We assume they are always correlated. Therefore most of the templates we show are charge summed for visualization purpose, while in template fit the charge separated templates are used for calculating likelihood.

A complete list of figures for templates that are used for the fitting is provided in Appendix.[**??**]. More details of all parameters are listed in Table.[6.3]

6.3.6 Priors

As described in Section.[6.3.2] the likelihood also include the prior distribution for each parameter. In addition, since the template morphine is based on interpolation of up/down/nominal templates, we also need to keep track of the choice of up/down templates corresponding to each parameters. We summarize these information in Table.[6.3]

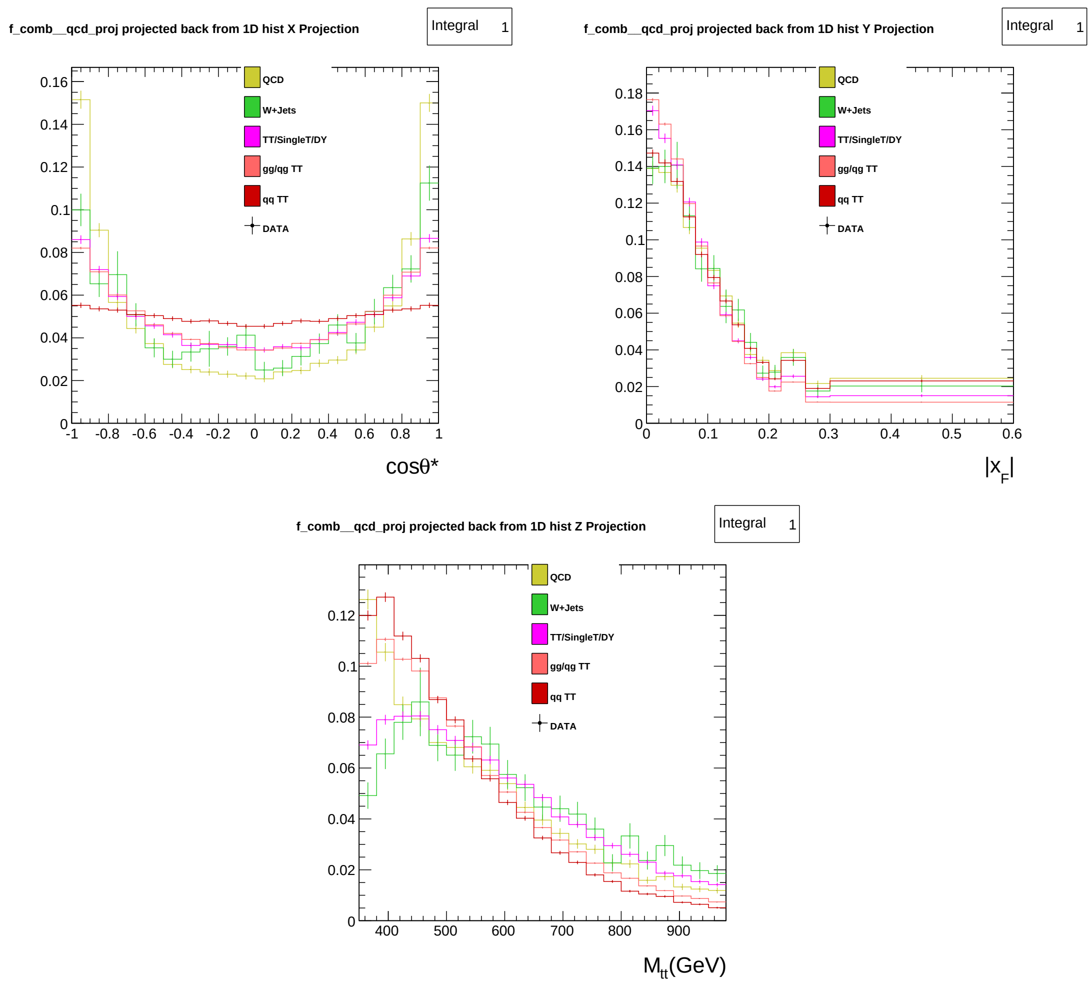


Figure 6.8: The profile of templates of all processes projected to each of the three dimensions for $e + jets$ channel.

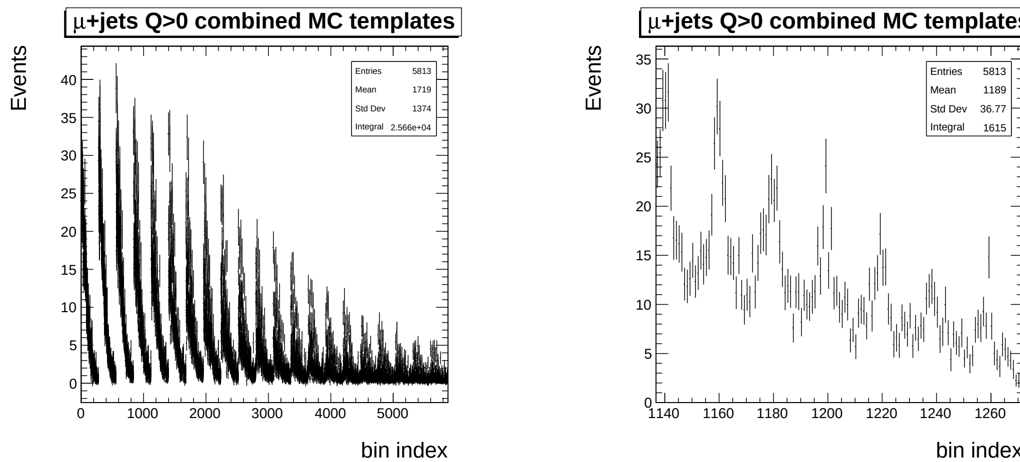


Figure 6.9: The unrolled 1D distribution of all simulated process combined together according to their cross sections and normalized to the same integrated luminosity as collected data. Showing $\mu + jets$ with $Q > 0$ only for simplicity. Left:entire distribution. Right: a zoom in of the figure in the left

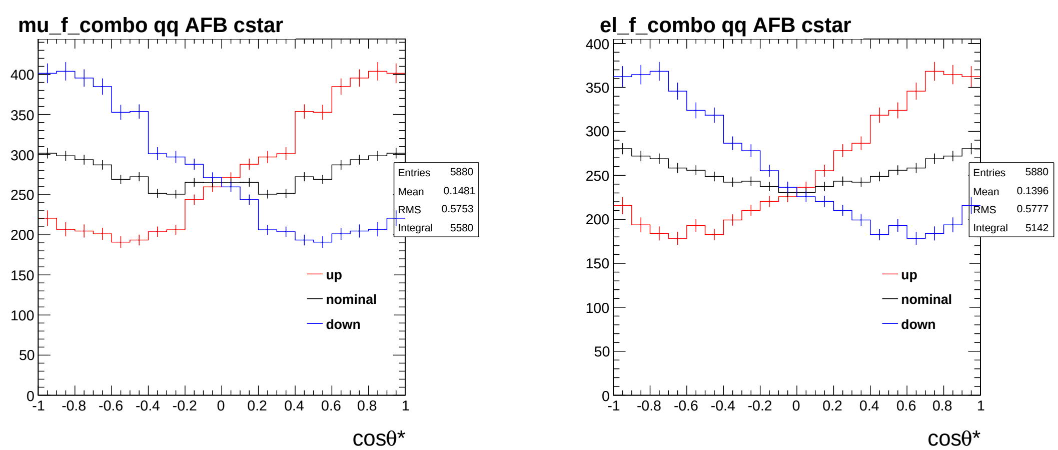


Figure 6.10: The distribution of MC simulated $q\bar{q} \to t\bar{t}$ events with A_{FB}= -1.0 (blue), 0 (black) and +1.0 (red), for $\mu + jets$(left) and $e + jets$(right)

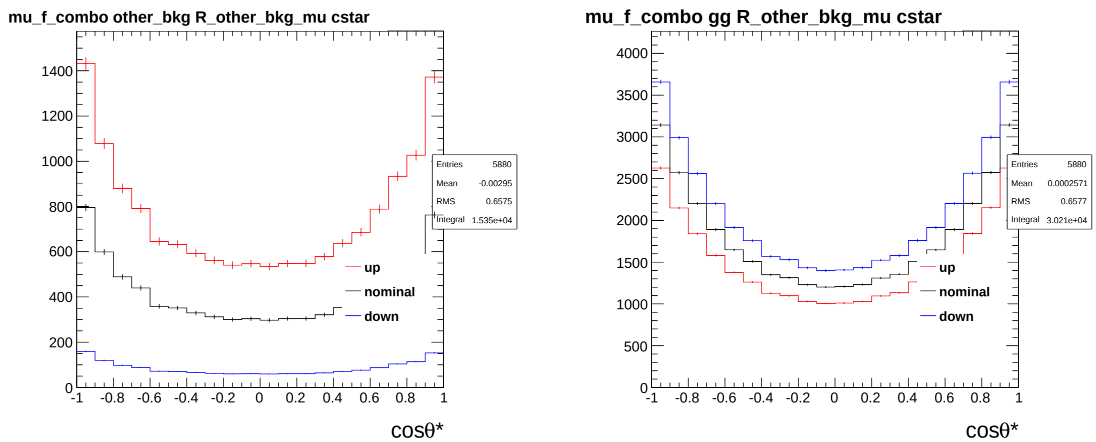


Figure 6.11: The $c*$ projection of F_{gg} (left) and F_{other_bkg} (right) templates with $SF_{other\_bkg} = 0.2$ (blue), 1.0 (black) and 1.8 (red)

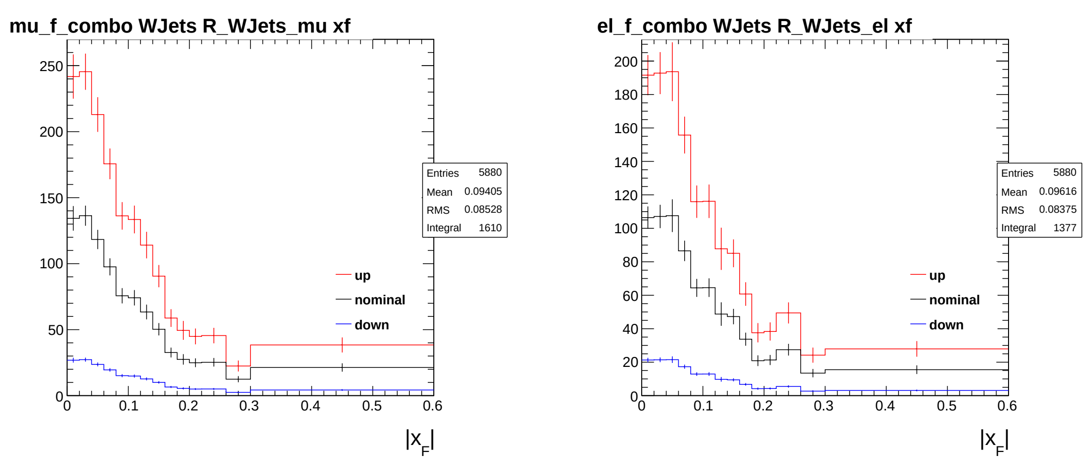


Figure 6.12: The $|x_F|$ projection of $F_{WJets}(\boldsymbol{x}; e|R_{WJets\_el})$ (left) and $F_{WJets}(\boldsymbol{x}; \mu|R_{WJets\_\mu})$ (right) templates with $R_{WJets\_el}/R_{WJets\_\mu} = 0.2$ (blue), 1.0 (black) and 1.8 (red)

Parameter	Template Type	Prior	down	central	up	channel
A_{FB}	shape	flat	-1.0	0.0	1.0	both
$R_{q\bar{q}}$	shape	flat	0.2	1.0	1.8	both
R_{WJets_μ}	shape	flat	0.2	1.0	1.8	μ+jets
R_{other_μ}	shape	flat	0.2	1.0	1.8	μ+jets
R_{WJets_e}	shape	flat	0.2	1.0	1.8	e+jets
R_{other_e}	shape	flat	0.2	1.0	1.8	e+jets
R_{QCD_e}	rate	log-normal	0.8	1.0	1.2	e+jets
Lumi	rate	log-normal	-0.045	0.0	0.045	both
Systematics	shape	Gauss	-1σ	0.0	1σ	depends

Table 6.3: Type and prior for all parameters. Flat prior means uniform prior distribution. Gauss prior means the prior distribution is a Normal distribution with $\mu = 0$,$\sigma = 1$. For nuisance parameters associated with shape based systematic uncertainties, we assume the up/down templates correspond to 1σ away from nominal values in the prior distributions. The up/down value for $R_process$ is relative to the nominal value. The corresponding templates are produced according to Eq. 6.23 and 6.26

6.4 Sensitivity Studies

6.4.1 Gluon Polarization Study

To tune the event weighting to use the Powheg and MagGraph samples listed in Table 4.3, generator-level $q\bar{q} \to t\bar{t}(j)$ events are fit to a distribution function derived from equation 6.4,

$$f_{\text{gen}}(\alpha; M, c_*) = \frac{1 + \beta^2 c_*^2 + (1 - \beta^2) + \alpha\,(1 - \beta^2 c_*^2)}{2\left[2 - \frac{2}{3}\beta^2 + \alpha\left(1 - \frac{1}{3}\beta^2\right)\right]}. \tag{6.30}$$

to determine best values for α. The Powheg fit yields the surprising value $\alpha = -0.129 \pm 0.010$ indicating that Powheg generates $q\bar{q} \to t\bar{t}$ events with a steeper-than-tree-level angular distribution. The presence of real longitudinal gluon polarization would manifest itself as a positive value for α. Note that the effect of positive or negative α is accounted in the definition of $A_{FB}^{(1)}$. The goodness of fit can be demonstrated by applying the weight f_{gen}^{-1} to each event and plotting the resulting $|c_*|$ distributions for $\alpha = 0$ and $\alpha = -0.129$ as shown in Fig. 6.13(a-b). The $\alpha = 0$ "unweighting" shows a monotonic increase of about 8% from smallest to large $|c_*|$ bin suggesting that the generated events are more strongly peaked at large $|c_*|$ than naive tree-level expectations. Using $\alpha = -0.130$ removes the effect and leads to a maximum bin to bin variation of 1.7%. To test this further, the procedure is repeated by dividing the sample into 0-(extra)jet and 1-jet subsamples. The effect of "negative gluon polarization" is seen more strongly in the 0-jet sample with a best fit of $\alpha = -0.256 \pm 0.011$

as shown in Fig. 6.13(c-d). In the 1-jet sample, the presence of real longitudinal gluon polarization increases the best fit to $\alpha = 0.143 \pm 0.019$ and is shown in Fig. 6.13(e-f). The same procedure is performed on a sample of $q\bar{q} \to t\bar{t}(j, jj, jjj)$ events generated by MadGraph5. A similar pattern is observed but the results, summarized in Table 6.4, are not identical. The Powheg and MadGraph5 predictions for the forward-backward asymmetry are also listed in Table 6.4. It is clear that the virtual NLO corrections contained in Powheg but not MadGraph5 are large and important.

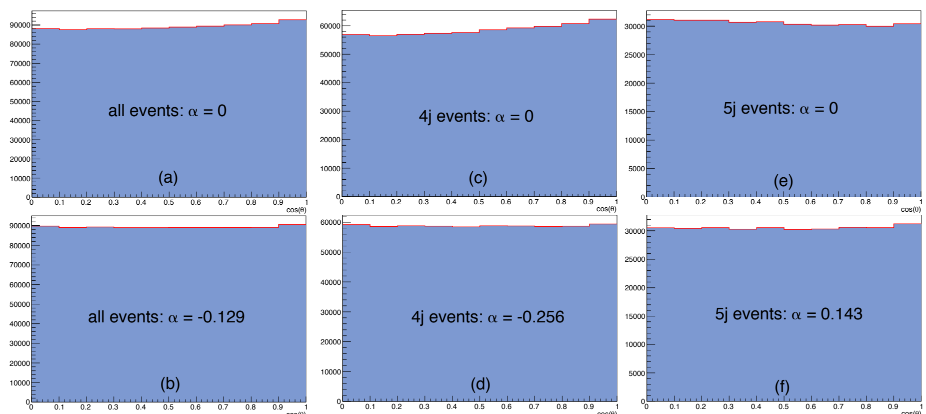


Figure 6.13: The "unweighted" $|c_*|$ distributions (events weighted by f_{gen}^{-1}) distributions of Powheg $q\bar{q} \to t\bar{t}(j)$ events for longitudinal gluon polarizations $\alpha = 0$ [(a), (c), (e)] and best fit values [(b), (d), (f)]. The distributions are shown for samples containing: all events (a-b), 0 extra jets (c-d), and 1 extra jet (e-f).

We can also fit for α as a parameter that dependent on $t\bar{t}$ invariant mass.[29] This allows for a more accurate description of the gluon longitudinal polarization based on the NLO MC simulation. We performed a binned likelihood fit of $c*$ distribution for

Table 6.4: The best fit values for the longitudinal gluon polarization α for samples of Powheg(hvq) and MadGraph5 events. The Powheg full NLO and MadGraph5 partial NLO expectations for the t-quark forward-backward asymmetry, the residual forward-backward asymmetry of the "gluon-gluon" sample from $q(\bar{q})$-g initial states, and the accepted $q\bar{q}$ event fractions are also listed. Note that the "gg" asymmetries are smaller than the $q\bar{q}$ asymmetries by an order of magnitude.

	Powheg(hvq)				MadGraph5		
Sample	α	A_{FB}	A_{FB}^{gg}	$R_{q\bar{q}}$	α	A_{FB}	A_{FB}^{gg}
All evts	−0.129(10)	+0.0356(15)	+0.0058(11)	0.066	−0.173(7)	−0.0283(27)	−0.0026(1

simulated $q\bar{q} \to t\bar{t}$ events before any selection is applied. We divide simulated events by the range of β, and fit these events to get β dependent α values. We then use the α acquired this way to make the asymmetric templates f_{qa} as described in Eq.[6.8].

The fit distribution and comparison to NLO MC simulated distributions are shown in Fig.[6.14]. All the simulations are generated with proton-proton $\sqrt{s} = 13$ TeV in the figures.

6.4.2 Closure Test

The statistical power of the technique was investigated by simulating and fitting 2000 pseudo experiments of similar number of events in Data. We scan over a range

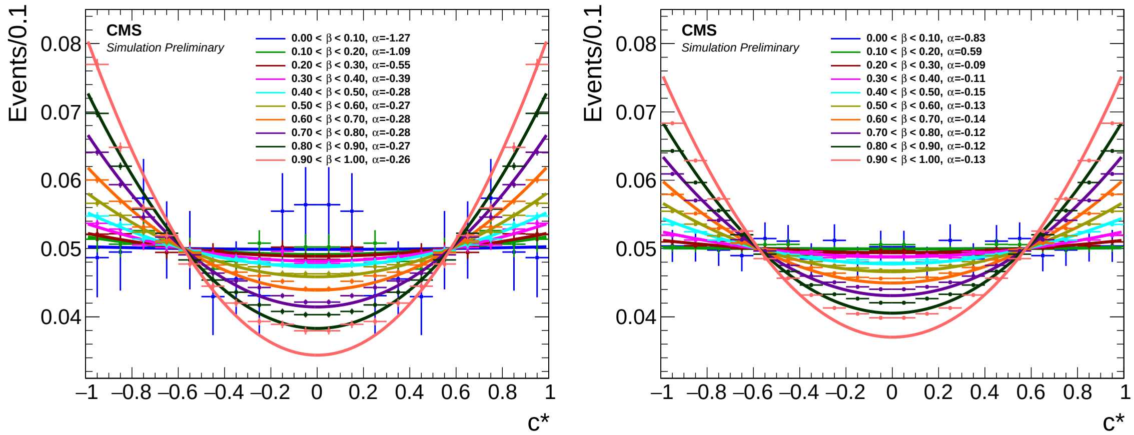


Figure 6.14: Fit comparison of $c*$ for simulated $q\bar{q} \rightarrow t\bar{t}$ events generated by aMC@NLO (left) and Powheg (right) generators.The best fit values for α are shown in the legend. Simulation distribution is shown as cross, while best fit distribution is shown as solid lines.

of values of A_{FB} and $R_{q\bar{q}}$, for every parameter value we generate 2000 pseudo experiments based on the statistical model described in Eq.6.16, then fit the pseudo experiment with the same templates that generate pseudo-data. We than estimate the mean and spread of the fit results of all experiment by fitting with a Gaussian distribution.

From the mean and standard deviation of fit value corresponding to every input value of parameters, we construct a Neyman band, which we use to extrapolate the confidence interval given the fit value of parameters from Data fit. We take the half of 68% confidence interval as the statistical uncertainty of the template fit, which is indicated as dashed red lines in Fig.[6.15], The estimated statistical uncertainties are listed below:

- $\sigma_{A_{FB}} = 0.50$

- $\sigma_{R_{q\bar{q}}} = 0.006$

An example distribution of pseudo experiments fit results for A_{FB} and $R_{q\bar{q}}$ is shown in Fig.[6.16]. The Neyman construction is shown in Fig.[6.15]. From these plots we find the template fit has very small bias and the confidence interval extrapolated this way is close to the statistical uncertainty we get from THETA.

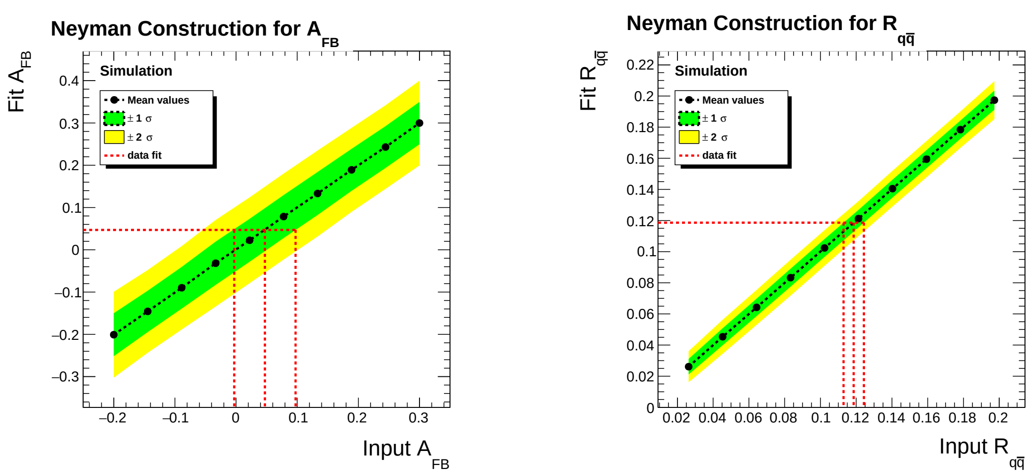


Figure 6.15: Neyman construction for A_{FB}(left) and $R_{q\bar{q}}$ (right). The dashed red line indicate the extrapolated fit result and the $\pm 1\sigma$ value given the measured value.

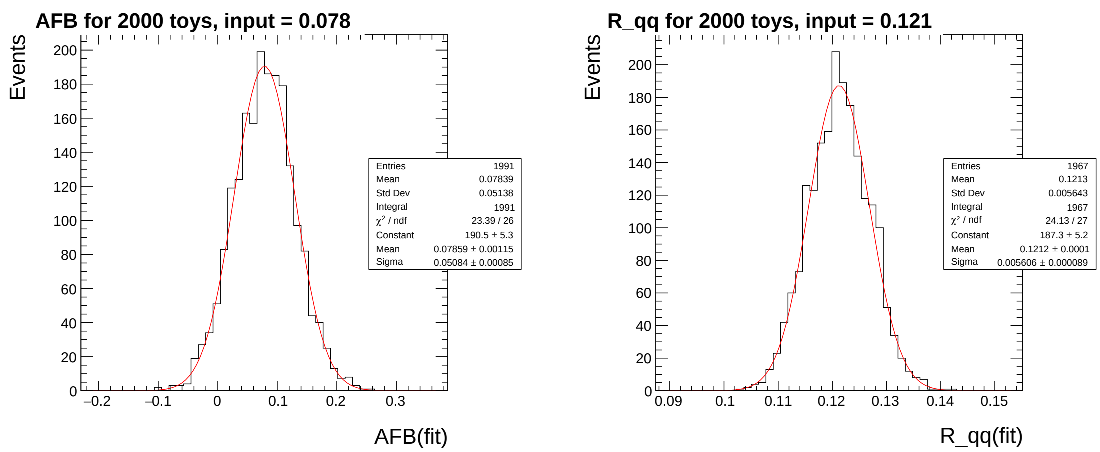


Figure 6.16: Fit parameter distribution of 2000 pseudo experiments for A_{FB}(left) and $R_{q\bar{q}}$ (right).

6.5 Corrections and Systematic Uncertainties

The CMSSW simulation does not account for a number of known detector and experimental effects. Standard CMS correction factors are applied to the simulated events to compensate for those deficiencies. In addition, there are uncertainties associated with theoretical models underling the event generation in both matrix element and parton showering stage. In this section we describe various corrections and associated systematic uncertainties related to our analysis.

6.5.1 Experimental Uncertainties

6.5.1.1 Jet Energy Scale

Jet energy scales are a set of scale factors that correct the 4-momentum of jets reconstructed from CMS detector response to the particle level jet momentum. The corrections are applied sequentially in different stages which handles different aspects. The L1 Pile-up correction removes energy coming from pile-up events and is applied to both Data and MC. L2/L3 MC-truth correction correct the p_T and η of reconstructed jets to the particle level ones, applied to both Data and MC as well. Finally, L2/L3 residual corrections handles the difference in jets between MC and data.

We then estimate the systematic uncertainty by adjusting the jet energy scale factor depend on the p_T and η of jet. The amount of change in JES is according to the recommendation of JetMET PAG based on 20 fb^{-1} of 2012 8 TeV Re-Reco Data[?] and listed in the following file.

- Winter14_V5_DATA_Uncertainty_AK5PFchs.txt

The templates corresponding to $\pm 1\sigma$ from nominal value of JES for $gg \to t\bar{t} \to \mu + jets$ are shown below in Fig.6.17. It can be seen that JES changes both the normalization and shape of this template. It turned out that JES is one of the dominate systematic uncertainties.

6.5.1.2 Jet Energy Resolution

Measurements show that the jet energy resolution (JER) in data is worse than in the simulation and the jets in MC need to be smeared to describe the data. We use scaling method to correct the transverse momentum of a reconstructed jet, p_T, by a facor w_{JER}, defined below:

$$w_{JER} = 1 + (SF_{JER} - 1)\frac{p_T - p_T^{ptcl}}{p_T} \tag{6.31}$$

where p_T^{ptcl} is the transverse momentum of jet clustered from generator-level particles, and s_{JER} is the scale factor measured from data and MC comparison which is recommended by the JetMET POG[?] and listed Table.[6.5]

We evaluated the systematic by adjusting SF_{JER} up and down as listed above to produce two more versions of templates for each MC sample. The effect of the JER

$\lvert\eta\rvert$ range	down	central	up
0.0-0.5	1.053	1.079	1.105
0.5-1.1	1.071	1.099	1.127
1.1-1.7	1.092	1.121	1.150
1.7-2.3	1.162	1.208	1.254
2.3-2.8	1.192	1.254	1.316

Table 6.5: Jet Energy Resolution scale factors and uncertainties for different $\lvert\eta\rvert$ range.

and JES systematic on $t\bar{t}$ templates are also shown below.

The templates corresponding to $\pm 1\sigma$ from nominal value of JES for $gg \to t\bar{t} \to \mu + jets$ are shown below in Fig.6.18. It can be seen that JES changes the shape of this template, especially on c^* and $M_{t\bar{t}}$ distributions.

6.5.1.3 Pileup Reweighting

All simulated samples are reweighted to reflect the distribution of pileup events observed in data by applying a scale factor that depends upon the number of reconstructed pileup events. The scale factor is calculated for each bin by dividing the estimated number of true interactions in the 2012 dataset by the number of true interactions in the simulated samples. Pileup estimates for data are obtained from the pileup JSON file provided by the Physics Validation Team after taking into account the appropriate HLT path as described on the Pileup Reweighting TWiki.[?] The number of true interactions in simulation is shown on the left-hand side of Fig. 6.19 and the number of measured interactions in data is shown on the right-hand side, illustrating the discrepancy.

The effect of applying the reweighting brings the two measured pileup distributions much closer into agreement as illustrated in Fig. 6.20, which shows pileup in both simulation and data after reweighting where the signal and background simulations have all been scaled according to their luminosities and cross sections, and the total distribution normalized to the data.

The systematic uncertainty associated with PU re-weighting mainly originate from the uncertainty of total cross-section of min-bias events as well as luminosity of bunch crossing. As recommended by the PVT POG, we apply 5% uncertainty on the number of primary interactions of data to produce up and down weights for PU. Use the new weights we get the PU systematic templates for the fit.

We have not include PU systematic yet and will added to the table soon.

6.5.1.4 b-tagging Efficiency

In our event selection a jet is tagged as a b jet if it passes a cut on its CSV discriminator value. However, the efficiency for a real b-jet to be tagged as a b quark is different in simulation and data, and so is the probability for a non-b jet to be misidentified as a b quark. A scale factor is applied to simulated events to correct for this discrepancy. The correction was done following the recommendation of BTEV POG,[?] using the method 1(a).

The scale factor (SF) is defined as the ratio of b-tagging efficiency for data and MC. It is a function of jet flavor, p_T and η. The b-tagging efficiency for a jet of flavor f and in the (p_T, η) bin of (i, j) is defined as follows:

$$\varepsilon_f(i,j) = \frac{N_f^{b-tagged}(i,j)}{N_f^{total}(i,j)} \tag{6.32}$$

Note here the b-tagging efficiency can be different for each MC sample. The weight that is applied for each event is then chosen as $w = \frac{P(data)}{P(MC)}$ where the probability of a given event in the MC distribution is

$$P(MC) = \prod_{i=tagged} \varepsilon_i \prod_{j=not\,tagged} (1 - \varepsilon_j) \tag{6.33}$$

And the corrected probability for the distribution in data is

$$P(data) = \prod_{i=tagged} SF_i \varepsilon_i \prod_{j=not\,tagged} (1 - SF_j \varepsilon_j) \tag{6.34}$$

6.5.1.5 Muon Tracking Efficiency

A tracking efficiency correction for muons is applied as an η-dependent scale factor. These scale factors are provided by the Tracking POG.[?]

6.5.1.6 Muon Trigger, ID, and Isolation Efficiencies

Muon trigger, ID, and isolation efficiences are corrected for by applying three scale factors, each dependent on the reconstructed number of primary vertices in the event as well as muon η and p_T. These scale factors are provided by the Muon POG, and the procedure used is dicussed in detail on the twiki page for muon ID and isolation efficiencies.[?]

6.5.1.7 Electron ID Efficiency

We applied scale factors to correct the difference of electron cut-based ID efficiency between data and MC. The scale factors are recommended by EGamma POG[??] , which is measured from the following Data and MC samples using Tag-and-Probe Method:

- Data: DoubleElectron Run2012A+B
- MC: DYJetsToLL-MadGraph (Summer12)

The SF measurement select events with opposite-sign di-electron events, with one electron as tag which pass tight electron cut-based ID and matched to the one leg of the trigger, and another electron as probe. The scale factors are measured in bins of p_T and $|eta|$ and is applied event by event as a weight to correct MC to Data.

In systematic evaluations, we introduce a nuisance parameter with Gaussian prior distribution in the likelihood definition. The up and down templates are produced by applying the corresponding scale factors, instead of the central scale factors, for each event.

6.5.1.8 Electron Trigger Efficiency

We apply SF to correct the `HLT_Ele27_WP80` trigger efficiency of MC to Data. The scale factors are from sources recommended on CMS Top EGamma Coordination twiki page.[?] It is measured by comparing MC simulation to 22Jan2013 ReReco Data, using tag and probe method[?].[?] The samples for the SF measurement is listed below:

- Data : `/SingleElectron/Run2012*-22Jan2013/AOD`
- MC : `/DYJetsToLL_M-50_TuneZ2Star_8TeV-madgraph-tarball`
  `/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM`

Similarly to Electron ID efficiency SF discussed above, we applied trigger efficiency correction to MC and introduce a nuisance parameter in systematic evaluations.

6.5.1.9 QCD Modeling and Background Composition

Due to the high cross section and wide variety of event types resulting from multijet QCD processes, Monte Carlo simulations cannot be generated with sufficient luminosity to provide a reasonable approximation of this background shape. Therefore a data-driven method has been implemented to estimate the shape of the QCD background.

The nature of the method is to build template distributions from each of the existing simulated samples (both signal and background) in a sideband of the lepton isolation variable. The sideband used for muons is $0.13 < \mathrm{PF}_{\mathrm{iso}}/p_T < 0.20$ and the sideband used for electrons is defined as $0.2 < \mathrm{PF}_{\mathrm{iso}}/p_T < 1.2$. These sideband regions are inversions of the lepton selection cuts and are designed to provide a sample enriched with multijet QCD events.

In the muon+jets channel with Run2012A-D data, it was found that only 485 events were selected in the lepton isolation sideband. Additionally, all of these events could be accounted for by the events selected from the existing signal and background simulations, indicating that QCD multijet contribution to the background is negligible in this channel. So for muon+jets channel we do not consider QCD multijets background.

On the other hand, QCD multijets process is not negligible for $e + jets$ channel. So we estimate the distribution of QCD process by using the distribution of observed data events in the lepton selection sideband region. This is assuming the distribution of QCD events is similar regardless of if the fake electron is isolated or non-isolated. In addition, we estimate the event rate for QCD process in signal region by using ABCD method, including the uncertainty of this estimation. We then introduce a nuisance parameter R_{QCD} with a log-normal prior, so the data-driven QCD background can be scaled. The width of the prior distribution of R_{QCD} is chosen as the percentage uncertainty estimated from ABCD method.

The QCD multijet background process modeling is described in more details in Appendix.[4.1.3]

6.5.2 Theoretical Uncertainties

6.5.2.1 Top p_T Reweighting

The normalized differential top-quark-pair cross section analysis in the CMS Top Group found a persistent inconsistency between the shapes of the individual top-quark p_T distributions in simulation and data, while the NNLO approximated calculation[?] provides a reasonable description.[?] Therefore an individual top-quark p_T dependent event scale factor has been derived to correct this shape. The scale factors recommended for use with 8TeV data for lepton plus jets events are

$$\text{weight} = \sqrt{e^{0.318-0.00141(p_{T_t}+p_{T_{\bar{t}}})}} \tag{6.35}$$

Here p_{T_t} and $p_{T_{\bar{t}}}$ are the generator-level transverse momenta of the individual top- and antitop-quarks respectively. Note that the application of this event scale factor does not conserve the $t\bar{t}$ cross section and this change in total cross section must be removed when renormalizing the $t\bar{t}$ samples by luminosity and cross section to derive expectations of R_{bk} and $R_{q\bar{q}}$. More details about the reweighting procedure, its motivation and investigation, and its application to samples of 7 TeV data can be found on the Top Quark Group's TWiki page.[?] The value of this event scale factor for semileptonic events is pictured in Fig. 6.21 as a function of c_{r}, x_{r}, and M_{r}. It shows that top p_T reweighting is correlated with c_r and $M_{t\bar{t}}$ for $t\bar{t}$ events. As a result, applying the reweighting changes the distribution of $t\bar{t}$ events.

In subsequent template fit we apply top p_T re-weighting as a default, for our nominal fit. We estimate the systematic uncertainty associated with top p_T re-weighting by measuring the difference of central fit value of A_{FB} and $R_{q\bar{q}}$ with or without applying the top p_T weights. We found that top p_T reweighting is a dominate systematic in this measurement.

6.5.2.2 MC systematics

The effect of having limited sized MC templates on the fit is discussed here. This systematic uncertainty has not been estimated yet and will be added in next version of the notes.

6.5.2.3 Parton Distribution Functions

We estimate the systematic uncertainty from PDF of protons by producing up/down templates based on all alternative PDF sets for each MC sample. For example, for our signal $t\bar{t}$ sample which is produced with `aMC@NLO+CTEQ66` , for every event we take the PDF weights that are maximally below (w_-) and above (w_+) the value of nominal weight (w_0) to produce $w_{down} = \frac{w_-}{w_0}$ and $w_{up} = \frac{w_+}{w_0}$. Then we re-weight the nominal templates using these two set of weights to produce systematic templates for PDF uncertainty.

6.5.3 Evaluation method and uncertainty table

Once we have systematic templates corresponding to each of the uncertainty sources, we propagate the uncertainties to the measured parameters by taking the following approach.

As mentioned in Section.?? for every systematic uncertainty sources we introduce a nuisance parameter with Gauss prior. The expected distribution can be interpolated from up,down and nominal templates provided. We first perform the template fit by fixing all nuisance parameters corresponding to systematics to the nominal value, only allowing other parameters to float. Then we allow each systematic nuisance parameter to float at a time, and take the difference between the new measured parameter value and nominal value as the systematic uncertainty from the respective source. Finally we add all systematic uncertainties in quadrature as the total systematic uncertainties.

The complete table of systematic uncertainties for both parameter of interest and other important nuisance parameters are listed below, in Table.[6.6],[6.7]

Systematics	A_{FB}	$R_{q\bar{q}}$	$R_{other\_bkg\_\mu}$	$R_{other\_bkg\_el}$	R_{WJets_μ}	R_{WJets_el}
Nominal	0.045	0.12	0.089	0.101	0.007	0.011
B-Tagging Eff.	0.044	0.119	0.089	0.101	0.007	0.011
Lepton ID Eff.	0.045	0.12	0.088	0.101	0.007	0.011
Lepton Iso Eff.	0.045	0.12	0.089	0.101	0.007	0.011
Tracking Eff.	0.045	0.12	0.089	0.101	0.007	0.011
Trigger Eff.	0.045	0.12	0.089	0.101	0.007	0.011
JES	0.05	0.114	0.106	0.12	0.011	0.014
JER	0.039	0.118	0.095	0.104	0.008	0.011
PDF	0.036	0.12	0.095	0.104	0.008	0.011
top p_T	0.034	0.108	0.073	0.084	0.006	0.01

Table 6.6: Central value of all fit parameters with each type of systematic nuisance parameters turn on at a time.

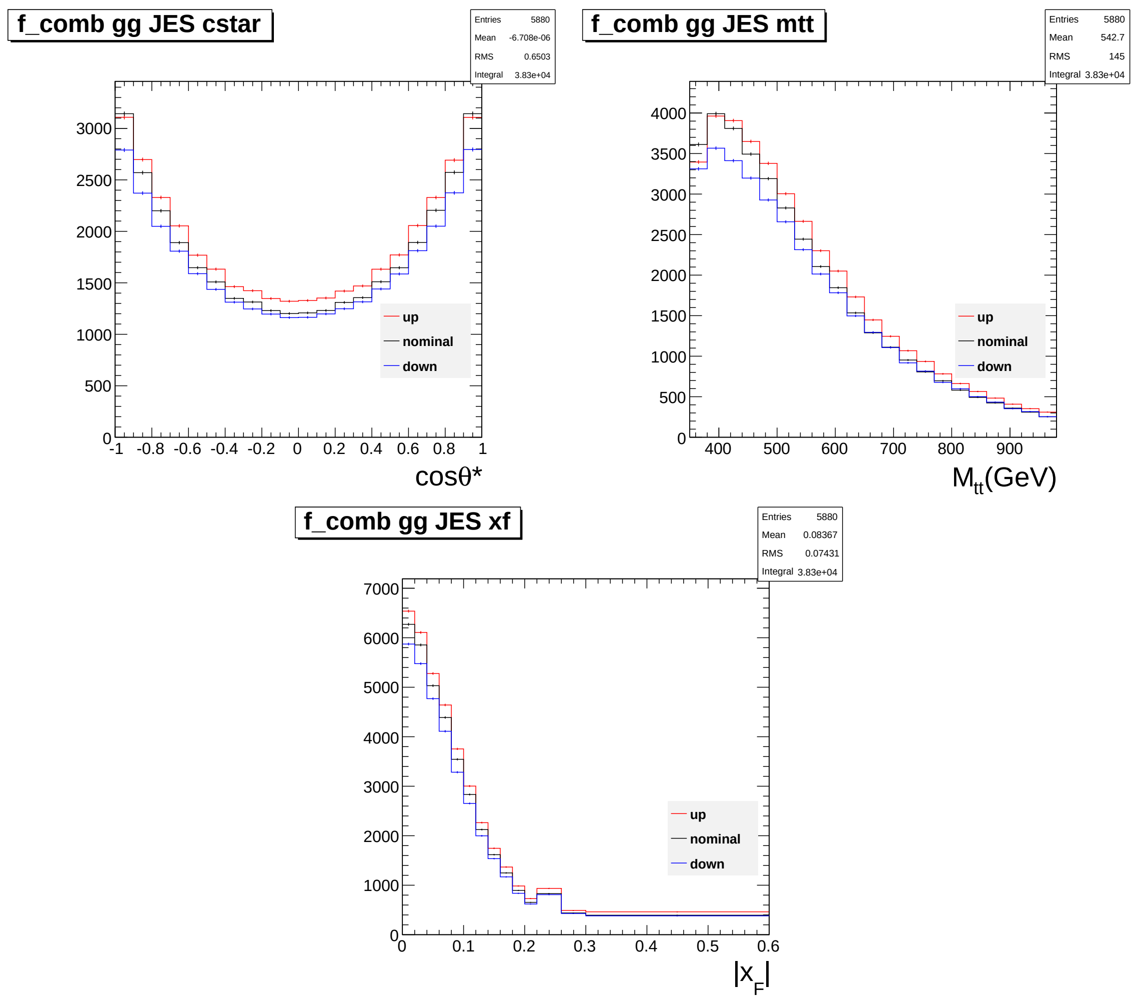


Figure 6.17: The distribution of MC simulated $ggqg \to t\bar{t} \to \mu + jets$ events with $SF_{JES} = -1\sigma$ (blue), 0 (black) and $+1\sigma$ (red)

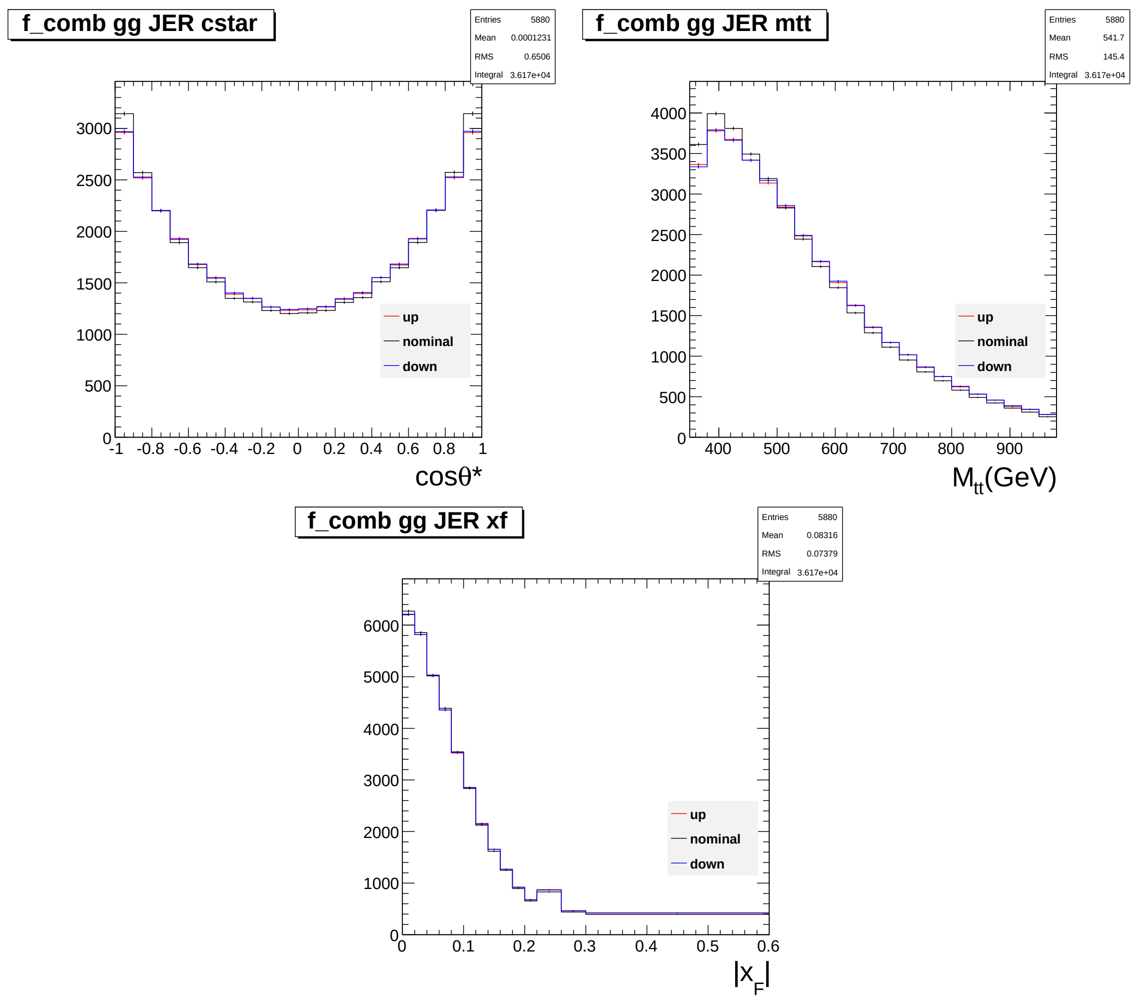


Figure 6.18: The distribution of MC simulated $gg/qg \rightarrow t\bar{t} \rightarrow \mu + jets$ events with w_{JER}= -1σ (blue), 0 (black) and $+1\sigma$ (red)

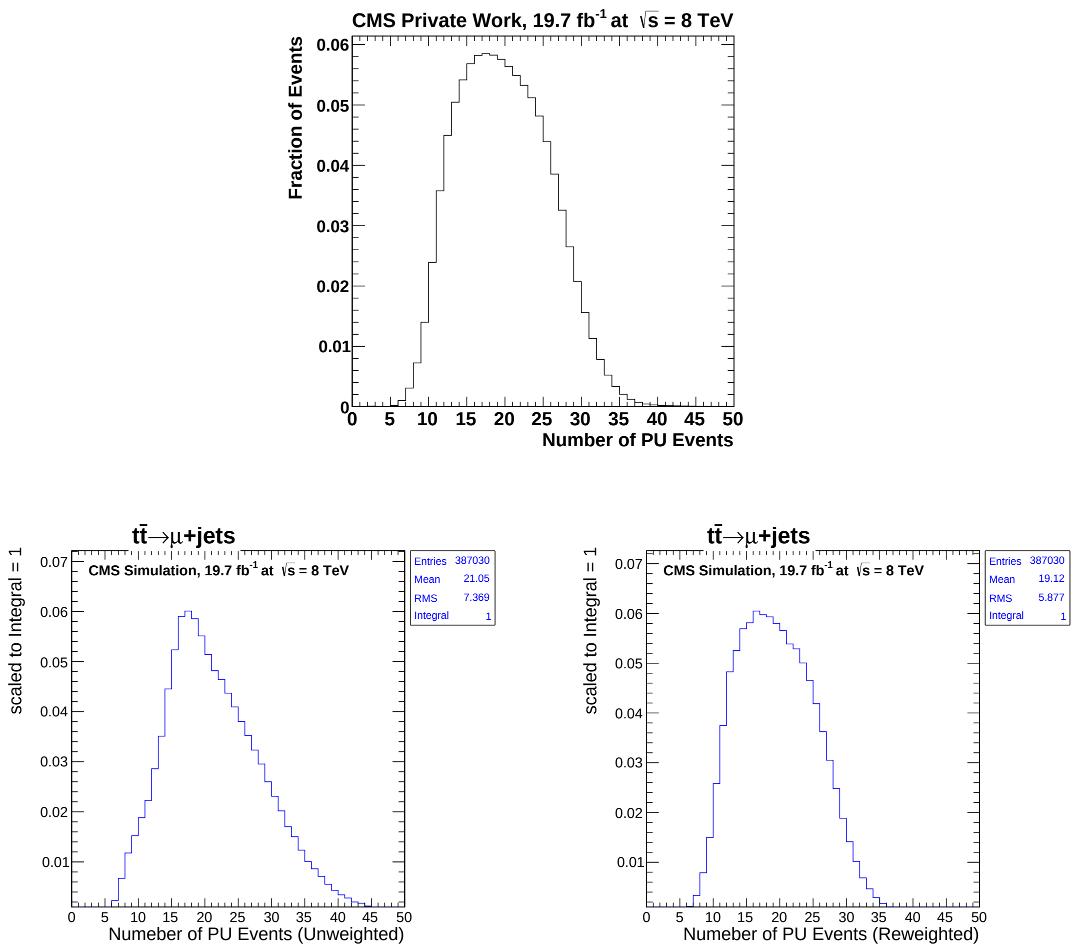


Figure 6.19: The distribution of simulated primary interactions in MC simulated $t\bar{t} \rightarrow \mu + jets$ events before applying PU reweighting (bottom left) and after reweighting (bottom right). The reference PU distribution from 2012 collision data in the top middle showing the discrepancy intended to be corrected for.

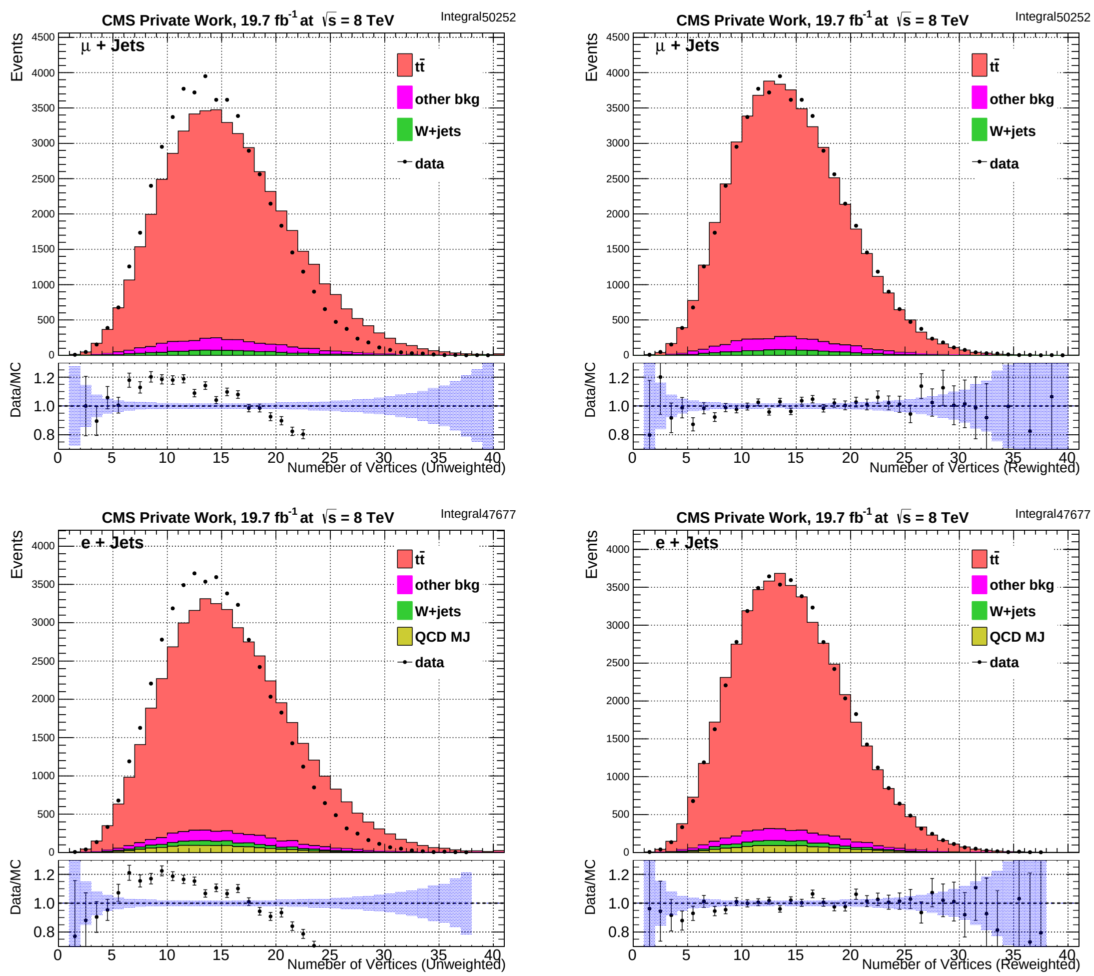


Figure 6.20: Measured pileup in simulation and data before reweighting (left) and after reweighting (right). The signal and background samples have been rescaled according to their luminosities and cross sections, and the entire distribution has been normalized to data. The simulated samples are pictured as stacked filled histograms, and the data are pictured as blue data points. The figures at top are from μ+jets channel, and bottom are e+jets channel

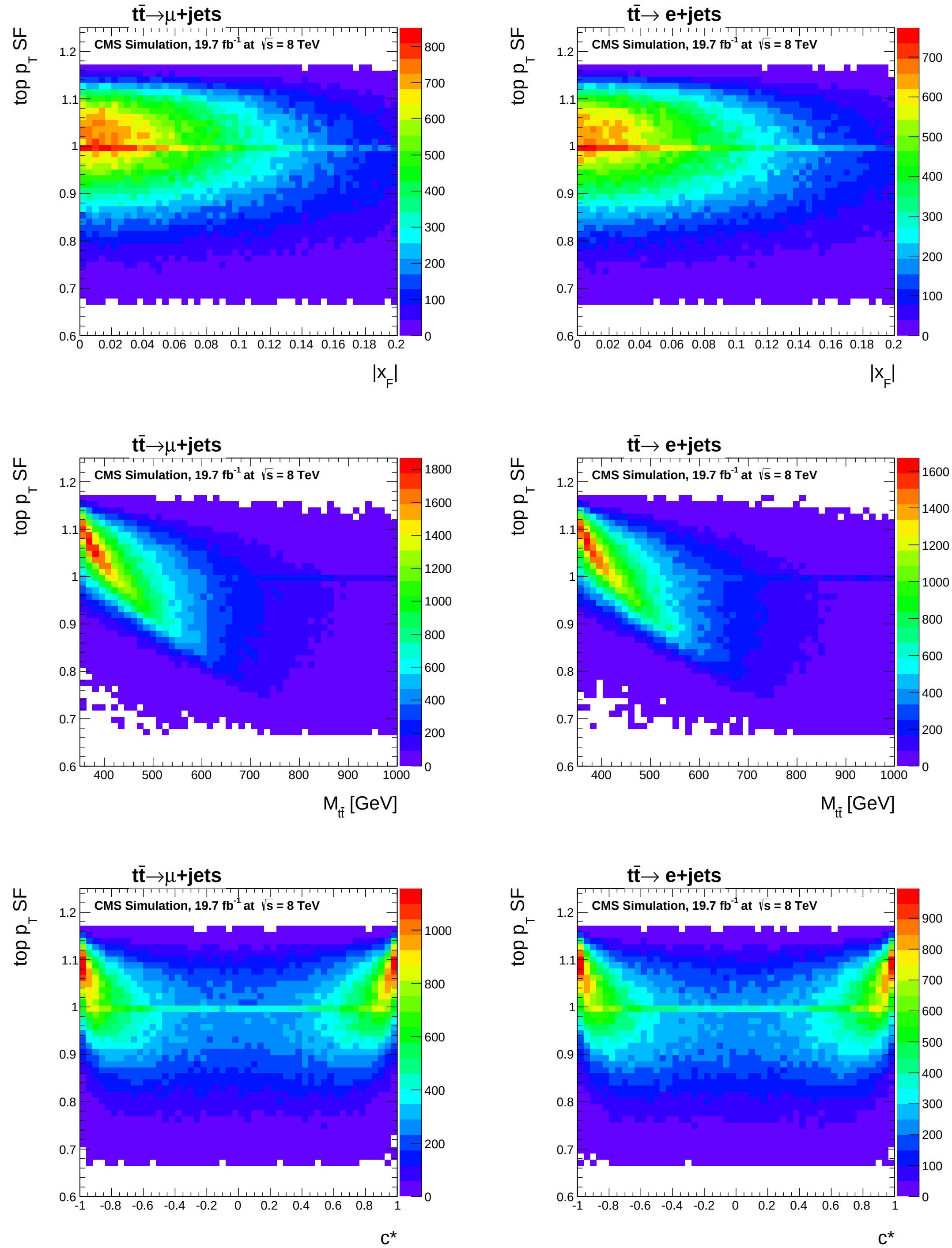


Figure 6.21: The top p_t reweighting event scale factor as a function of c_{r} (top), x_{r} (middle), and M_{r} (bottom) for a sample of aMC@NLO simulated semileptonic $t\bar{t}$ events. The figures at the left are from μ+jets channel, at right are e+jets channel.

Systematics	σ^{sys}_{AFB}	$\sigma^{sys}_{R_{q\bar{q}}}$	$\sigma^{sys}_{R_{other\_bkg\_\mu}}$	$\sigma^{sys}_{R_{other\_bkg\_el}}$	$\sigma^{sys}_{R_{WJets\_\mu}}$	$\sigma^{sys}_{R_{WJets\_el}}$
B-Tagging Eff.	0.001	0.001	0	0	0	0
Lepton ID Eff.	0	0	0.001	0	0	0
Lepton Iso Eff.	0	0	0	0	0	0
Tracking Eff.	0	0	0	0	0	0
Trigger Eff.	0	0	0	0	0	0
JES	0.005	0.006	0.017	0.019	0.004	0.003
JER	0.006	0.002	0.006	0.003	0.001	0
PDF	0.009	0	0.006	0.003	0.001	0
top p_T	0.011	0.012	0.016	0.017	0.001	0.001
Total	0.0162	0.0136	0.0249	0.0258	0.00436	0.00316

Table 6.7: Systematic uncertainties of fit parameters from different sources. The total is the individual sources add in quadrature.

6.6 Results

The result of measuring A_{FB} and $R_{q\bar{q}}$ from 19.6 fb^{-1} of 8 TeV proton-proton collision data collected by CMS experiment in 2012 is given below. It is based on the binned likelihood fit of MC simulated templates (and Data driven QCD multijets template for e+jets) to 45321/42923 mu+jets/el+jets data events.

- $A_{FB} = 0.045 \pm 0.050\,(stat) \pm 0.016\,(sys)$
- $R_{q\bar{q}} = 0.120 \pm 0.006\,(stat) \pm 0.014\,(sys)$

The expected distribution of observed data events for the best fit is compared with actual observed data in the figures below. Fig.[6.22] shows the combined event distribution, by summing over $e + jets$ and $\mu + jets$ channels and over lepton charge types. The Fig[6.23] - Fig.[6.25] shows the individual post fit comparisons for all four observable, which are fit simuteneusly as described in Section.[6.3.5]. The fit agrees with data reasonably well.

In order to compare to the expected values of A_{FB} and $R_{q\bar{q}}$ suggested by NLO simulation, we fit the pseudo data events which is the combination of MC simulated events. The same MC that is used for building the templates are taken to form the pseudo data. These MC samples are normalized to the same integrated luminosity of analyzed data. The fit central value and statistical uncertainty are also listed in the Table.**??**.

We found that the measured A_{FB} and $R_{q\bar{q}}$ are consistent with the expected values from NLO MC simulations. We note that just by simple counting definition of A_{FB}, we found $A_{FB} = -0.02$ using the generated $c*$ for $q\bar{q} \to t\bar{t}$ events from our signal MC samples. So we actually managed to extract this value with our template fit. On the other hand, this suggest our signal MC samples, which is generated using aMC@NLO may not be accurate enough to describe A_{FB} from SM theory.

We also compared our measurement with the result of both D0 and CDF experiments of Tevatron, which are the measurement of A_{FB} of e/μ+jets channel combined based on full Tevatron Data of proton anti-proton collision at 1.96 TeV. Our results are consistent with the result of Tevatron,[6,8] and we get competitive uncertainty on A_{FB} despite significant dilution from gg initiated $t\bar{t}$ events.

Finally we compared to the NNLO SM calculation,[?] which is consistent with our measurement as well.

In conclusion, we measured the Forward-Backward Asymmetry of $q\bar{q} \to t\bar{t}$ process using the $l + 4/5jets$ events from 8 TeV proton-proton collision in LHC, collected by CMS during 2012. We are able to measure A_{FB} with good accuracy, and found the result to be consistent from NNLO QCD calculation as well as the latest results from D0 and CDF experiments in Tevatron. In addition, we managed to measure the fraction of $q\bar{q}$ initiated $t\bar{t}$ events , which is interesting in its own.

Parameter	Simulation	Tevatron	SM Theory
A_{FB}	-0.018 ± 0.052	0.106 $\pm$ 0.03 (D0), 0.164$\pm$0.047 (CDF)	0.095 $\pm$ 0.007
$R_{q\bar{q}}$	0.132 ± 0.015	NA	??

Table 6.8: Result of template fit to single muon data using 2012 8 TeV Data collected by CMS. The expected value of parameters are from template fit to MC simulations.

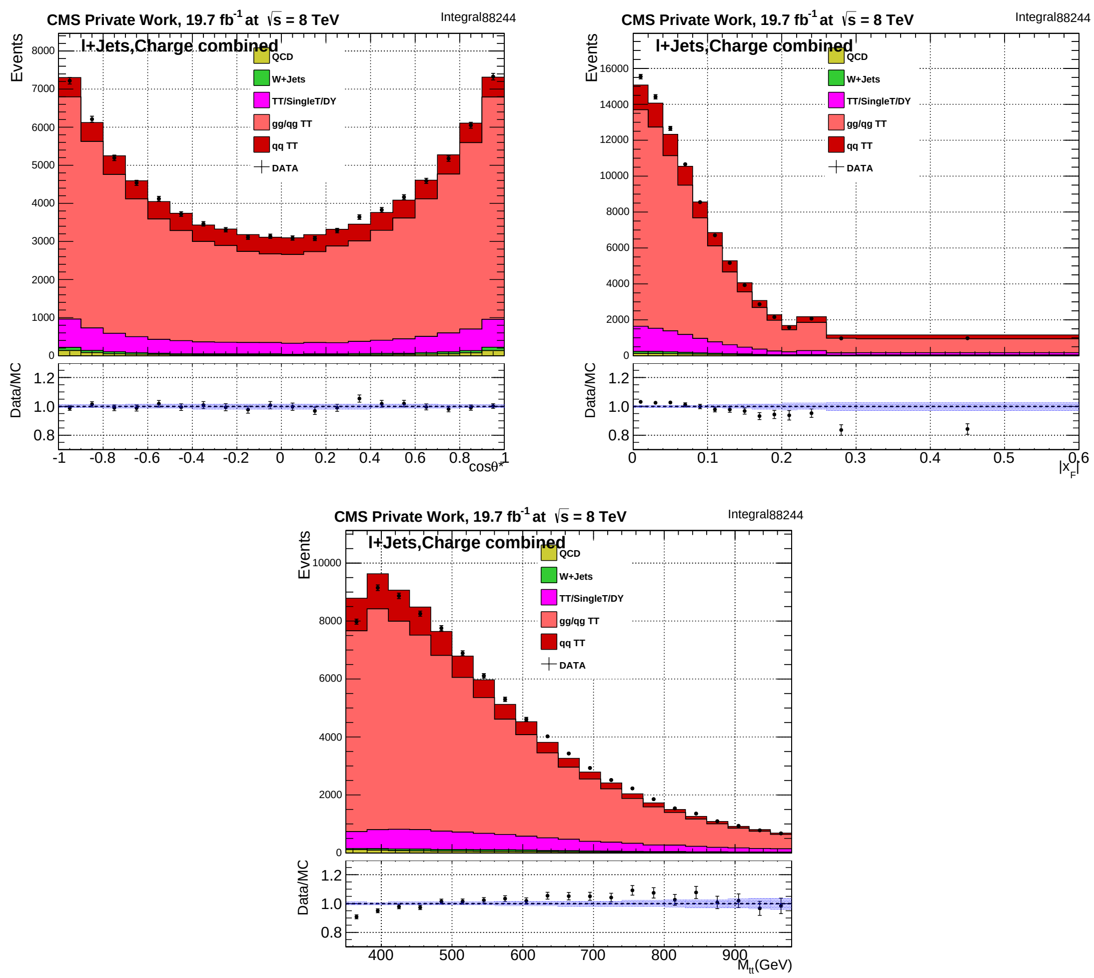


Figure 6.22: Postfit plots of lepton and charge combined template after the fit (colored) and data (solid dots with error bar). All errors, including the shaded band in the Data/MC comparison plots, indicate Poisson error only.

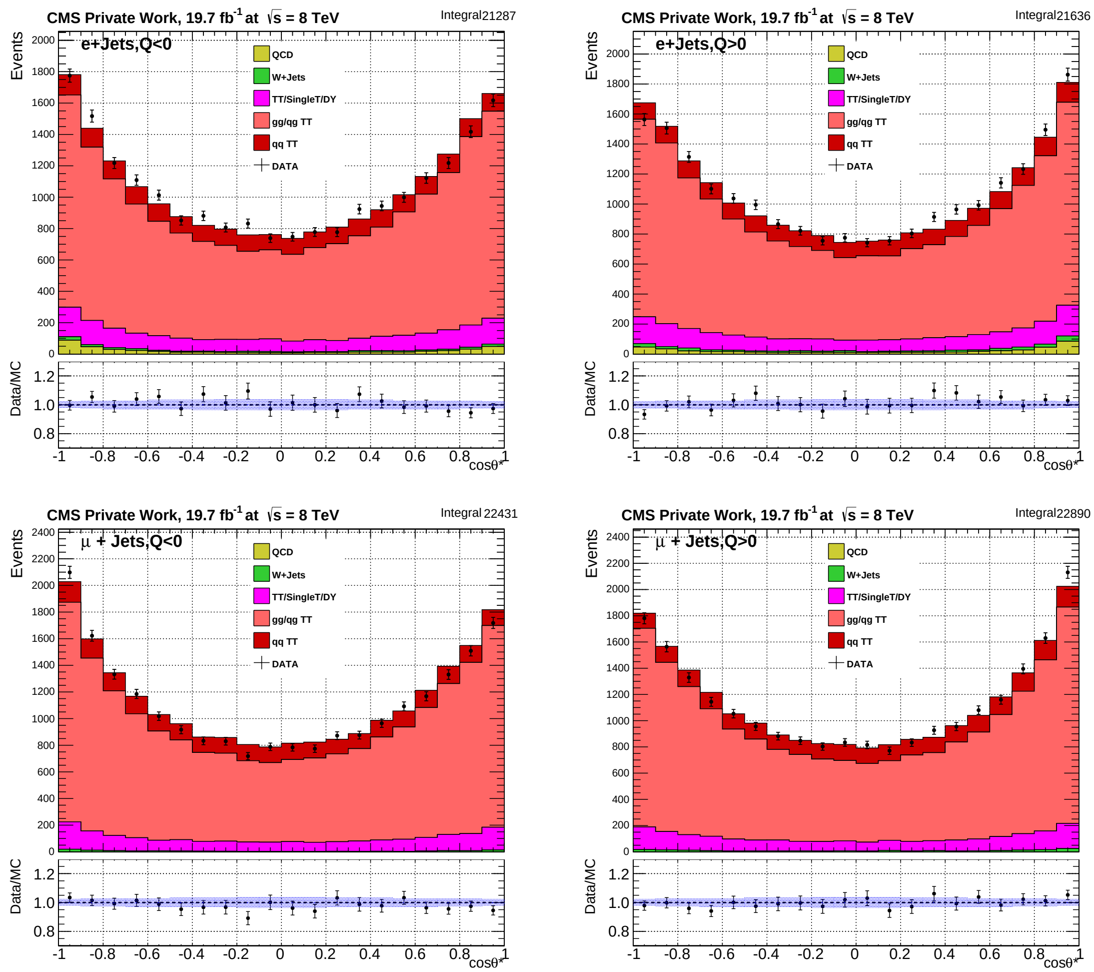


Figure 6.23: $c*$ projection of post-fit distribution of all four observable, as labeled in the figures. All errors, including the shaded band in the Data/MC comparison plots, indicate Poisson error only.

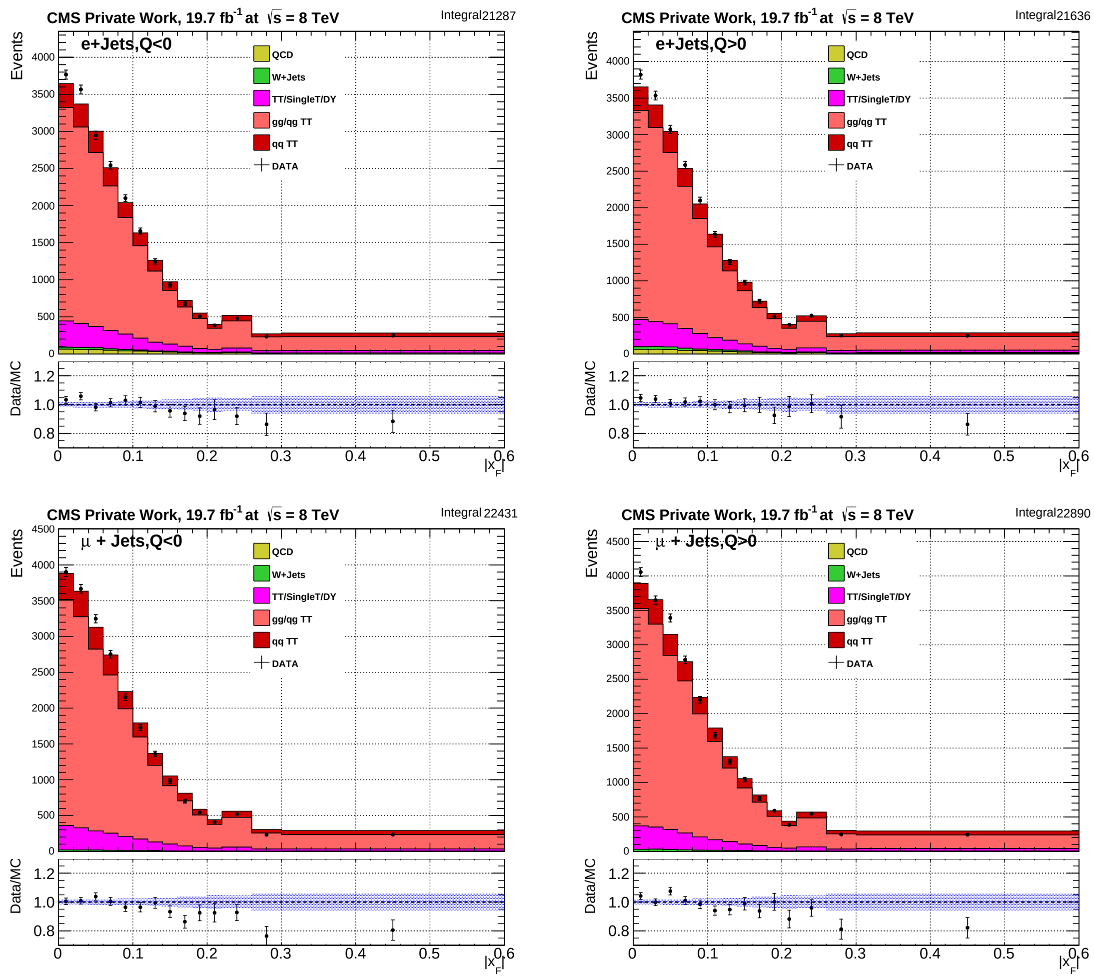


Figure 6.24: $|x_F|$ projection of post-fit distribution of all four observable, as labeled in the figures.All errors, including the shaded band in the Data/MC comparison plots, indicate Poisson error only.

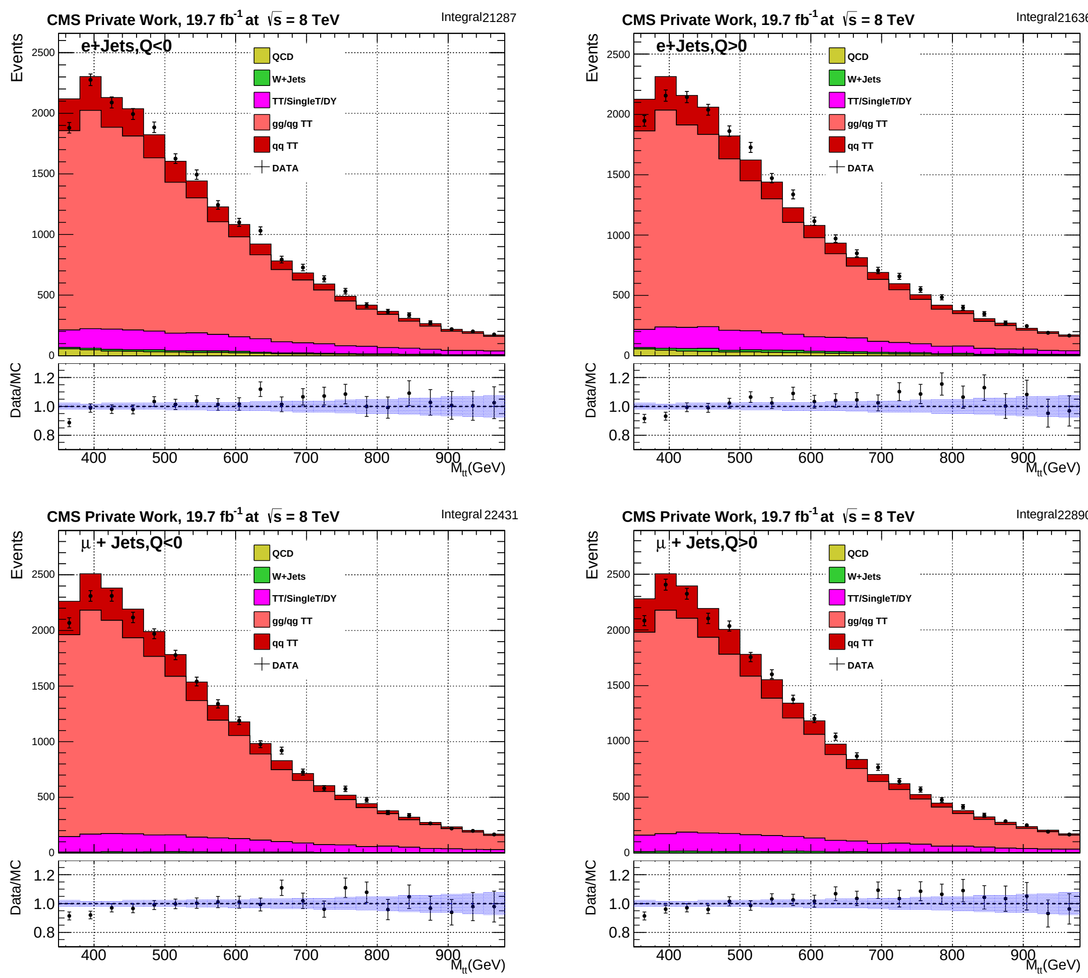


Figure 6.25: $M_{t\bar{t}}$ projection of post-fit distribution of all four observable, as labeled in the figures.All errors, including the shaded band in the Data/MC comparison plots, indicate Poisson error only.

Conclusion and Outlook

In this thesis the Foward-backward asymmetry in $t\bar{t}$ production at Large Hadron Collider is measured using 19.7 fb^{-1} of proton proton collision at 8 TeV. Only semileptonic channel of $t\bar{t}$ events are analyzed, with the final states of electron or muon , four or five jets with two originated from bottom quarks.

A new template based measurement method is introduced in this thesis. Using this method, the parton level A_{FB} originated from $q\bar{q} \to t\bar{t}$ process is measured. In addition, the relative abundance of $q\bar{q} \to t\bar{t}$ process among all $t\bar{t}$ production processes, denoted as $R_{q\bar{q}}$ is measured simultaneously.

The measurement is performed via a maximal likelihood fit that simultaneous fit both e+jets and μ+jets events, with common parameters of interest, A_{FB} and $R_{q\bar{q}}$, and separate background process normalization estimation.

Both A_{FB} and $R_{q\bar{q}}$ are found to be consistent with theoretical prediction given by standard model, within the uncertainty of the measurement. The dominant uncertainty in A_{FB} measurement originates from the limited number of data events observed. The dominant uncertainty in $R_{q\bar{q}}$ is of the systematical origin.

One highlight of the measurement provide in this thesis is the direct measurement of A_{FB} from $q\bar{q} \rightarrow t\bar{t}$ process, allowing a closer comparison with the measurement of A_{FB} in proton anti-proton collision in Tevatron.

To put the measurement result into perspective , we compared our result to other related measurements in LHC and Tevatron in recent years. As other measurements in LHC measured charge asymmetry, a different observable from what is measured in this thesis and in Tevatron measurements, instead of compare the results directly, we convert each individual measurement result to their relative difference from the expected value predicted by SM.

At the time of writing this thesis, the LHC Run2 has been extremely successful since its start in 2015. With a higher collision energy at 13 TeV indicating a larger cross section for $\mathrm{t\bar{t}}$ production (832 pb at 13 TeV vs 245 pb at 8 TeV), and a much larger integrated luminosity recorded by CMS so far (95 fb^{-1} compare with 19.7 fb^{-1}), about 14 times more $\mathrm{t\bar{t}}$ events are expected using the LHC Run2 data collected so far. As the measurement presented in this thesis is limited by the size of data, a similar measurement is expect to have a 3 times smaller statistical uncertainty, which will greatly benefit the precise test of SM in the matter of A_{FB}

A challenge of measuring A_{FB} in LHC Run2 is the increase of fraction of $\mathrm{t\bar{t}}$ events originated from the symmetric gluon-gluon fusion process (increase from 85% to 90%) , which further dilute the expected charge asymmetry. Our approach, on the other hand , is less affected, as it managed to measure the A_{FB} from $q\bar{q} \rightarrow t\bar{t}$ process directly.

In conclusion, the template based A_{FB} measurement method proposed in this thesis is the first of its kind in CMS, and successfully measured the $\mathrm{t\bar{t}}$ A_{FB} using 8 TeV LHC data with competitive accuracy compare with previous measurements in CMS. It has even more potential in providing a more precise measurement using LHC Run2 data.

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