

TOP QUARK STUDIES WITH THE CMS EXPERIMENT: RARE PROCESS AND PRECISION MEASUREMENTS

by

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- The CMS Experiment, advisor: Meenakshi Narain
 - *Top quark mass and decay width measurement in di-lepton final state with 2016 data.* This is a combined measurement of the mass and the decay width of the top quark in dileptonic tt decay events resulting from proton-proton collisions at center-of-mass energy of 13 TeV. Data was collected with the CMS detector during Run 2 of the CERN LHC in 2016. The invariant mass of lepton and b-jet pairs, called mlb, is used as observable. Events are categorized by lepton flavor (ee, e μ , $\mu\mu$), b-quark jet multiplicity, and the transverse momentum of the lepton b-jet pairs. Simulated expectations for different top mass and width scenarios are compared to the data via a profile likelihood method.
 - *Four top quark production search in single lepton final state with Run 2 data.*

This is a search for the rare production process $t\bar{t}t\bar{t}$. We study single lepton final state where one of the four top quarks decays leptonically, and three top quarks decay hadronically. We analyze the proton-proton collision data collected by the CMS experiment at center-of-mass energy of 13 TeV, data taken in 2016, 2017 and 2018. The distributions of H_T , the scalar sum of jet p_T , along with a resolved top quark tagging algorithm are used in order to discriminate signal from background and, in the absence of signal, set limits on the four tops production cross section. In addition, another improved study is done with a discriminant produced by multivariate analysis.

- *Delphes fast simulation production and validation.* Delphes samples production, worked as team leader in 2021 production campaign. Development of validation framework. This framework aims to study the objects and compare Delphes and fullsim performances. I started the ntuple analyser framework, plotter, and posting tool. The analyser works on various physics objects, such as jets, electrons, muons, photons, etc. It studies kinematics of gen/reco level, multiplicity, reco efficiency, reco resolution, energy response, fakerate.
- *High Lumi LHC and High Energy LHC perspectives.* Worked on two analyses for the future detector performance. Analysis 1, Heavy composite Majorana neutrino search in HE-LHC. This is a search for heavy composite Majorana neutrinos in a final state of two leptons and at least one fat jet. The detector simulations are done with Delphes package and CMS Phase II detector design at center-of-mass energy of 27 TeV. Analysis 2, Search for resonant $t\bar{t}$ production. This is a search for heavy resonances decaying to $t\bar{t}$ pairs with the Phase 2 upgraded CMS detector. The detector response is simulated with the Delphes package. The projections are performed for both HL-LHC and HE-LHC at center-of-mass energies of 14 and 27 TeV.

- *CMS tracker sensor assembly.*
- Measurement of Rb-vapor Density in Single Photon Level (Undergraduate thesis), advisor Liqing Chen
 - Measured fluorescence signal using single photon detecting system. Calculated Rubidium vapor density curve through the resonance-fluorescence method. Studied the absorption effects to fluorescence, adding probe beam and reference beam to avoid absorption.

Teaching Experience

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Preface and Acknowledgments

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CHAPTER 1

Introduction

Particle physics is a science of fundamental particles. It studies the micro world at a scale which is much much smaller than an atomic nuclei. Even though these particles are not familiar in our daily life, understanding their interactions has a significant impact on our universe. Particle physics is the study of the microscopic world and addresses topics for example, how many types of fundamental particles and forces exist, how fundamental particles interact, and why matter has mass.

The Standard Model (SM) of particle physics is by now the best model to describe all the elementary particles and fundamental forces. It was formulated in 1960s and 1970s based on many observations of new particles. It is verified by many discoveries and precision measurements, and predicted the existence of the Higgs boson which was later observed in 2012. In the past decades, physicists built various particle colliders and detectors to look for the unknown particles, to validate the complex theory models and to measure the properties of existing known particles. The Large Hadron Collider (LHC) is the most powerful particle accelerator in the world, located in Switzerland. The Compact Muon Solenoid (CMS) is a multipurpose particle detector around LHC.

This dissertation focuses on the fundamental particle, the top quark (t) and its anti-particle. It is the heaviest amongst quarks, and the most unstable. Investigations of the top quark

properties give us an insight into the strong interactions and top decays lead us to verify weak interactions. Since its discovery in 1995 [1], scientists have carried out many measurement of its properties, including the cross sections of a variety of top quark production processes, mass, couplings and decay branching ratios.

We discuss the Standard Model in Chapter 2, and give a overall introduction of different types of particles and what we will see in the studies. Chapter 3, discusses the CMS experiment. In this section we describe the structure of the detector and how the final state particles are recognized. In chapter 4, we present the top quark mass and decay width measurement. Chapter 5 shows a search for a rare process, four top quark production. Appendix A, has a study on Delphes fast simulation validation.

CHAPTER 2

The Standard Model of Particle Physics

2.1. The Standard Model

2.1.1. History of Fundamental Particles

Elementary particle physics began with the the discovery of electron in 1897. Since then, physicists gradually understood the nucleus and the structure of the atom. Around 1900, the concept of photon came about, with the electromagnetic energy quantization. A quantized electric field is an important step in the development of quantum theory. In this model, we can say that a force is mediated by an exchange of particles or quanta of the field. In 1934, Yukawa proposed the first critical theory for strong force to explain the origin that proton and neutron are attracted to each other [2]. Yukawa theoretically predicted mesons.

In 1964, while physicists tried to classify all the discovered particles, Gell-Mann proposed that hadrons are composed of elementary constituents, called quarks [3]. Initially, he proposed three quark flavors, up, down and strange, which are distinguished by their charge (Q) and strangeness (S). This is called quark model. In the same year, O.W.Greenberg proposed that quarks carry colors. Naturally occurring particles are all colorless. In 1968, Glashow, Weinberg and Salam predicted three intermediate vector bosons, $W^{\pm}$ and Z. They

were confirmed in experiments in CERN proton-antiproton collision in 1983.

All particles can be classified into two types according to their spin. Particles with half-integer spin are fermions, such as leptons and quarks; particles with integer spin are bosons, such as mesons and mediators.

2.1.2. The Standard Model Particles

There are four fundamental forces in nature: strong, weak, electromagnetic, and gravitational. The physical theory that describes electromagnetic forces is electrodynamics, and similarly, chromodynamics for strong forces, weak theory for weak forces. Einstein's general theory of relativity is the theory for gravity.

Since 1970s, physicists created the Standard Model (SM) of particle physics. It is a theory that describes three of the four known fundamental forces in the universe, and classifies all known elementary particles.

There are three types of elementary particles: leptons, quarks, and mediators. In total, there are 12 leptons, including six leptons and six antileptons. Six leptons are classified by their charge (Q), electron number (L_e), muon number (L_μ) and tau number (L_τ) in Table 1. They fall into three generations, e and ν_e as first generation, μ and ν_μ in second generation, τ and ν_τ in third generation. Typically, the stable and lightest particles are from the first generation, and the heavier and unstable particles belong to the second or the third generation. However, we do not have any measurements for neutrino mass by now. The antileptons carry the opposite signs of their charge, electron number, muon number and tau number.

There are six flavors of quarks, as shown in Table 2. Quarks are classified according to charge (Q), strangeness (S), charm (C), beauty (B), truth (T). Also, they fall into three

Table 1: Leptons in SM.

l	Q	L_e	L_μ	L_τ
e	-1	1	0	0
ν_e	0	1	0	0
μ	-1	0	1	0
ν_μ	0	0	1	0
τ	-1	0	0	1
ν_τ	0	0	0	1

generations, d and u in first generation, s and c in second generation, b and t in the third generation. The antiquarks carry the opposite signs. Quarks and antiquarks have three colors, so in total, there are 36 different varieties.

Table 2: Quarks in SM.

q	Q	D	U	S	C	B	T
d	-1/3	-1	0	0	0	0	0
u	2/3	0	1	0	0	0	0
s	-1/3	0	0	-1	0	0	0
c	2/3	0	0	0	1	0	0
b	-1/3	0	0	0	0	-1	0
t	2/3	0	0	0	0	0	1

The photon is the mediator for the electromagnetic force, W and Z bosons are mediators for the weak interaction. There are eight gluons as the mediators for strong force. A scalar boson was brought into the Standard Model in order to resolve the mass of W and Z in the Electroweak Symmetry Breaking mechanism [4]. The discovery of Higgs boson was reported in 2012 by ATLAS and CMS collaborations with a mass of about 125 GeV [5, 6].

2.2. Elementary Particle Dynamics

2.2.1. Quantum Field Theory

Paul Dirac introduced the idea of second quantization in 1927, and this is considered to be the start of quantum field theory (QFT). As an example, a simple problem is the quantized

energy of harmonic oscillator. In this picture, the electromagnetic field is a system of infinite harmonic oscillators. The definition of QFT is kind of complicated. It combines classical field theory, quantum mechanics, and special relativity theory. QFT is a theory to solve the problem of many relativistic particles. When the particle has a speed close to light speed $v/c \sim 1$, the effect of Lorentz symmetry is maximized.

In field theory, we use Hamiltonian or Lagrangian densities to define a system. Although in classical theory we find kinetic energy and potential energy, we use kinetic terms and interactions in QFT. The kinetic terms have two factors, while interactions have three or more factors. If the coefficients of interaction terms are small, we can do perturbation theory. With given Lagrangian formulation and perturbation theory, we can derive Feynman rules and diagrams. They are extremely useful ways to calculate physical results, for example, determining the scattering amplitude and cross section of an interaction process. In Feynman diagrams we will see infinite loops that result in divergent integrals. These loops are common when calculating the matrix elements beyond the leading order in perturbation. Higher order loops are mathematically difficult to compute. However, theorists are continuously improving techniques to compute the loops. In order to resolve this difficulty, a regulating parameter is added into the integral to make it finite, and the regulator is removed in the end. This process is called renormalization.

2.2.2. Quantum Electrodynamics

Quantum electrodynamics (QED) is the basic dynamical theory among all the theories for fundamental forces. The other theories are built on it.

A QED process can be broken into a series of elementary process in Figure 1. An electron enters, emits or absorbs a photon, then exits. The particle can be any lepton or a quark. This particle cannot be a neutrino, because only charged particles experience an electromagnetic

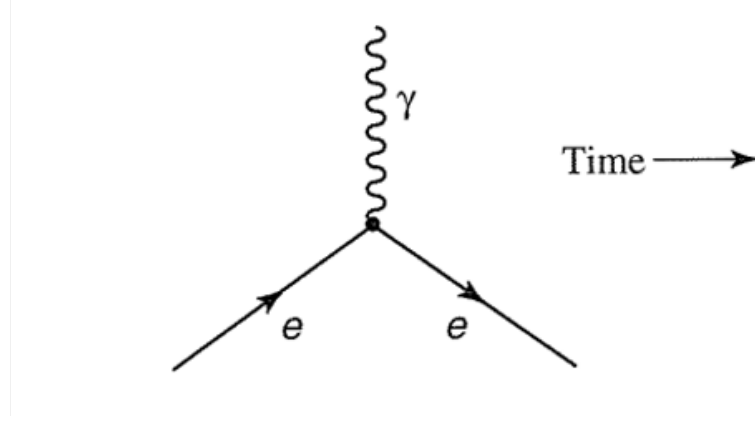


Figure 1: QED fundamental vertex.

force.

In QFT, the lagrangian that describes photons interacting with electrons or positrons is in the form

$$\begin{aligned}\mathcal{L} &= \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} \\ &= -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + i\bar{\psi}\gamma^\mu\partial_\mu\psi + e\bar{\psi}\gamma^\mu\psi A_\mu - m\bar{\psi}\psi.\end{aligned}\tag{2.1}$$

Here e is the charge of electron in Heaviside-Lorentz units. In these units, the fine-structure constant $\alpha = e^2/4\pi = 1/137$, and this is the coupling coefficient for QED. $F^{\mu\nu}$ is the electromagnetic field, A_μ is the four-vector potential. $D_\mu = \partial_\mu - ieA_\mu$ is the defined gauge covariant derivative. γ^μ is Dirac gamma matrices, $\gamma^\mu = \{\gamma^0, \gamma^1, \gamma^2, \gamma^3\}$.

2.2.3. Quantum Chromodynamics

In quantum chromodynamics (QCD), the fundamental process is a vertex of interaction between quarks and gluons, as in Figure 2. Just as in QED, color takes the position of charge in QCD. However, there is only one kind of electric charge, while there are three kinds of color charges (red, green and blue). Color is conserved in this $q \rightarrow q + g$ process. The flavor on the quark holds, but the color may change. Gluons carry a positive unit of color and a negative unit. In addition to the quark-gluon vertex, there are also gluon-gluon

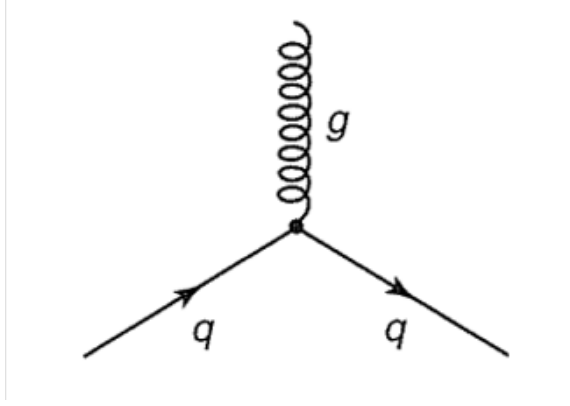


Figure 2: QCD fundamental vertex.

vertices.

Apart from color, a difference between QCD and QED is that the coupling constant α_s is greater than 1, much bigger than QED coupling constant α at low momentum transfer case.

The lagrangian of QCD is given by [7]

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a} (i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t_{ab}^C \mathcal{A}_\mu^C - m_q \delta_{ab}) \psi_{q,b} - \frac{1}{4} F_{\mu\nu}^A F^{A\mu\nu} \quad (2.2)$$

$\psi_{q,a}$ are quark-field spinors for a quark of flavor q , color a and mass m_q . Quarks come in three colors, $N_c = 3$. $\mathcal{A}_\mu^C$ are gluon fields, and C runs from 1 to $N_c^2 - 1 = 8$, which means there are eight kinds of gluons. t_{ab}^C correspond to eight 3 by 3 matrices and are the generators of the SU(3) group. g_s is the QCD coupling constant ($\alpha_s = \frac{g_s^2}{4\pi}$). The field tensor $F_{\mu\nu}^A$ is given by

$$F_{\mu\nu}^A = \partial_\mu \mathcal{A}_\nu^A - \partial_\nu \mathcal{A}_\mu^A - g_s f_{ABC} \mathcal{A}_\mu^B \mathcal{A}_\nu^C \quad (2.3)$$

$$[t^A, t^B] = i f_{ABC} t^C$$

where the f_{ABC} are the structure constants of the SU(3) group.

In perturbative QCD, observable predictions are expressed in terms of $\alpha_s(\mu_R^2)$, the coupling constant is a function of a re-normalization scale μ_R [7]. The coupling follows a

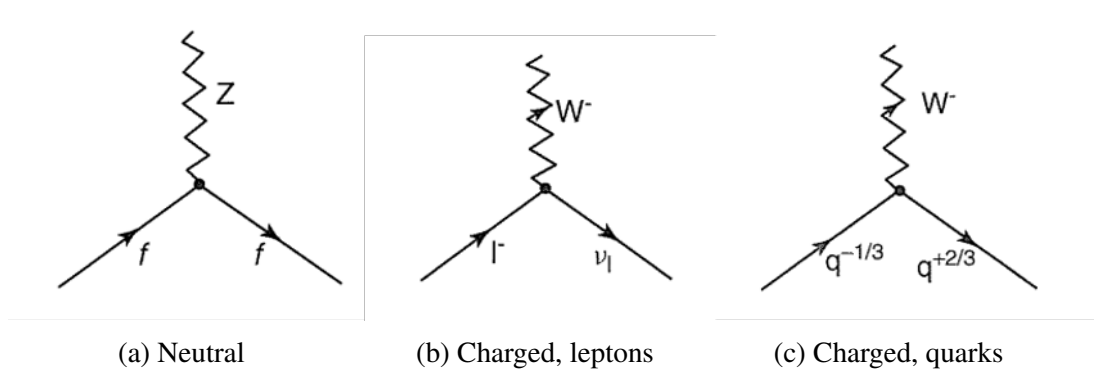


Figure 3: Weak interaction fundamental vertices.

renormalization group equation

$$\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \dots) \quad (2.4)$$

$b_0 = (33 - 2n_f)/(12\pi)$ is the 1-loop β -function coefficient, n_f is the number of quark flavors. Other coefficients can be found in this review article[7]. The minus sign in the equation explains the phenomenon of asymptotic freedom, such that the strong force is weaker for processes with larger energy transfer.

2.2.4. Weak Interaction and Electroweak Model

All leptons and quarks experience weak interactions. There are charged current weak interaction mediated by W bosons, and neutral current weak interactions mediated by Z boson. Their fundamental processes can be described by diagrams in Figure 3.

The neutral current weak interaction is a process including leptons (or quarks) and a Z boson, in Figure 3 (a). The charged current weak interaction is the only process in which a particle's flavor changes. As shown in Figure 3 (b), a negative lepton decays into a neutrino and emits a W^- . This process connects lepton members of the same generation, and it follows the conservation of electron number, muon number and tau number. A similar

process for quarks in Figure 3 (c). The quark flavor changed, but the outgoing quark carries the same color.

There are other interactions between Ws and Z, and W couples to photon, too.

At high energies, the strength of weak interactions is measured by coupling constant $\alpha_W = g_W/4\pi \approx 1/30$, which means it is no longer weak. Glashow, Weinberg, Salam presented a Electro-Weak theory in 1970s. Electromagnetism and weak force is unified under a $SU(2) \times U(1)$ gauge group. The standard electro-weak lagrangian, breaking into two parts,

$$\mathcal{L} = \mathcal{L}_{symm} + \mathcal{L}_{higgs}, \quad (2.5)$$

$\mathcal{L}_{symm}$ has interactions only between gauge bosons and fermions

$$\mathcal{L}_{symm} = -\frac{1}{4}W_{\mu\nu}^i W^{i\mu\nu} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu} + \bar{\psi}_L i\gamma^\mu D_\mu \psi_L + \bar{\psi}_R i\gamma^\mu D_\mu \psi_R \quad (2.6)$$

$i = 1, 2, 3$, and here

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad (2.7)$$

$$W_{\mu\nu}^A = \partial_\mu W_\nu^A - \partial_\nu W_\mu^A - g\epsilon_{ABC} W_\mu^B W_\nu^C$$

B_μ is the gauge field for U(1), and W_μ^A are three generators of SU(2). The generators of SU(2) and U(1) are called weak isospin and hypercharge, respectively. ϵ_{ABC} is the group structure constant for SU(2), which is the same as anti-symmetric Levi-Civita tensor.

Left-handed, right-handed fermion fields are

$$\begin{aligned} \psi_{L,R} &= \frac{1 \mp \gamma_5}{2} \psi \\ \bar{\psi}_{L,R} &= \bar{\psi} \frac{1 \pm \gamma_5}{2} \end{aligned} \quad (2.8)$$

γ_5 is another Dirac matrix. The standard model EW theory is a chiral theory, such that ψ_L and ψ_R behave differently under the gauge. Fermion masses will be brought in by

symmetry breaking mechanism. The covariant derivatives are

$$D_\mu \psi_{L,R} = (\partial_\mu + ig t_{L,R}^i W_\mu^i + ig' \frac{1}{2} Y_{L,R} B_\mu) \psi_{L,R} \quad (2.9)$$

and here $t_{L,R}^i$ are the SU(2) generators and $\frac{1}{2} Y_{L,R}$ are the U(1) generators in reducible representations $\psi_{L,R}$. The electric charge Q is

$$Q = t_L^3 + \frac{1}{2} Y_L = t_R^3 + \frac{1}{2} Y_R, \quad (2.10)$$

that means the Higgs and the electromagnetic field do not interact at tree level.

The physical mediators $W^\pm$, Z, and photon (A_μ generators are defined as linear combinations of the mentioned representations

$$\begin{aligned} W^\pm &= \frac{W^1 \mp iW^2}{\sqrt{2}}, \\ A_\mu &= \cos\theta_W B_\mu + \sin\theta_W W_\mu^3, \\ Z_\mu &= -\sin\theta_W B_\mu + \cos\theta_W W_\mu^3. \end{aligned} \quad (2.11)$$

θ_W is called weak mixing angle.

The EW lagrangian related to Higgs field is given by

$$\mathcal{L}_{higgs} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi^\dagger \phi) - \bar{\psi}_L \Gamma \psi_R \phi - \bar{\psi}_R \Gamma^\dagger \psi_L \phi^\dagger \quad (2.12)$$

ϕ is a vector for all Higgs fields. Γ is a matrix for coupling constants to make sure the Yukawa couplings are invariant. $V(\phi^\dagger \phi)$ is symmetric under SU(2) $\times$ U(1),

$$V(\phi^\dagger \phi) = -\frac{1}{2} \mu^2 V \phi^\dagger \phi + \frac{1}{4} \lambda (\phi^\dagger \phi)^2. \quad (2.13)$$

Let the minimum of ϕ , also called vacuum expectation value be v

$$\langle 0|\phi(x)|0\rangle = v \neq 0. \quad (2.14)$$

We can find the gauge-boson masses from the $\mathcal{L}_{higgs}$ term $(D_\mu\phi)^\dagger(D^\mu\phi)$. Expand it as

$$D_\mu\phi = (\partial_\mu + ig t^i W_\mu^i + ig' \frac{1}{2} Y_{L,R} B_\mu)\phi \quad (2.15)$$

and then $W^\pm$ mass is found by the quadratic terms

$$m_W^2 W_\mu^+ W^{-\mu} = g^2 \left| \frac{t^+ v}{\sqrt{2}} \right|^2 W_\mu^+ W^{-\mu}. \quad (2.16)$$

For Z mass, use Equation 2.11,

$$\frac{1}{2} m_Z^2 Z_\mu Z^\mu = |(g \cos \theta_W t^3 - g' \sin \theta_W \frac{Y}{2}) v|^2 Z_\mu Z^\mu. \quad (2.17)$$

Consider the condition that photon is massless, so

$$Q|v\rangle = (t^3 + \frac{Y}{2})|v\rangle = 0. \quad (2.18)$$

For Higgs doublet, the field is in the form

$$\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix}, v = \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad (2.19)$$

we can get

$$\begin{aligned} m_W^2 &= \frac{g^2 v^2}{2} \\ m_Z^2 &= \frac{g^2 v^2}{2 \cos^2 \theta_W} \end{aligned} \quad (2.20)$$

The gauge bosons acquired masses from the $\mathcal{L}_{higgs}$ as the vacuum state is obtained with a

non-vanishing ϕ . This is the situation of spontaneous symmetry breaking, or referred as Higgs Mechanism.

CHAPTER 3

The Compact Muon Solenoid Experiment

3.1. Compact Muon Solenoid Experiment at CERN

The Large Hadron Collider (LHC) is the largest and most powerful particle accelerator in the world. It accelerates proton beams in opposite directions, and the protons collide at various locations around the LHC ring. The Compact Muon Solenoid (CMS) detector is located at one of these sites.

A schematic map of LHC is in Figure 4. The LHC consists of a 27-kilometre ring of superconducting magnets and complicated accelerating structures. It is located at the European Organization for Nuclear Research (CERN) accelerator complex, near Geneva, Switzerland. The proton beams inside LHC are accelerated and travel close to light speed. The two beams travel in opposite direction in two separate pipes with high vacuum. The magnetic field guides them to move along a designed orientation. A low temperature of -271.3°C is required to maintain the superconducting state of the electromagnets. Four large particle detectors are located around the LHC, and they are placed at the points where proton beams collide. ATLAS and CMS are general purpose particle detectors. Two smaller ones, A Large Ion Collider Experiment (ALICE) and LHCb (Large Hadron Collider beauty), have more specific roles.

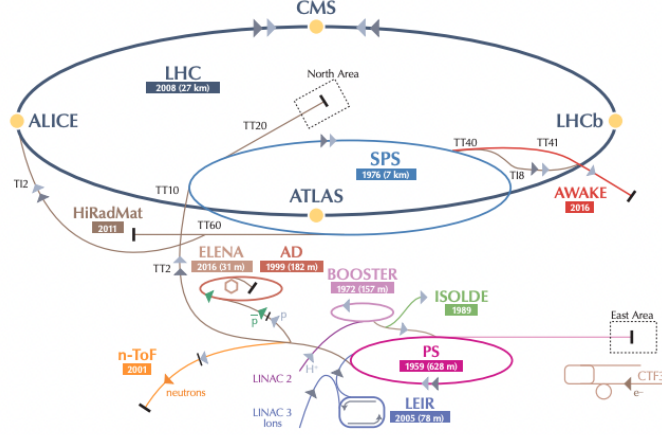


Figure 4: LHC map [8]. CMS, ATLAS, ALICE and LHCb are particle detectors.

LHC is designed to understand physics up to a center-of-mass energy of 14 TeV. The number of events per second generated in the LHC collisions has the following relation with event cross section σ and machine luminosity:

$$N_{event} = \sigma_{event} L \quad (3.1)$$

ATLAS and CMS proton-proton collision experiments which have an operational peak luminosity of $L \approx 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

The CMS detector is a general-purpose particle detector. CMS measures particle collisions from all directions at 40 million times per second. Most of the particles decay and then transform to stable particles which can be detected by CMS. CMS collects the information of their momenta, positions, and energies, and finally we can rebuild the image of the collisions.

The CMS experiment had the first run (Run 1) between 2010 and 2012 when the proton-proton collisions happened at center-of-mass energy of 7 TeV and 8 TeV. The discovery of Higgs boson with a mass of around 125 GeV is a highlight of CMS results [6]. From year 2015 to 2018 (Run 2), LHC ran at a center-of-mass energy of 13 TeV.

3.2. The CMS Detector

3.2.1. Introduction

CMS looks like a cylinder, and is 28.7 meters long with 15 meters in diameter. Its total weight is 14000 tonne so it is quite compact. Looking from outside, the overall view of CMS is as Figure 5.

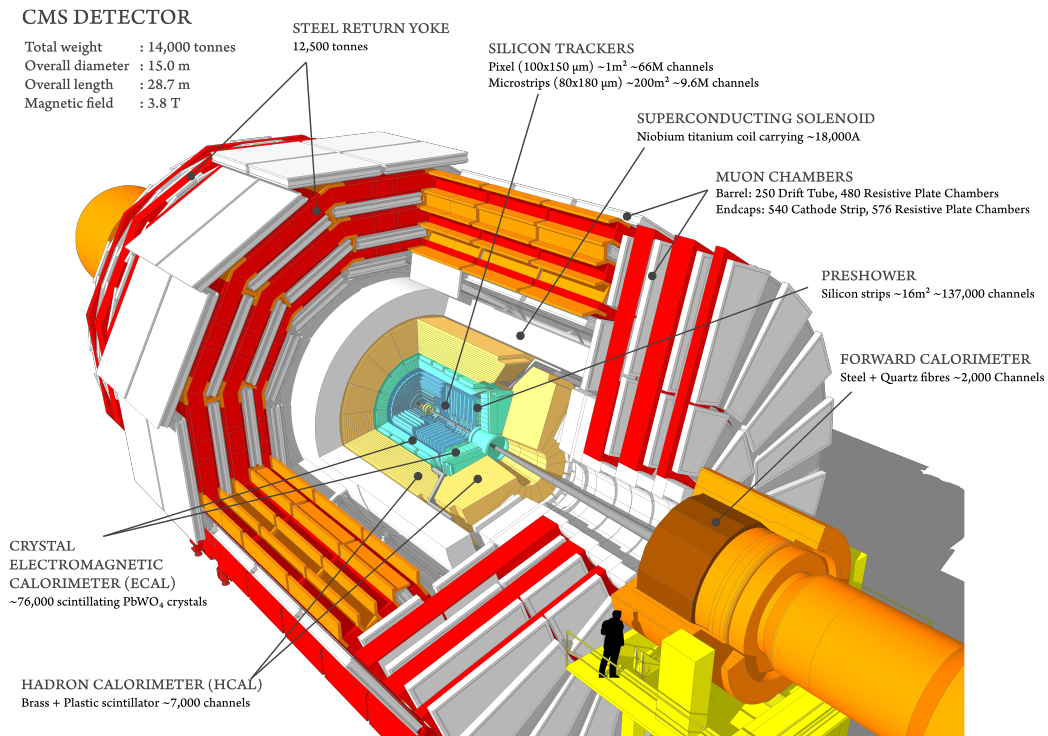


Figure 5: Sectional view of the CMS Detector [9].

CMS has one of the most powerful solenoid magnets ever built until now. The magnet aims to bend charged particles when they fly out from the collision point. By bending particles, one can find the charge and momentum of the particle. The solenoid magnet is made by cylindrical coil of superconducting wires. The coil is cooled to $-268.5\text{ }^\circ\text{C}$ and it can generate a magnetic field of about 4 Tesla [10]. The magnetic field is confined to the inside of the detector by the steel return yoke which forms most part of the detector's mass.

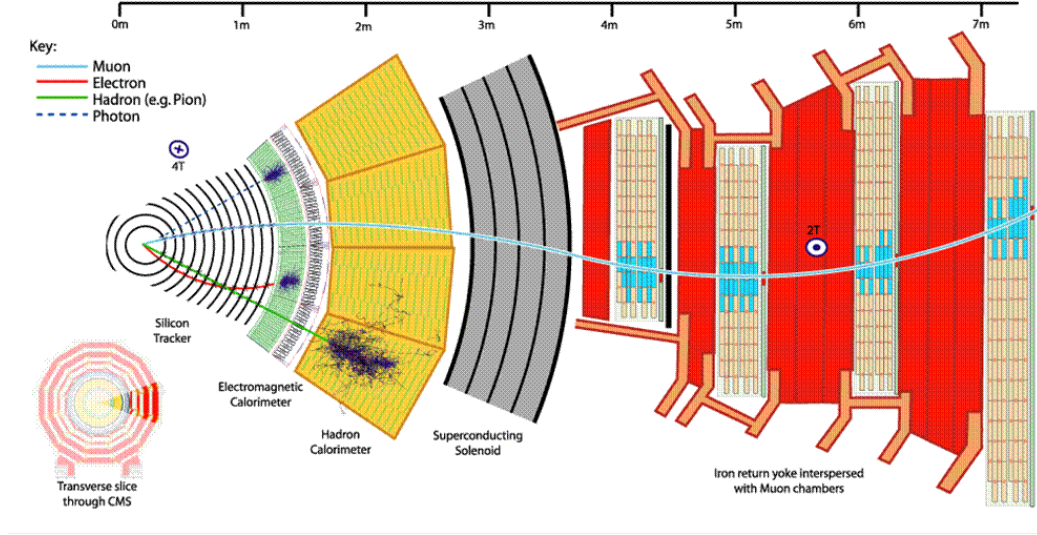


Figure 6: Particle detection process in CMS [11].

CMS consists of several layers of detector material that measure the properties of various types of particles. The path of a particle emerges from the collision through the detector layers of CMS can be described in Figure 6. A particle first encounters the silicon tracker which measures the position of charged particles. Charged particles create spiralling paths in the CMS magnetic field, under Lorentz force $\vec{F}$,

$$\vec{F} = q\vec{v} \times \vec{B} \quad (3.2)$$

where q is the particle's charge, $\vec{v}$ is its velocity, $\vec{B}$ is magnetic field.

After the silicon tracker, the particle travels to two layers of calorimeters. Information about the particles' energies are collected by these two types of calorimeters in CMS. The inner calorimeter, Electromagnetic Calorimeter (ECAL) measures the energy of electrons and photons. The outer one, Hadron Calorimeter (HCAL) measures energy of hadrons, namely particles made of quarks and gluons. Electrons, photons and jets (sprays of particles produced by quarks) will then be absorbed by the calorimeters.

The only known particles that possibly pass the calorimeters are muons and weakly inter-

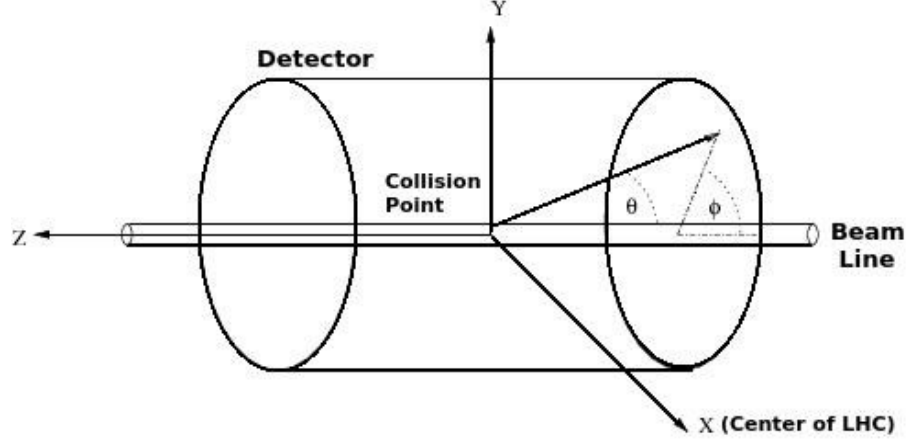


Figure 7: Coordinate system used in CMS detector [12].

acting particles. Muons with high momentum have little interaction with calorimeters and can reach the muon detector system. The paths of muons are measured also in muon chamber detectors. They are built interspersed with the yoke of the solenoid to detect muons and measure their momentum. While neutrinos, which are weakly interacting particles, do not interact with tracker or calorimeters. Their momenta is then calculated from the information of other detected particles.

The coordinate system used in CMS is shown in Figure 7.

The origin centered at the proton beam collision point. The x-axis points radially towards the center of LHC. The y-axis points vertically upward. The z-axis points along the beam direction.

The azimuthal angle ϕ is measured from the x-axis in the x-y plane. The radial coordinate in this plane is denoted as r . The polar angle θ is measured from the z-axis. Pseudorapidity is defined as $\eta = \ln \tan(\theta/2)$. In later sections, we will talk about transverse momentum, denoted by p_T , respectively. It is computed from the x and y components of the momentum p . When mass of a particle is close to zero, we can estimate the transverse energy E_T by p_T .

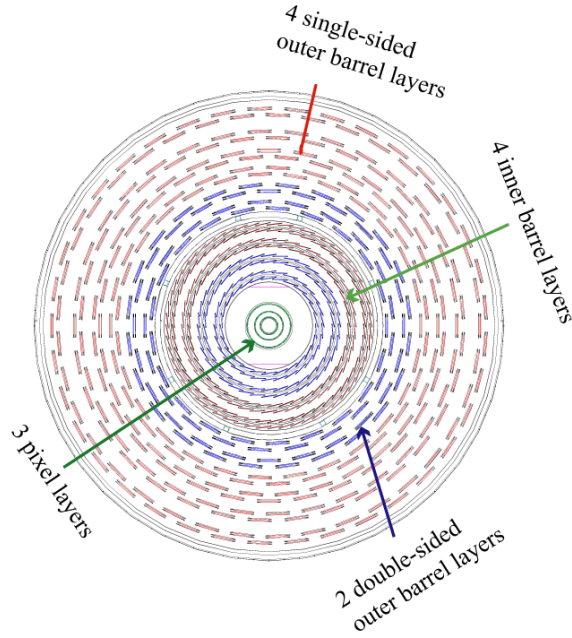


Figure 8: CMS Tracker layers perpendicular to the beam [13].

3.2.2. *Silicon Tracker*

CMS first identifies the paths of particles by a silicon tracker. Figure 8 is a schematic of tracker when looking at the travelling direction of the proton beam. The tracker is made of about 75 million electronic sensors. A charged particle interacts electromagnetically with the silicon when it flies through the tracker layer, and then it creates a hit while ionization. An array of hits from different layers of the tracker are associated with a charged particle and then are used to identify the charge and momentum of the particle. The measurement of the tracks is accurate to $10\ \mu\text{m}$ [13].

The tracker can reconstruct the paths of charged particles: muons, electrons and hadrons. It also identifies tracks coming from the decay of very short-lived particles.

The tracker is the innermost layer of the CMS detector and it collects the largest amount of particles. Therefore, the materials were chosen in order to avoid radiation damage. At the end, the tracker is made entirely of silicon: the pixels, and the silicon micro-strip.

The silicon pixel detector lies at the core of the detector, and it consists of 65 million pixels. It includes cylindrical layers at 44, 73, and 102 mm to the beam pipe and disks at both ends. Each layer contains segments of silicon sensors of $100\text{ }\mu\text{m}$ by $150\text{ }\mu\text{m}$. At the end of year 2016, CMS pixel detector was upgraded, the new system, CMS Phase-1 pixel detector has four layers, at radii of 29, 68, 109, and 160 mm [14].

When a charged particle passes through the pixel, the electrons in the silicon atoms are ejected and electron-hole pairs are generated. An electric current is then created in the pixel and a small electric signal is built. An electric silicon chip is attached to each pixel, and it amplifies the signal.

The detector is made of 2D pixel structure, and it has a number of layers, so we can create a three-dimensional picture.

After pixel layers going outwards, there are ten layers of silicon strip detectors. Figure 9 shows the structure of CMS tracker. The strip detector includes four inner barrel (TIB) layers, two inner endcaps (TID), six outer barrel (TOB) layers and two endcaps (TEC). This part of the tracker has 15200 sensitive modules, and each module has a set of sensors, and the support structure and readout electronics.

A silicon strip detector works in the same way as pixel detector. When a charged particle hits it, it creates an electric signal. On the microstrip, charges are amplified by an Analog Pipeline Voltage chip. Such chips can monitor sensor temperature and provide time information.

3.2.3. Electromagnetic Calorimeter

Electrons and photons are measured by Electromagnetic Calorimeter (ECAL). Special materials, lead tungstate crystals, are used in order to provide precise measurement in such a

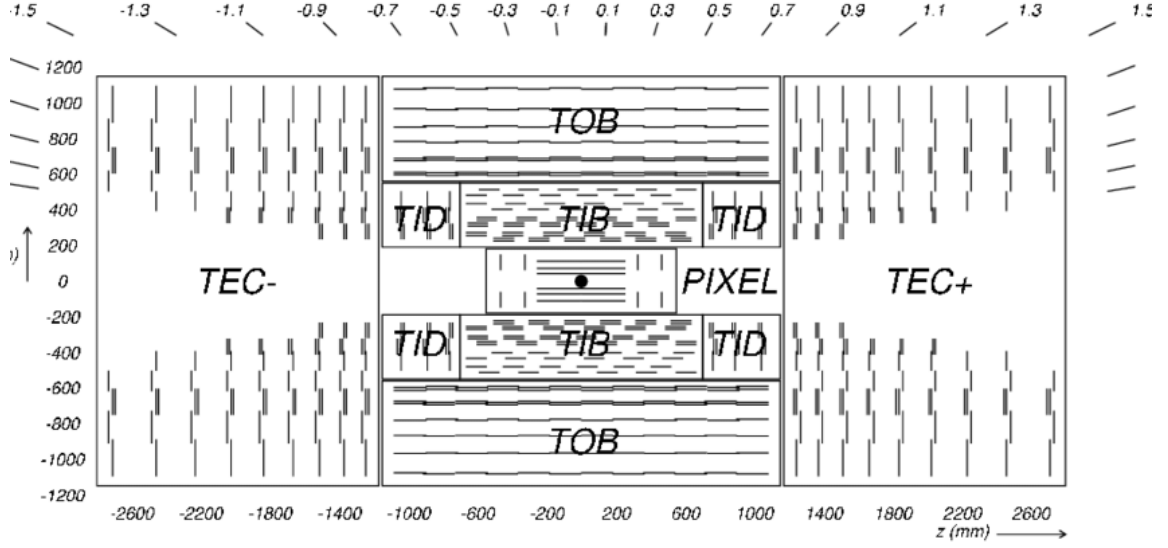


Figure 9: Schematic cross section through the CMS tracker. The beam goes along z -direction [10]. The strip detector includes four inner barrel (TIB) layers, two inner endcaps (TID), six outer barrel (TOB) layers and two endcaps (TEC).

high magnetic field, high radiation environment. This type of crystal produces light as a measure of the particle's energy. Photo detectors are attached on the back of the crystals, and they can detect the scintillation light, produce an electrical signal and amplify it.

The ECAL consists of a cylindrical barrel section and two endcap sections. The barrel section has 61200 crystals, which form 36 supermodules. Each endcap section has 7324 crystals. Figure 10 shows the structure of ECAL. There are Preshower detectors in front of the endcaps which help the measurement of close photon pairs.

Lead tungstate ($PbWO_4$) is a material that produces scintillation light in fast, small, well-defined photon showers. It has high density (8.28 g/cm^3), short radiation length (0.89 cm) which results in a fine granularity and a compact calorimeter. For $PbWO_4$ crystal, the yield of light depends strongly on its temperature, and the heat from nearby electronic units will cause a problem. A cooling system is built so that the temperature of crystals remains stable within $0.1 \text{ }^\circ\text{C}$.

The CMS Preshower detector is built to help identify neutral pions in the endcaps. Neutral

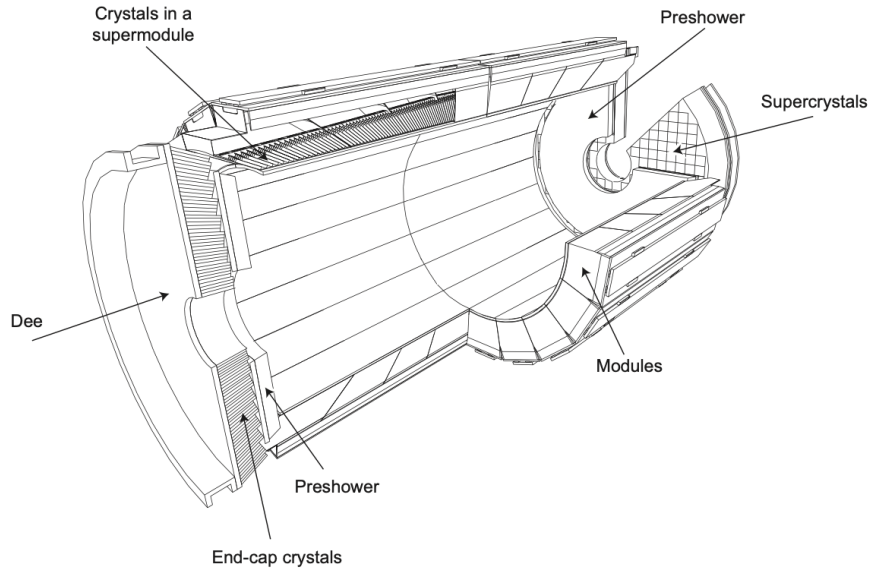


Figure 10: Layout of the CMS electromagnetic calorimeter [10]. Modules and Supermodules are assembled groups of crystals.

pions can decay into closely spaced photon pairs, and they form a small angle in the endcap region which may cause a false signal of a one energetic photon. The Preshower with a thickness of 20 cm is made of two layers, one of lead radiators creating electromagnetic showers from incoming photons or electrons and the other, silicon strip sensors to measure the deposited energy.

3.2.4. *Hadron Calorimeter*

The Hadron Calorimeter, also called HCAL, aims to measure the energy of hadrons. Hadrons are particles made of quarks and gluons. HCAL works as a sampling calorimeter. When particles pass through, its materials produce a light pulse, then photodetectors amplify the signal. The light over a regional area is summed up and the particle's position, time and energy information can be found.

HCAL material is massive, and in order to fit it into CMS, it is distributed into four sections: barrel (HB), outer (HO), endcap (HE) and forward (HF) sections. The layout is shown in

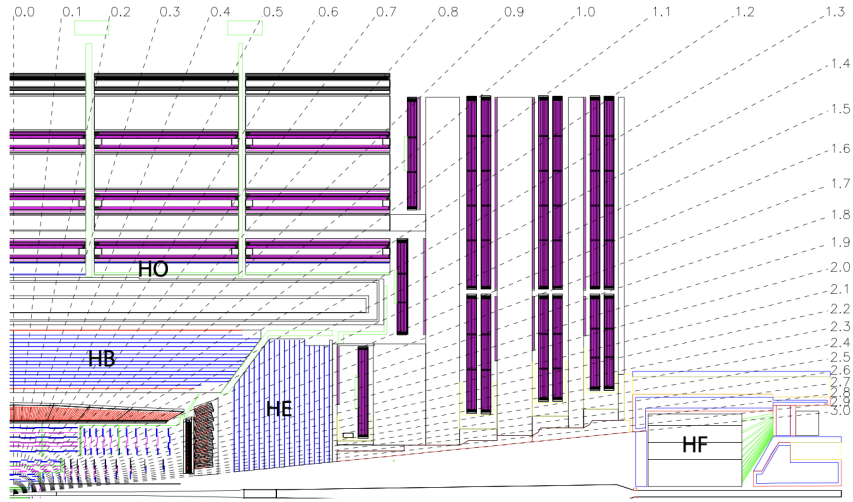


Figure 11: Longitudinal view of the CMS detector, highlighting hadron calorimeter [10]: barrel (HB), outer (HO), endcap (HE) and forward (HF) sections.

Figure 11. HB is in the radial region from the outer layer of ECAL to the inner layer of magnet coil, corresponding to $1.77m < R < 2.95m$. HO calorimeter is placed outside the solenoid. HF covers the region $3 < |\eta| < 5.2$.

The HB and HE sampling calorimeters are made of light absorber and plastic scintillator alternating layers. A hadronic particle hits the absorber, and this interaction produces secondary particles. The secondary particles successively interact with other layers of absorber and produce a shower of particles. This shower passes the active scintillation material and cause them to emit light. The optical fibers absorb the light and carry the light into readout boxes. The optical signal goes through megatile layers before arrives at readout box. Megatile layers are made such that each tile receives the same number of particles. Therefore, the optical tower covers the path of the particle and can be a measure of the particle's energy.

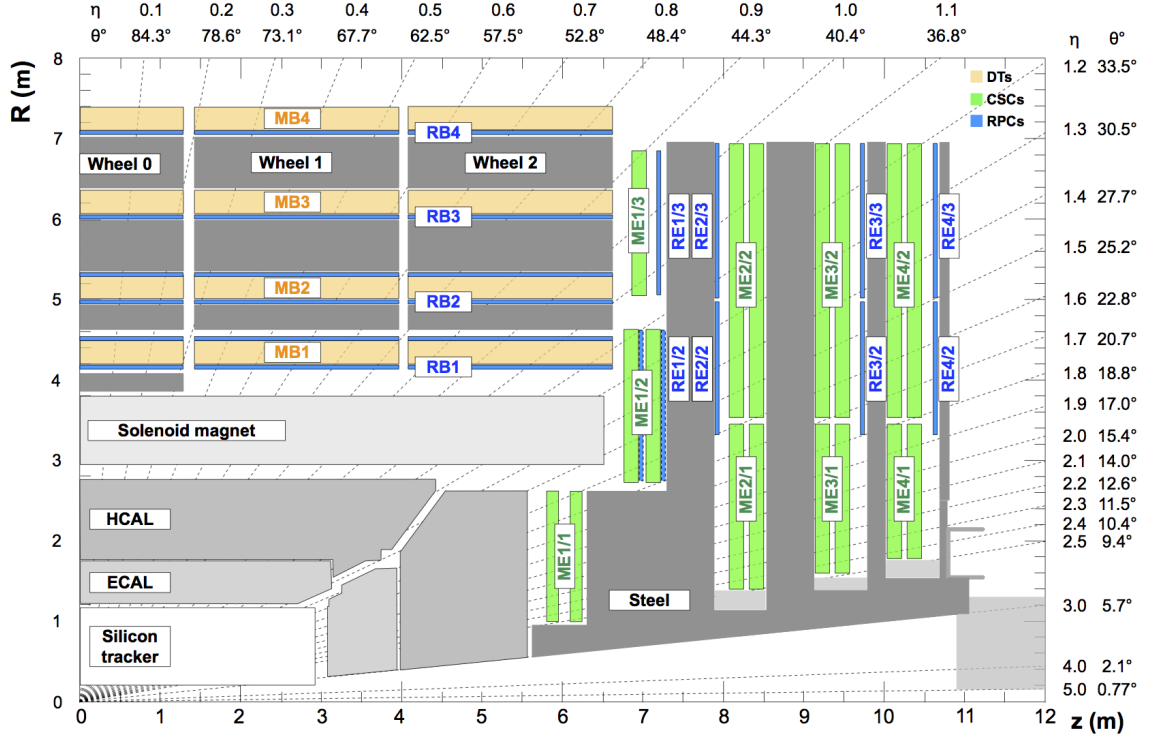


Figure 12: CMS quarter-view, highlighting the muon system. The drift tube stations (DTs) are labeled as MB (namely Muon Barrel) and the cathode strip chambers (CSCs) are labeled as ME (namely Muon Endcap). Resistive plate chambers (RPCs) are mounted in both the barrel and endcaps of CMS, where they are labeled RB and RE [15].

3.2.5. Muon System

The CMS is most powerful in the measurement of muons compared with other existing particle detectors. Muons are not stopped by the ECAL and HCAL and reach the outermost part in CMS. A muon hits the muon detectors, and its trajectory and momentum can be measured from the curve of hits, combined with the information from the silicon tracker. There are 1400 muon chambers in total, consisting 250 drift tubes (DTs), 540 cathode strip chambers (CSCs) and 610 resistive plate chambers (RPCs). DTs and CSCs track the particles' positions and provide a trigger, and PRCs serves as a second trigger to decide whether to keep the data. Figure 12 shows the structure of muon system.

The drift tubes are located in the barrel part of CMS. A drift tube is a wire like tube con-

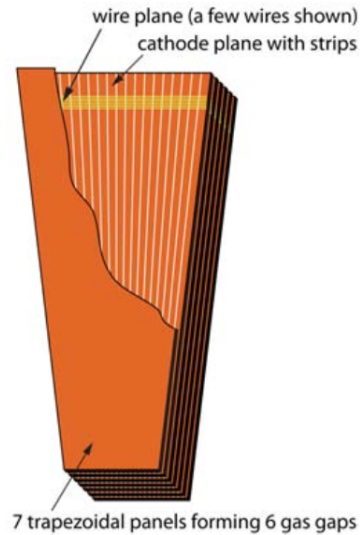


Figure 13: CMS Cathode strip chambers (CSCs) layout.

taining gas. A particle ejects electrons off the gas atoms when passing the gas volume. By collecting the positions of the wire electrons, DT can find the position of the particle.

The cathode strip chamber are located in the endcap, and it consists of positively-charged wires crossed and negatively-charged copper strips. Electrons ejected off the gas atoms create an avalanche in wires, and positive ions move to the copper strips, which induce a charge pulse. The strips and wires are perpendicular so we can get two-dimensional position of a passing particle. Figure 13 is a layout of the CSC [10].

Resistive plate chambers are gaseous detectors to provide a muon trigger system. They are mounted in the barrel and endcap as shown in Figure 12. RPCs have two parallel plates, a positively-charged anode and a negatively-charged cathode. When a particle passes the gas material, electrons will be knocked off and then an avalanche is created. The electronic signal is collected by external metallic strips. The pattern of hits on strips gives a measure of the particle's momentum.

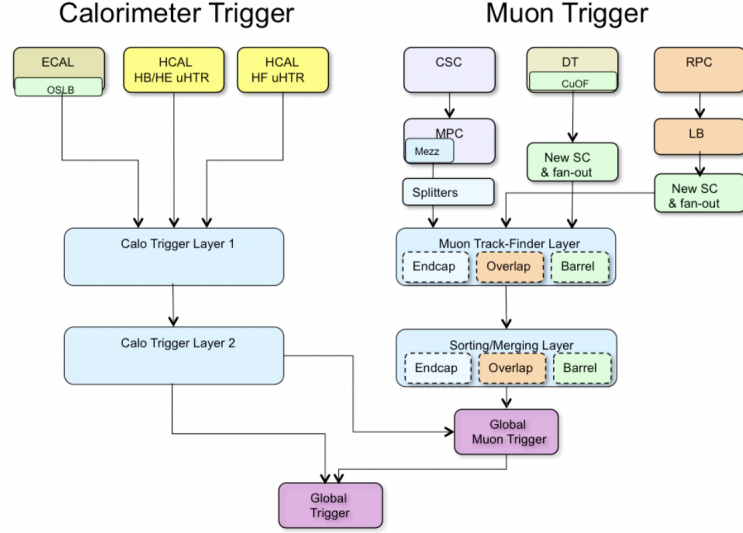


Figure 14: CMS L1 trigger system schematics.

3.3. Trigger System

The LHC provides proton-proton collisions at a very high rate with a beam crossing frequency of 40 MHz. It is impossible to store and process such a large amount of collision data. Therefore, a trigger system is designed to select only the data that are useful to discover new physics. The trigger system reduces the event rate in two steps, Level-1 (L1) Trigger and High-Level Trigger (HLT).

The structure of L1 Trigger is shown in Figure 14, and it consists of electronic units in calorimeters and muon detectors. After L1 Trigger, the output event rate is 100 kHz. L1 Trigger analyzes each crossing within 4 μ s [16]. L1 Trigger has local components called Trigger Primitive Generators (TPGs). TPGs collect information of energy deposits in calorimeter trigger tower, track segments or muon chamber hits. Then, the Regional Calorimeter Trigger determines object candidates, like electron or photon, and transverse energy in each calorimeter region. The Global Calorimeter Trigger determines jets, the total transverse energy, the missing transverse energy, and other information about jets. Details about jets will be discussed in later section.

As we discussed in Section 3.2.5, drift tubes (DTs), cathode strip chambers (CSCs) and resistive plate chambers (RPCs) all have the function of a trigger. The local triggers in DTs provide track segments or hit patterns. The CSCs provide track segments. Regional muon trigger is made of DT and CSC Track Finders, which can build complete tracks. RPC triggers create their track candidates from the regional hit patterns. All the different local triggers can also record the bunch crossing point of the collision. Finally, the Global Muon Trigger combines information from the sub-detectors, and get better momentum resolution and efficiency.

HLT is a software system. HLT consists of a processor farm called event filter farm. It first builds each event from fragments of different parts of the detector. The builder units send assembled events to filter units, and a filter unit unpacks the data and performs trigger filtering. HLT processes data in various HLT path. A path is a set of algorithms that reconstruct physics objects and make selections. The HLT selects less than 1000 events per second. After HLT, the accepted events are sent to a storage process software.

3.4. Physics Object Reconstruction

3.4.1. Particle Flow Elements

The structure of the CMS detector has different advantages for measuring different objects in each detector layer, which gives us capability to reconstruct physics object based on signals in a given detector layer. For example, we can build jets, which consist of hadrons and photons, from the energy measured by calorimeters. We can build electrons and photons through ECAL information, and build muon primarily from information collected in muon detectors. However, reconstruction performance can be improved significantly by correlating all the basic elements in various detector layers. This approach is called Particle Flow (PF) reconstruction [17]. With that said, the object reconstruction has two main

steps: detector reconstruction and combined reconstruction.

Detector reconstructions build particle flow elements: tracks from tracker and calorimeter clusters from both ECAL and HCAL. Tracking aims to measure momentum of energetic particles, and tracks are reconstructed based on Kalman Filtering (KF) [18]. The algorithm finds a few hits as initial seeds, builds a trajectory, then does a fitting to a curve and to obtain the origin, transverse momentum, and direction of a charged particle. The calorimeter clustering is processed in ECAL barrel, ECAL endcap, HCAL barrel, HCAL endcap and pre-shower layers separately. Cluster seed cells are selected if the energy is greater than a threshold and if they are cells with highest energy in the local area. Topological cluster is constructed by combining seed cells if they have a corner in common.

Muons can be classified as three types depending on how they are reconstructed. If a muon is determined by DT, CSC, and RPC hits, it is called a “standalone muon”. If a standalone-muon track is spatially matched to a track in the inner tracker, it is a “global muon”. If there is an inner track with $p_T > 0.5$ GeV, total momentum $p > 2.5$ GeV, after an extrapolation to muon system, it matches at least one muon segment, it is called a “tracker muon”. Global-muon reconstruction have better efficiency for muon with higher momentum that reaches more than one muon detector layers. While for muons of p_T less than 10 GeV, the tracker muon reconstruction works better [19]. Charged hadrons may reach the muon detector and are reconstructed as muons. The PF algorithm can improve the muon identification performance by combining energy deposits in HCAL, ECAL, and outer hadron calorimeter (HO) as well as tracks.

3.4.2. Particle Flow Algorithm

PF algorithm is used to reconstruct the following particles: muon, electron, photon and hadrons. At first, a link algorithm is deployed in order to connect the elements in different

detector layers that may come from the same particle. The link algorithm tries to connect a pair of elements depending on the distance in (η, ϕ) plane as well as their nature [17].

Since electrons often emit photons due to the material in tracker, and photons convert to electrons, electron and photon reconstructions face similar difficulties. Isolated photon is reconstructed together with electron by combining information from inner tracker and calorimeters. For ECAL-based electron candidates (which uses ECAL seeds) and for photon candidates, it is required that the sum of the energies in the HCAL cells with a distance $\Delta R < 0.15$ to the supercluster position cannot exceed 10% of the supercluster energy. Supercluster is a group of ECAL clusters in a η, ϕ window. Electron candidates are then selected by an identification process based on boosted-decision-tree (BDT) classification. The ECAL superclusters suffer from overlapping deposits from other particles, so the efficiency is limited by strict isolation. Electrons in jets or low p_T electrons might not be reconstructed. A tracker-based method is developed for electrons, too. A photon is kept if it is isolated from tracks and calorimeter clusters and if the ECAL energy pattern matches the photon shower.

PF algorithm implements a series of selections for muon identification. Global muons are considered as “isolated” by verifying additional inner tracks and calorimeter energy deposits which have a distance $\Delta R < 0.3$ to the muon direction. Non-isolated global muons need to pass a tight selection [19]. If a muon has $p_T < 200$ GeV, its momentum is determined that of the inner track. Otherwise, its momentum is chosen to be the best fit by χ^2 among different track fits.

After the muons, electrons and isolated photons are removed, the remaining elements are identified as hadrons which are from jet hadronization and fragmentation.

3.4.3. *Jets and Missing Transverse Momentum*

The particles reconstructed from PF algorithm are used to build jets, and missing transverse momentum p_T^{miss} . CMS uses anti- k_T algorithm (AK) to reconstruct jets [20]. If it clusters all PF particles, we call them PF jets. If it only clusters the sum of the ECAL and HCAL energies deposits, we call them Calo jets. The anti- k_T algorithm iteratively finds two particles in the event which are closest in some distance measure R and combines them into one jets. The AK4 jet algorithm uses a distance parameter $R = 0.4$.

There are particles that do not interact with detector material like neutrinos. They can be measured by computing the missing transverse momentum p_T^{miss} , the inverse vector sum of momenta of all PF particles in the event,

$$\vec{p}_{T,PF}^{miss} = - \sum_{i=1}^{N_{particles}} \vec{p}_{T,i} . \quad (3.3)$$

CHAPTER 4

Top Mass and Decay Width Measurement in Di-lepton Final States

4.1. The Top Quark

The top quark has a charge of $+2/3$. It is the heaviest among all types of quarks, and also heavier than a W boson. Top quark decays predominantly semi-weakly into a W boson and a b quark. It has a short lifetime of $\sim 10^{-25}$ s and it decays before hadronization. The top quark Yukawa coupling strength is close to 1, which is due to the large value of measured m_t . Therefore, study of top quark is a test to the Standard Model, and it helps us to constrain many beyond standard model theories.

In hadron collisions, the dominant process for production of top quarks is to top anti-top ($t\bar{t}$) pairs. At the Tevatron accelerator, where proton-proton beams collide at center of mass energy of 1.96 TeV, about 85% of the top quarks are produced in quark anti-quark annihilation. While at the LHC, when proton-proton collisions occur at 7 TeV, about 80% of $t\bar{t}$ production arises from gluon-gluon fusion [21] as in Figure 15. The LHC has measured the cross section of top quark pair production to be $\sigma_{t\bar{t}} = 252.9^{+6.1+11.5}_{-8.6-11.5}$ pb at $\sqrt{s} = 8$ TeV, and $\sigma_{t\bar{t}} = 831.8^{+19.8+35.1}_{-29.2-35.1}$ pb at $\sqrt{s} = 13$ TeV [22] assuming a top quark mass

of 172.5 GeV. Single top quark production is an electroweak mechanism: two processes $q\bar{q}' \rightarrow t\bar{b}$ and $qb \rightarrow q't$ are mediated by virtual s-channel and t-channel W bosons, while the process $bg \rightarrow W^-t$, top is produced accompanied by a W boson.

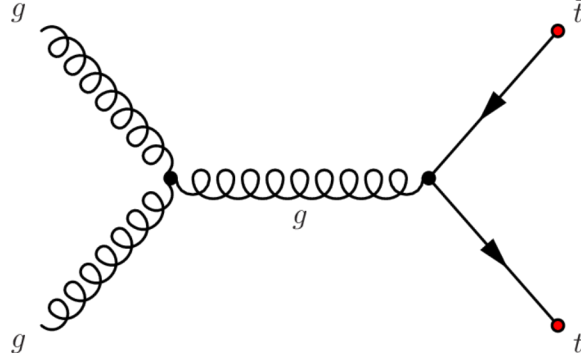


Figure 15: Top antitop production via gluon-gluon fusion diagram.

The decay of top quark is dominated by the process $t \rightarrow Wb$. The decay width predicted at NLO is [23]

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_S}{3\pi} \left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right] \quad (4.1)$$

which yields $\Gamma_t = 1.35$ GeV for $m_t = 173.3$ GeV, using $\alpha_S = 0.118$. For $m_t = 172.5$ GeV, the equation predicts $\Gamma_t \sim 1.33$ GeV.

Top quark decays can be divided into three final states distinguished by the number of leptons:

all-hadronic: $t \rightarrow W^+ b W^- \bar{b} \rightarrow q\bar{q}' b q'' \bar{q}''' \bar{b}$ (45.7%);

lepton+jets: $t \rightarrow W^+ b W^- \bar{b} \rightarrow q\bar{q}' b \ell^- \bar{\nu}_\ell \bar{b} + \ell^+ \nu_\ell b q'' \bar{q}''' \bar{b}$ (43.8%);

dilepton: $t \rightarrow W^+ b W^- \bar{b} \rightarrow \ell^+ \nu_\ell b \ell'^- \bar{\nu}_{\ell'} \bar{b}$ (10.5%).

We will encounter these final states often in particle physics. As the quarks evolve through strong interactions into “jets” in the detection or reconstruction stage, the all-hadronic channel is also known as all-jets channel. The branching fraction of these states is stated in the parentheses.

4.2. Introduction to Top Mass and Width Measurement

This chapter provides a measurement of top quark mass and decay width. We use the $t\bar{t}$ dilepton final state from the proton-proton collision data at center-of-mass energy $\sqrt{s} = 13$ TeV. The data were taken during CMS Run 2 in 2016. The method for the measurement is based on comparing data to expected simulation through a likelihood method.

To measure m_t , the idea is to either reconstruct the top quark mass or have a variable which tracks the mass of the top quark. The top quark mass has been studied extensively in the past, in lepton+ jets, dilepton or all jets channels in Tevatron and LHC experiments. The most precise result was produced in the lepton plus jets channel, as there is only one neutrino in this final state and we have large data statistics available. In this final state the neutrino momentum can be solved by the known W mass constraint. The common technique used for measuring m_t is called “template method” [24]. The template method compares simulated data at a variety of top quark mass to extract top quark mass from the data. As this method is most sensitive to jets, a strategy has been developed to deal with the systematic uncertainty of jet energy scale which makes use of lepton plus jets channel, where jet energy can be controlled by a fit to $W \rightarrow jj$. CMS most recent result with such technique using $\sqrt{s} = 13$ TeV data gets $m_t = 172.26 \pm 0.07(stat. + JSF) \pm 0.61(syst.)$ [25]. JSF represents the uncertainty from jet energy scale. In dilepton channel, the challenge is how to reconstruct the two neutrinos in the final state. To date, the most precise measurement in this channel uses the variable $m(\ell b)$ which is the invariant mass of lepton b-jet system. A previous CMS study [26] obtained a mass and JSF measurement by simultaneously fitting $m(\ell b)$ and a transverse-mass-like variable M_{T2} built from b and $\bar{b}$ daughters of the $t\bar{t}$ system [27]. This analysis determined a total uncertainty of 0.54%. In the all-jets channel, we face the problem that the QCD multijets events in the background

harm the data and simulation agreement. Background modeling and reducing irrelevant events are the major complication. CMS paper [25] used an ideogram method, with a simultaneous fit on m_t and JSF. ATLAS did a template fit to the ratio of tri-jet mass and di-jet mass, where tri-jet mass represents a top quark and di-jet mass represents a W boson system [28].

The methods to measure the decay width of a fundamental particle can be classified into two types, direct measurement or indirect measurement. Direct measurements make use of the reconstructed top quark mass distribution or the shape of lepton b-jet combined mass. The result presented [29] from ATLAS collaboration yields $\Gamma_t = 1.76 \pm 0.33^{+0.79}_{-0.68}$ GeV, assuming $m_t = 172.5$ GeV. A recent measurement, which is also the most precise to date, is a result from ATLAS with 139 fb^{-1} of data at $\sqrt{s} = 13$ TeV [30]. It uses a template fit to the lepton b-quark invariant mass in dilepton final states. The result is $\Gamma_t = (1.9 \pm 0.5)$ GeV. Indirect measurements take the result of the single top t-channel cross section and combines it with the branching fraction $\mathcal{B}(t \rightarrow Wb)/\mathcal{B}(t \rightarrow Wq)$ to measure Γ_t . CMS used this measure to determine $\Gamma_t = 1.36 \pm 0.02(\text{stat.})^{+0.14}_{-0.11}(\text{syst.})$ GeV with data at $\sqrt{s} = 8$ TeV [31].

This analysis is a direct measurement of top quark decay width Γ_t . The observable $m(\ell b)$, mass of lepton b-jet pairs, is reconstructed from the final state products of the top quark decay. We take two leptons and do not use the missing transverse energy or large number of jets in order to avoid the problem of poor resolution in reconstruction and higher uncertainties. The Monte Carlo (MC) simulation samples consider only the leading order (LO) of the top quark decay. In this case, the shape of the top mass distribution follow a relativistic Breit-Wigner distribution. Since the matched parton shower calculations are not available, the LO predictions would restrict our measurement to those kinematics for which the next-to-leading-order effects are minimal.

4.3. Data and Simulation Samples

The data and simulation samples for analysis are produced by the official CMS software, CMSSW_9_4_11.

The data of 2016 have a total integrated luminosity of $35.9 \pm 2.5 fb^{-1}$. Table 3 shows all the data used in this analysis.

Table 3: Data samples used in this analysis.
PD = SingleMuon, SingleElectron, DoubleMuon, DoubleEG or MuonEG.

Data
/PD/Run2016B-17Jul2018_ver2-v1/MINIAOD
/PD/Run2016C-17Jul2018-v1/MINIAOD
/PD/Run2016D-17Jul2018-v1/MINIAOD
/PD/Run2016E-17Jul2018-v1/MINIAOD
/PD/Run2016F-17Jul2018-v1/MINIAOD
/PD/Run2016G-17Jul2018-v1/MINIAOD
/PD/Run2016H-17Jul2018-v1/MINIAOD

In the early stages of the analysis, we used the MC inclusive $t\bar{t}$ samples produced by CMS official production, but we found the limited statistics raised some difficulties and limitations. We proceed to generate private high statistics $t\bar{t}$ samples, designed to decay to di-lepton final states. Private samples are generated by us for this analysis and are not produced by the CMS official MC production campaign. They follow the same configuration as the official CMS MC production. In the $t\bar{t}$ simulation, it is assumed that $m_t = 172.5$ GeV, and $\Gamma_t = 1.31$ GeV, which is considered as “nominal” scenario in this analysis.

There are many other Standard Model processes that produce similar dilepton final states, namely Drell-Yan (DY), di-boson (WW,WZ,ZZ) and single top process tW channel. These processes all produce two leptons and two jets in the final state, from the leptonic decay of W bosons. They are treated as background events in this analysis. The simulation samples are summarized in Table 4. We have additional MC samples for some alternative $t\bar{t}$, single top processes which are used for systematic uncertainty estimation, and

they are listed in Table 5. All simulation samples are from RunIISummer16MiniAODv3-PUMoriond17_94X_mcRun2_asymptotic_v3 production.

Table 4: MC simulation samples, samples marked with [†] have been privately produced.

Process	Dataset	Generator	σ [pb]
Signal			
$t\bar{t}$	MC13TeV_2016_tt2l_0p90 [†]	powheg-pythia8	87.5
	MC13TeV_2016_tt2l_1p31 [†]		
	MC13TeV_2016_tt2l_1p90 [†]		
Background			
WZ	WZ	pythia8	27.6
WW	WW	pythia8	75.8
ZZ	ZZ	pythia8	12.1
W+jets	WJetsToLNu	madgraphMLM-pythia8	61527
tW	ST_tW_antitop_5f_NoFullyHadronicDecays	powheg	19.5
	ST_tW_top_5f_NoFullyHadronicDecays	powheg	19.5
	DYJetsToLL_M-10to50	amcatnloFXFX-pythia8	18610
Drell-Yan	DYToLL_0J	amcatnloFXFX-pythia8	4757
	DYToLL_1J	amcatnloFXFX-pythia8	859.6
	DYToLL_2J	amcatnloFXFX-pythia8	340.5

Table 5: Simulation samples used for systematics.

Systematic uncertainty	Dataset	Generator
Underlying event	TT_TuneCUETP8M2T4up	powheg-pythia8
	TT_TuneCUETP8M2T4down	powheg-pythia8
Resummation (hdamp)	TT_hdampUP	powheg-pythia8
	TT_hdampDOWN	powheg-pythia8
color reconnection	TT_TuneCUETP8M2T4_erdON	powheg-pythia8
	TT_TuneCUETP8M2T4_QCDbasedCRTune_erdON	powheg-pythia8
	TT_TuneCUETP8M2T4_GluonMoveCRTune	powheg-pythia8
Top mass	TT_TuneCUETP8M2T4_mtop1695	powheg-pythia8
	TT_TuneCUETP8M2T4_mtop1715	powheg-pythia8
	TT_TuneCUETP8M2T4_mtop1735	powheg-pythia8
	TT_TuneCUETP8M2T4_mtop1755	powheg-pythia8
	ST_tW_top_5f_mtop1695_NoFullyHadronicDecays	powheg-pythia8
	ST_tW_antitop_5f_mtop1695_NoFullyHadronicDecays	powheg-pythia8
	ST_tW_top_5f_mtop1755_NoFullyHadronicDecays	powheg-pythia8
	ST_tW_antitop_5f_mtop1755_NoFullyHadronicDecays	powheg-pythia8
tW/t $\bar{t}$ interference	ST_tW_top_5f_DS_NoFullyHadronicDecays	powheg-pythia8
	ST_tW_antitop_5f_DS_NoFullyHadronicDecays	powheg-pythia8

4.4. MC Corrections

Many corrections to MC samples are applied in order to better match the data taken from the detector.

Pileup re-weighting Pileup are minimum-bias interactions to include the effects which are not from collision of the primary vertices. We re-weighted the number of pileup in generator level to match the estimation in data, with a minimum-bias of 69.2 mb[32]. Also, a 5% uncertainty for minimum-bias cross section is considered. Figure 16 shows the number of primary vertices and the mean energy density reconstructed in the data and MC simulation events after MC corrections.

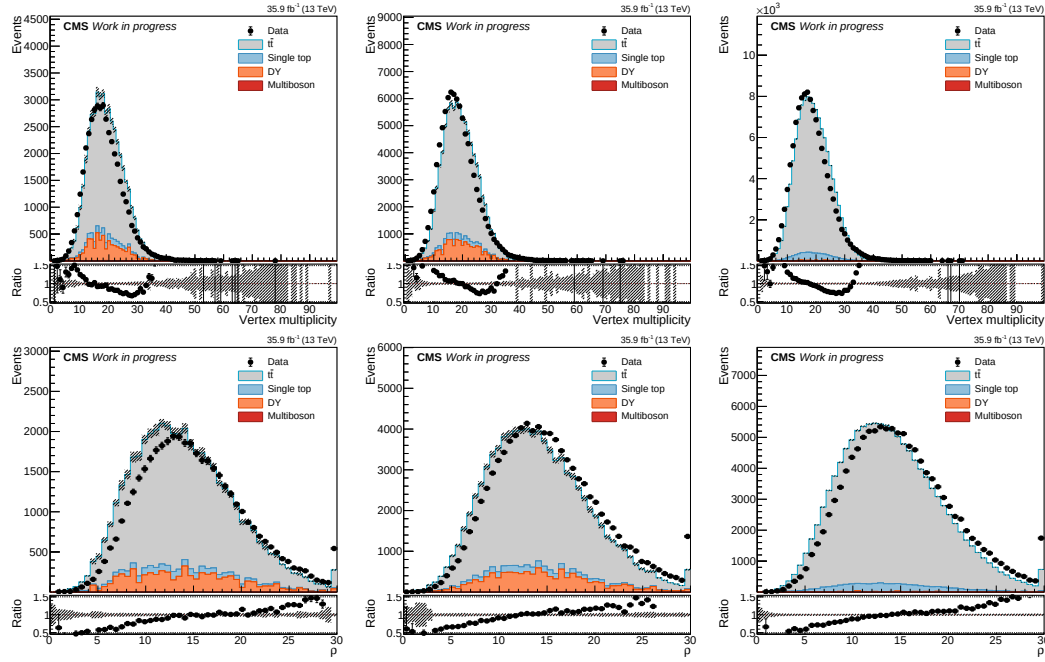


Figure 16: Distributions of the number of primary vertices (top) and ρ (bottom) in the ee (left), $\mu\mu$ (center) and $e\mu$ (right) channels. The uncertainties are of statistical nature.

Trigger efficiency A scale factor to account for the difference in data and MC trigger efficiencies is applied as a function of p_T and η . The scale factors are derived in a CMS study [33].

Lepton efficiencies Corrections to account for the difference in data and MC efficiencies for lepton tracking, reconstruction, identification and isolation are applied as a p_T , η dependent factor. Extra corrections are applied for lepton resolution and scale.

Jet energy scale and resolution We applied jet energy scale correction

Summer16_07Aug2017_V11 following the recommendation [34]. Jet energy resolution is corrected by a p_T , η dependent factor, as the process described [35].

b-tagging efficiency A p_T -dependent data-to-MC scale factor is applied to correct the performance of the b-tagging algorithm in MC to match that of data. The method creates an event-weight based on the expected flavor composition and the scale factors are derived from a muon enriched QCD sample [36].

Generator level weights We want to normalize the simulation process to the effective integrated luminosity. To calculate the number of events expected for a process is

$$\hat{N} = \mathcal{L} \cdot \sigma \cdot \sum_{i=1}^{N_{\text{sel}}} w_i / \sum_{i=1}^{N_{\text{gen}}} w_i \quad (4.2)$$

where $\mathcal{L}$ is the integrated luminosity, σ is a theory prediction for cross section and w_i are the per-event generator level weights.

L1 prefire efficiency In 2016 data-taking era we found the L1 trigger has an inefficiency for events in the endcap region. This effect would lead to a shift of the ECAL L1 trigger timing. An additional weight based on the jet kinematics is applied [37].

MC-to-MC corrections This correction is a consideration for MC samples dedicated for systematic uncertainty processes. The above mentioned b-tagging efficiency and jet energy scale factors are designed for our nominal $t\bar{t}$ samples listed in Table 4 and it has a particular underlying events (UE) tune, TuneCUETP8M2T4. These systematic $t\bar{t}$ samples have rather different UE settings, which are shown in Table 5. So we need to apply such

MC-to-MC corrections so that the b-tagging efficiency and jet energy scale factor match the corresponding configurations.

4.5. Event Selection

To select events for the final analysis, we require at least two leptons, where lepton can be either muon or electron, two jets, and request that at least one of them is b-tagged jet.

A set of dilepton and single lepton triggers is applied as the first selection, shown in Table 6. If an event is found in both the single lepton and double lepton datasets, it is only counted once. For example, ee events are extracted from double electron and single electron datasets. When an event is found from the SingleElectron dataset, it should not have been triggered by a double electron trigger.

Table 6: HLT triggers. The last column reports the dataset where the triggers are considered to be valid.

Final state	Triggers used	PD
$\mu\mu$	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v	DoubleMuon
$\mu+X$	HLT_IsoMu24_v or HLT_IsoTkMu24_v	SingleMuon
$e\mu$	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v (except 2016H) HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v (except 2016H) HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v (run $\geq$ 278273) HLT_Mu12_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v (run $\geq$ 278273)	MuonEG
ee	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v	DoubleEG
$e+X$	HLT_Ele32_eta2p1_WPTight_Gsf_v	SingleElectron

The offline selections are described as follows.

We select tight electrons or muons, and their $p_T > 20$ GeV, $|\eta| < 2.5$. Electrons reconstructed in the ECAL barrel to endcap region are not considered. Two leptons need to be with opposite charges. The pair of leptons with highest $p_{T\text{sum}}$ is considered to be the candidates from a $t\bar{t}$ decay. We require that the leading lepton has a $p_T > 30$ GeV and the mass of the lepton pair $m(\ell, \ell') > 20$ GeV.

Tight, medium, and loose are the commonly used identification quality levels (ID) for leptons. There are different algorithms to define an ID, like MVA based ID, cut based ID [38]. Tight working point(s) has lower signal efficiency, and loose working point has higher signal efficiency. Figure 17 shows an example of muon ID efficiencies using 2015 data [39]. Efficiencies are determined by a tag-and-probe method described in the paper.

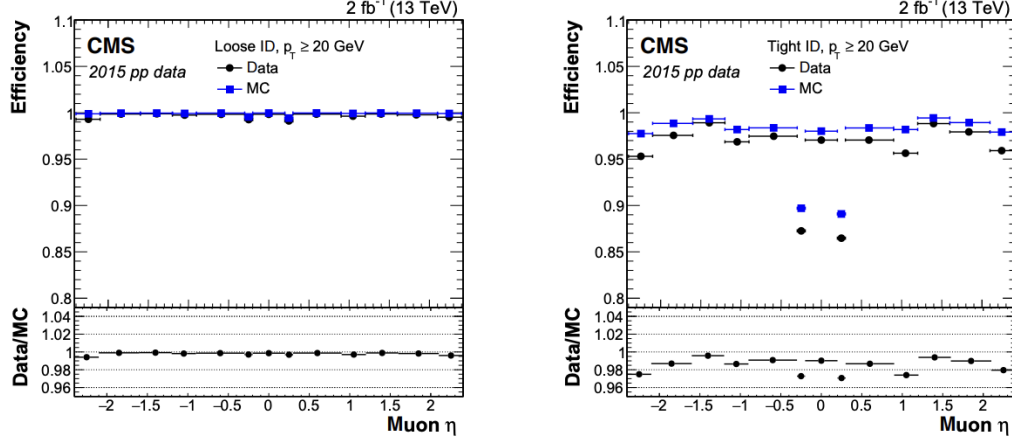


Figure 17: Muon reconstruction and identification efficiencies for loose (left) and tight (right). Plots are from a dedicated muon reconstruction study [39].

In this analysis, we use AK4 CHS jets with $p_T > 30 \text{ GeV}$ and $|\eta| < 2.4$. The distance between jet and selected lepton meets the criterion that $\Delta R(\ell, \text{jet}) > 0.4$. DeepCSV algorithm [40] medium working point, of 1% fake rate, is used for b-tagging. Figure 18 shows the expected b-tagging efficiency in $t\bar{t}$ events, and the b-tagging efficiency is around 80%. We keep the event if it has at least two jets and at least one of them is a b-tagged jet.

Here we show some control distributions after the event selection procedure. Figure 19 are kinematics of leptons, and Figure 20 shows the selected di-lepton kinematics. The uncertainty shown in the figures does not include systematic uncertainties. The overall agreement between data and MC is good, while the p_T of leptons is slightly higher in MC. Jet kinematics are shown in Figure 21 and jet, b-jet multiplicity in Figure 22.

Lepton b-jet pairs' kinematics can be found in Figure 23. We observe that the p_T of the lep-b system is softer in data, coming from the same behavior of leptons and jets. We will

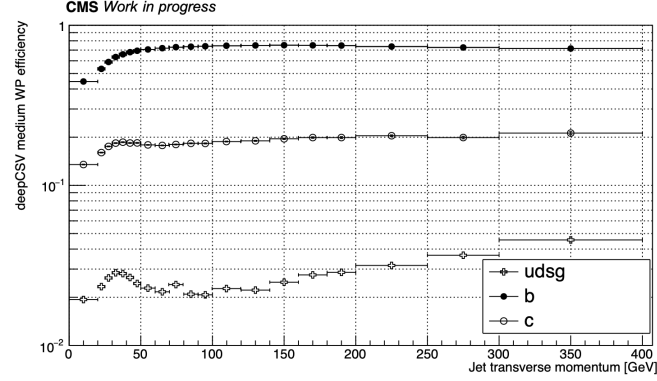


Figure 18: Expected b-tagging efficiency for different jet flavours as function of the jet p_T .

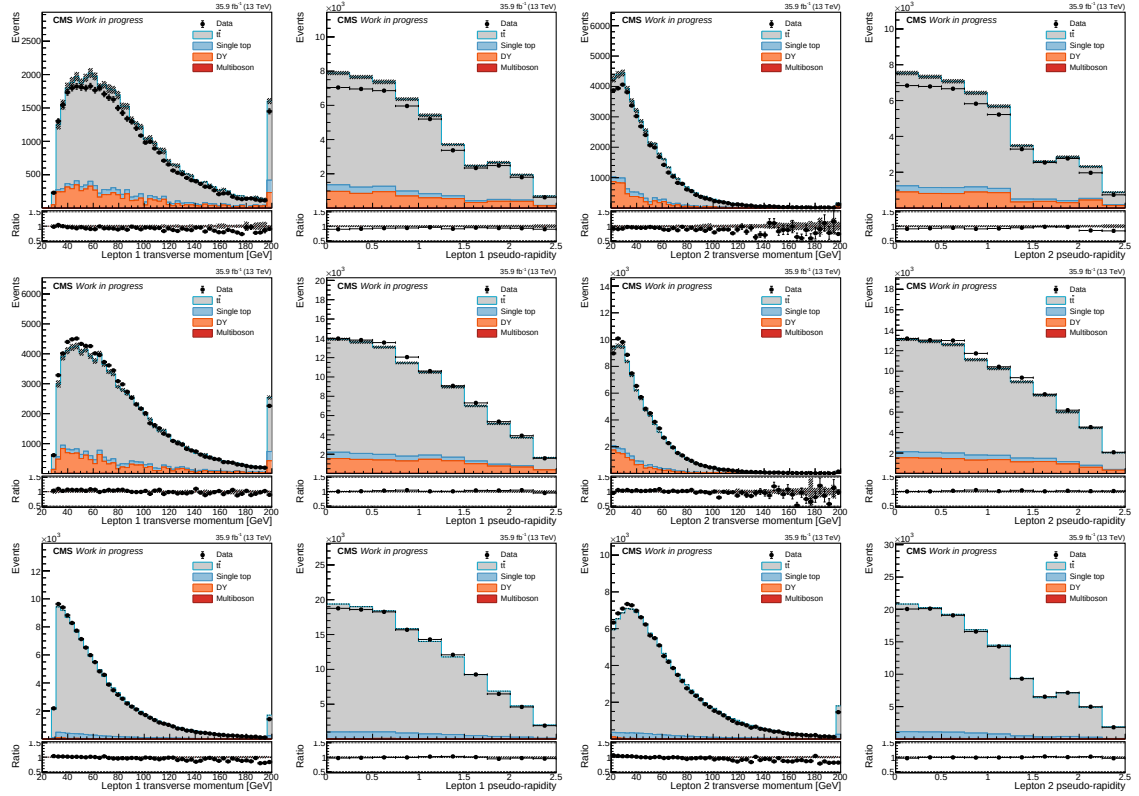


Figure 19: Leading and sub-leading lepton kinematics in the ee (top), $\mu\mu$ (center), and $e\mu$ (bottom) channels. From left to right, leading lepton p_T , η , sub-leading lepton p_T , η . Uncertainties are statistical only.

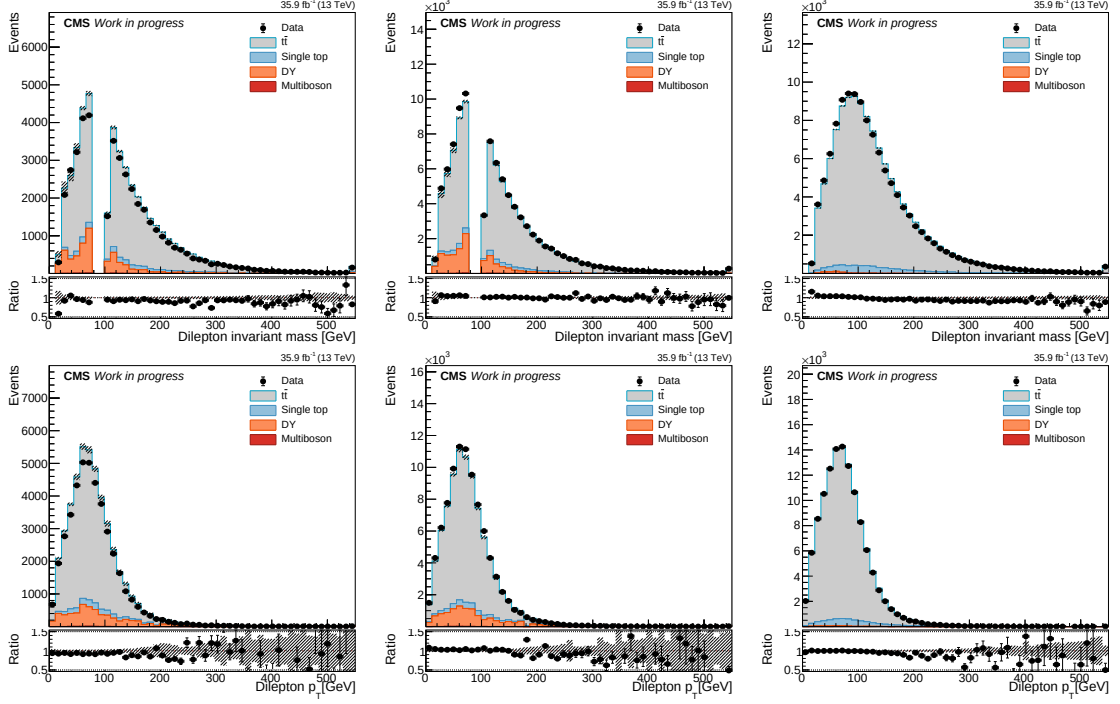


Figure 20: Dilepton kinematics in the ee (left), $\mu\mu$ (center), and $e\mu$ (right) channels. The top (bottom) plots correspond to the dilepton invariant mass (transverse momentum). Uncertainties are statistical only.

discuss systematic uncertainties in Section 4.8 and they will cover the discrepancy between MC and data.

4.6. Experimental Observable

4.6.1. $m(\ell b)$ Variable Construction

The variable $m(\ell b)$ is used in this analysis to study the effect of m_t and Γ_t . It is constructed from the mass of lepton b-jet (b-tagged jet) pairs in an event. We take the leading two (or one) b-jet in an event. We select at most two lepton b-jet pairs in each event, depending on the number of b-jets in the event.

The following ranking method is used in order to find the lepton b-jet pairs of the best

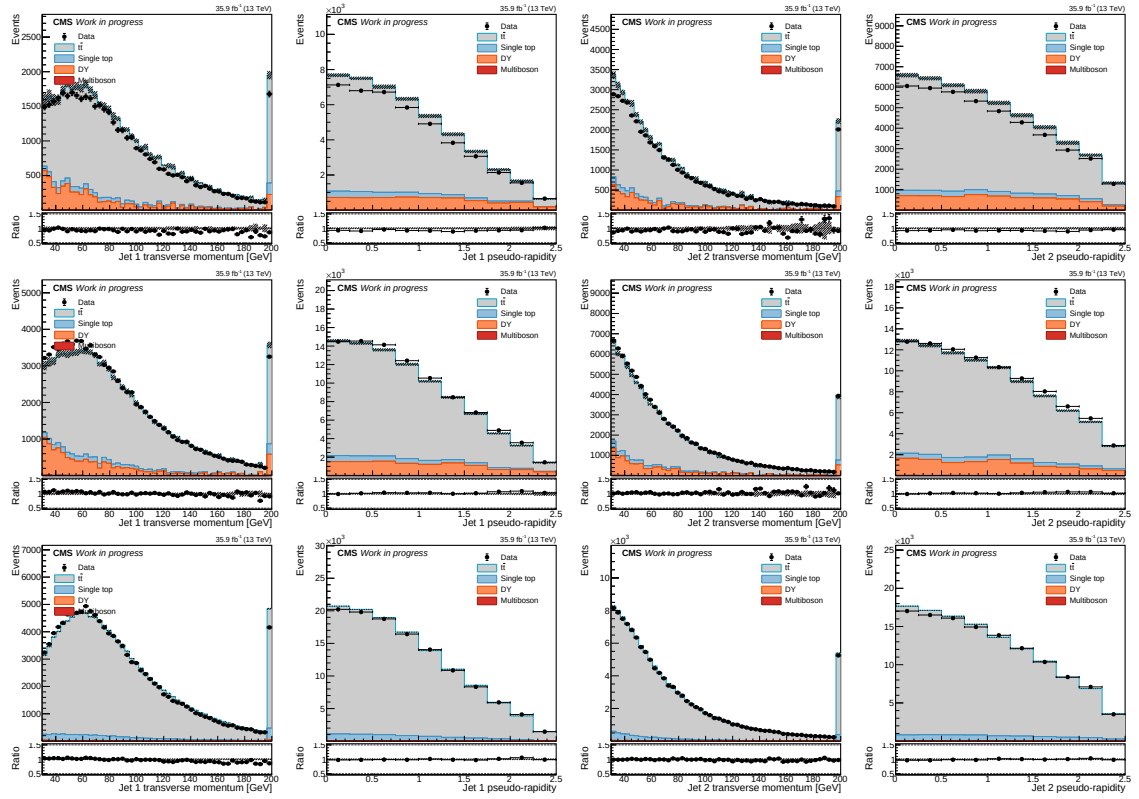


Figure 21: Leading and sub-leading jet kinematics in the ee (top), $\mu\mu$ (center), and $e\mu$ (bottom) channels. From left to right, leading jet p_T , η , sub-leading jet p_T , η . Uncertainties are statistical only.

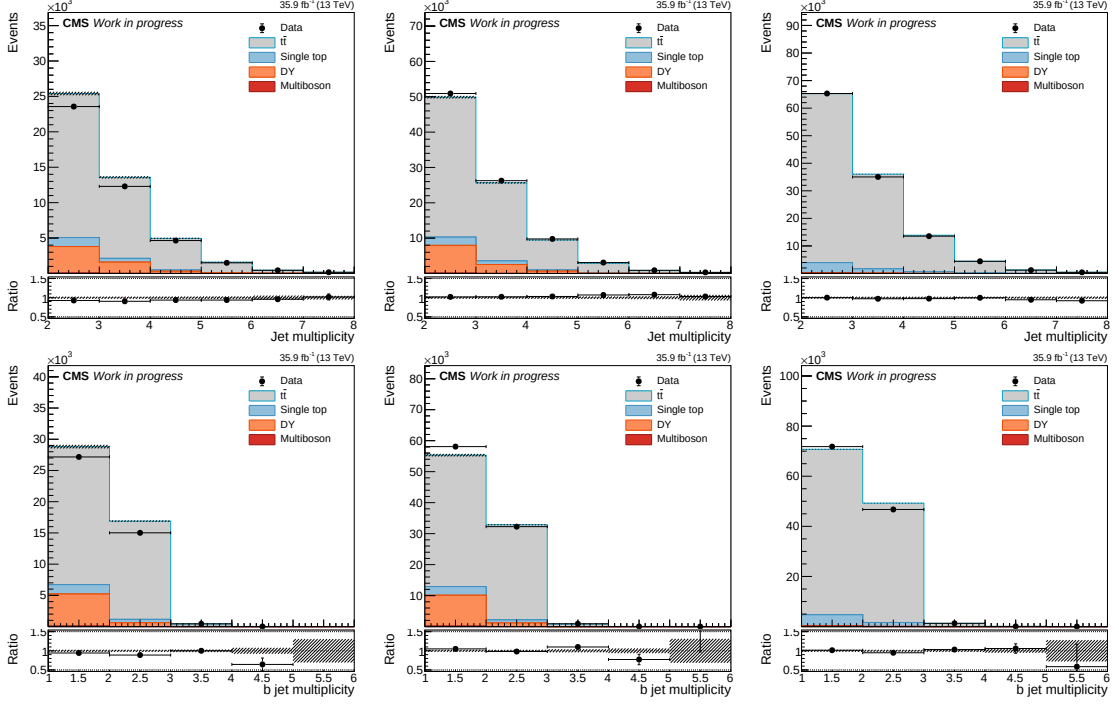


Figure 22: Jet counting in the ee (left), $\mu\mu$ (center), and $e\mu$ (right) channels. The top (bottom) plots correspond to the multiplicity of non- b -tagged (b -tagged) number of jets. At least 1 b -tagged jet has been required. Uncertainties are statistical only.

assignment and to avoid repeatedly using the same object. Best assignment means the pair is likely to come from the same top quark decay. We first build all possible lepton b -jet pairs, then rank them by p_T ($p_T(\ell b)$). We choose two (one) pairs when the event has two (one) b -jets. The distribution of $p_T(\ell b)$ is shown in Figure 24. The MC modeled well compared with data given the uncertainties.

After a study with generator level information, we confirmed that the higher $p_T(\ell b)$ for a lepton b -jet pair, the more likely that it comes from the same top quark decay. Although this method tends to select boosted top quarks, it meets our aim of measuring m_t and Γ_t precisely. In this way we reduce the systematic uncertainties and gain better purity. Figure 25 shows the correct assignment portion and $m(\ell b)$ resolution as a function of $p_T(\ell b)$. This study is on a set of $t\bar{t}$ events. We can observe as well that at higher $p_T(\ell b)$ the correct assignment fraction is higher. This gives a motivation on the event categorization that we split the lepton b -jet pairs with respect to their p_T .

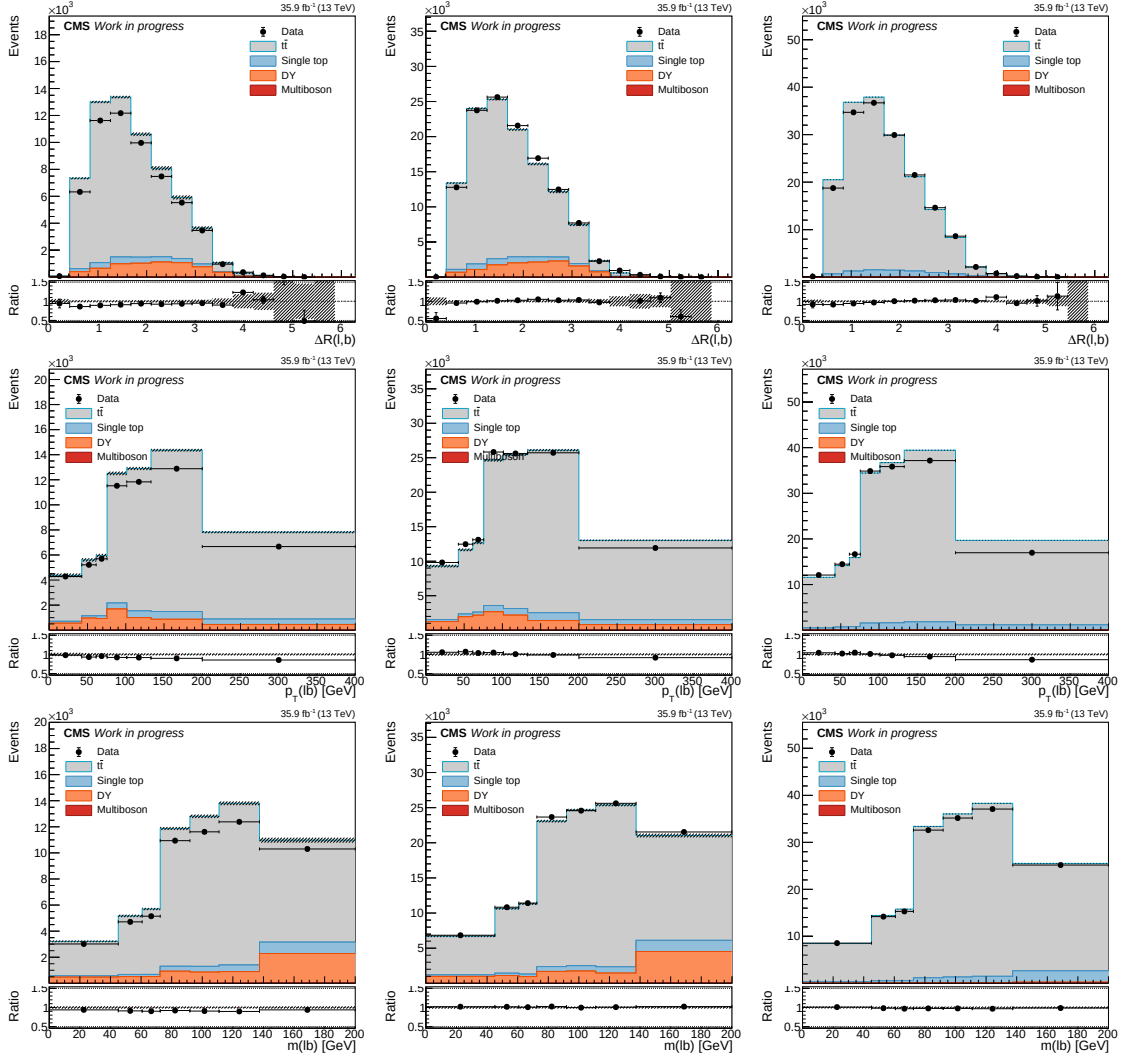


Figure 23: Lepton-b-jet kinematics in the ee (left), $\mu\mu$ (center), and $e\mu$ (right) channels. The plots correspond to the $\Delta R(\ell, b)$ (top), $p_T(\ell b)$ (center) and $m(\ell b)$ (bottom) distributions. Uncertainties are statistical only.

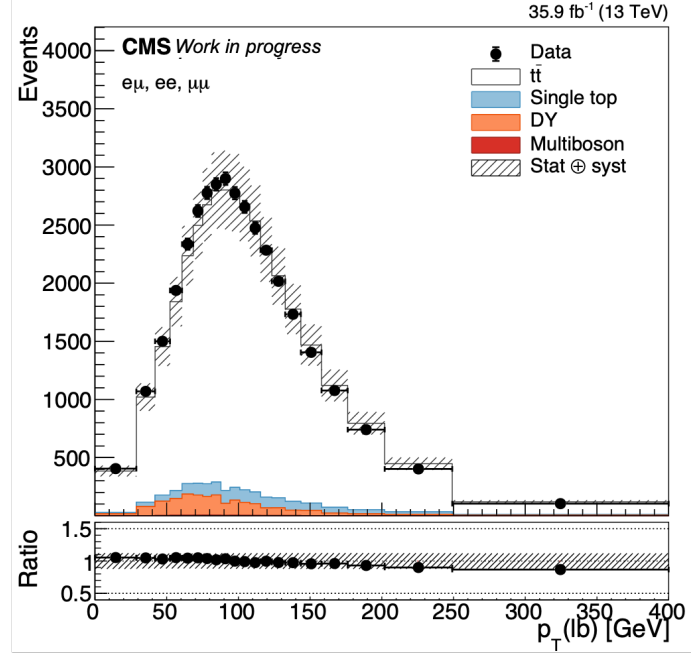


Figure 24: $p_T(\ell b)$ distribution for $\ell\ell$ events with at least 1 b-tagged jet. The dashed band superimposed to the distributions and ratios represents the systematic uncertainty from the main sources, as described in the text.

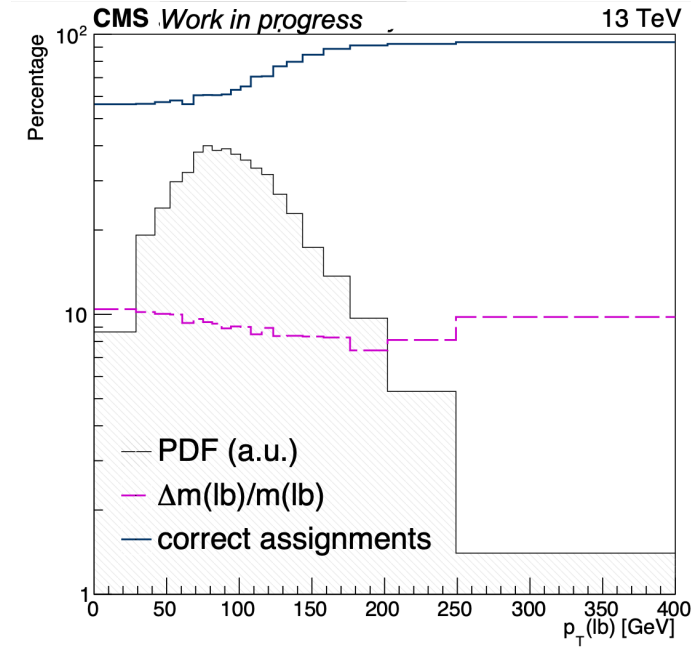


Figure 25: Evolution of the fraction of correct assignments and $p_T(\ell b)$ resolution, as function of $p_T(\ell b)$, for the selected events in a $t\bar{t}$ simulation. The $p_T(\ell b)$ PDF is also superimposed for reference. Note that all $p_T(\ell b)$ and $m(\ell b)$ distribution plots in this analysis have a divide by bin width procedure that the count of events in each bin of the histogram is divided by the width of the bin.

We finally categorize the pairs based on the di-lepton flavor (ee , $e\mu$ and $\mu\mu$) of the event, $p_T(\ell b)$ (“highpt” with $p_T > 100$ and “lowpt” with $p_T \leq 100$). In addition, we consider events with two b-jets to define a “high purity” category of $t\bar{t}$. Events with one b-jet have tW enriched background, so we add this categorization by the number of b-jets. Thus, there are 12 final categories.

4.6.2. *Binning of $m(\ell b)$ Observable*

The binning of the observable is constructed firstly based on the quantiles of the $m(\ell b)$ distribution, in order to guarantee equal statistical distribution of the signal events in each bin. After establishing the initial binning we check the average expected resolution by comparing the reconstructed and generated $m(\ell b)$ variable for each pair. If a bin width is smaller than the resolution we merge it with the next bin until its width is equal or larger than the average resolution. This procedure is used to avoid over-fitting the details of the distribution at reconstruction level. With the exception of few first and last bins, the resolution is better than 10 GeV. This method leads to we get fourteen bins. In the later studies we found the need to reduce statistical uncertainty, therefore, seven bins were used in the final analysis. Figure 26 shows the final binning obtained with this procedure. Again, the evolution of the fraction of correct assignments and the average resolution of the quantity shown are superimposed. The pre-fit distributions of the $m(\ell b)$ observable are compared to data in Figs. 27, 28, and 29. Overall the pre-fit agreement is good in shape.

4.6.3. m_t and Γ_t Definitions at Generator Level

As we have limited MC full simulation samples, we need to produce the observable for alternative m_t and Γ_t by re-weighting the distributions in generator level. We consider the nominal $t\bar{t}$ sample assumes $m_{SM} = 172.5$ GeV and $\Gamma_{SM} = 1.31$ GeV. We know that the

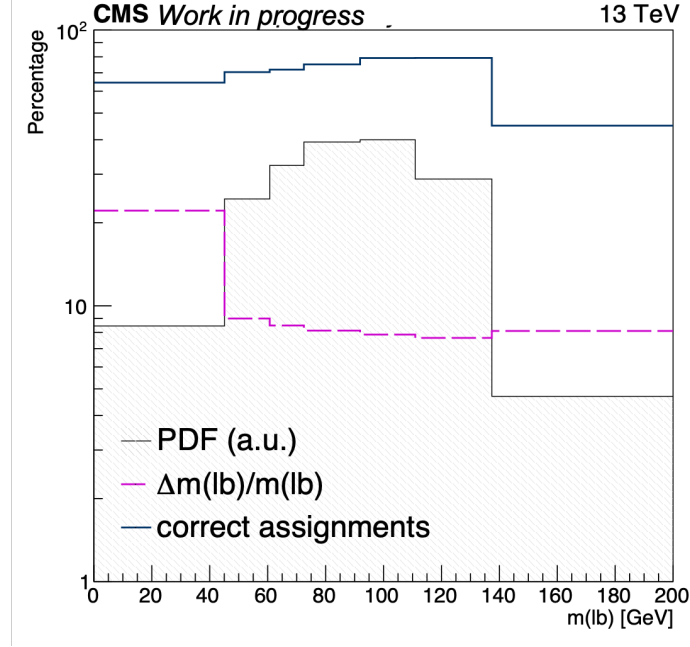


Figure 26: Similar to Fig. 25 for the $m(\ell b)$ distribution after binning optimization.

generator level top mass distribution follow a relativistic Breit-Wigner shape

$$BW(s|m_t, \Gamma_t) = \frac{Nm_t\Gamma_t\sqrt{m_t^2(m_t^2 + \Gamma_t^2)}}{((s^2 - m_t^2)^2 + m_t^2\Gamma_t^2)\sqrt{m_t^2 + \sqrt{m_t^2(m_t^2 + \Gamma_t^2)}}}, \quad (4.3)$$

s represent the mass of two top quarks in the event. We created mass points in the range of 169.5 to 175.5 GeV and width points 0.5 to 4.0 GeV. Per-event weight is produced as follows

$$\frac{BW(s_1|m', \Gamma')}{BW(s_1|m_{SM}, \Gamma_{SM})} * \frac{BW(s_2|m', \Gamma')}{BW(s_2|m_{SM}, \Gamma_{SM})} \quad (4.4)$$

Figure 30 shows the top quark mass distribution in generator level for a series of (m_t, Γ_t) combinations. Figure 31 demonstrates the reconstruction level m_t and Γ_t after this re-weighting procedure, in the inclusive category. We observe that a shift of m_t would give rise to a horizontal translation of the $m(\ell b)$ spectrum, particular in the end point of mas $m(\ell b)$. A shift in Γ_t would induce a broadening or narrowing effect on the $m(\ell b)$ distribution. However, we note that the $m(\ell b)$ spectrum variation for the width changing cases is rather small compared to that of mass changing cases. Shift in Γ_t does not cause

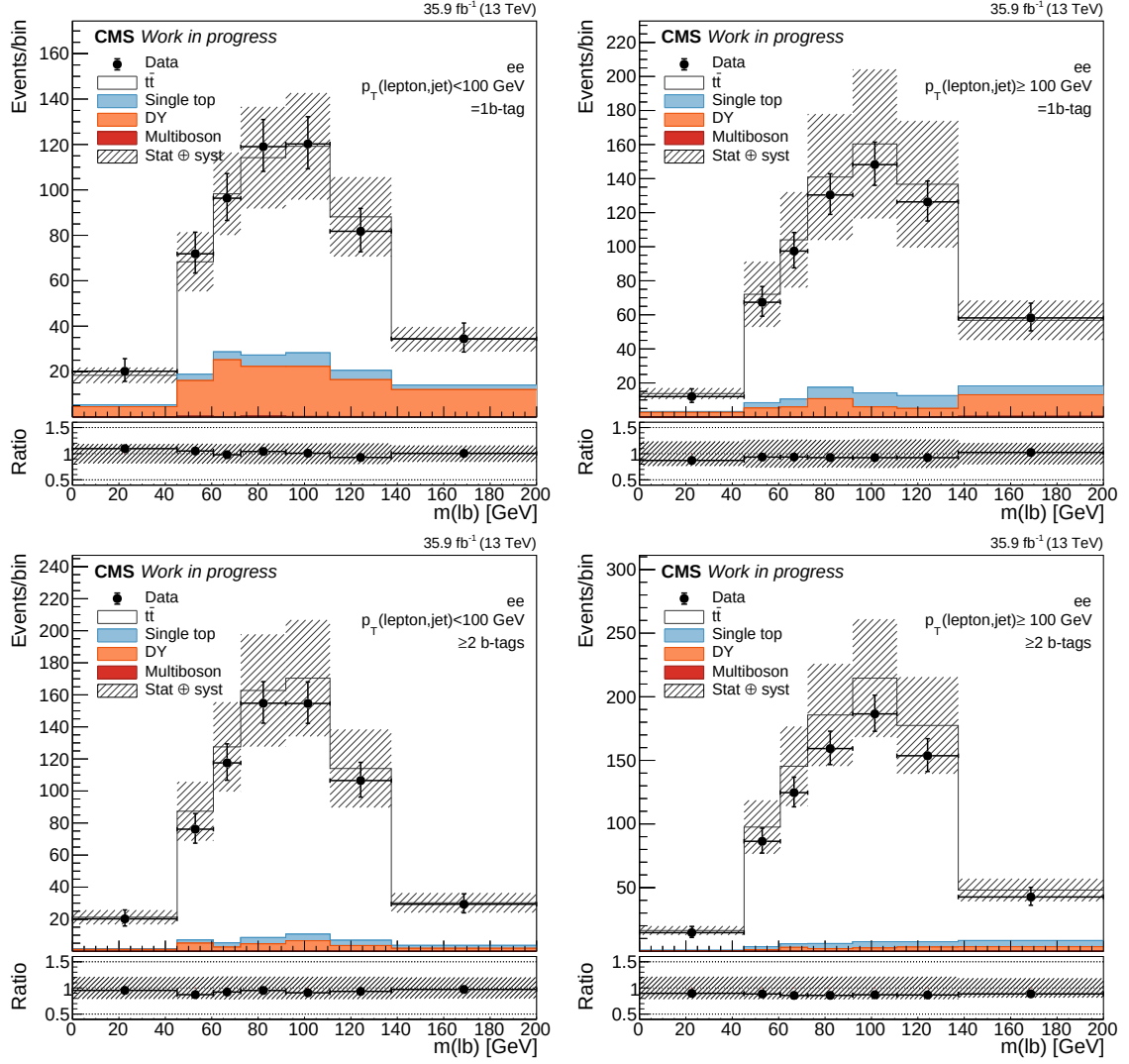


Figure 27: $m(\ell b)$ distributions in the ee channel for events with 1b-tagged jets (top) or at least 2b-tagged jets (bottom). The left (right) distributions correspond to pairs in the low (high) $p_T(\ell b)$ category.

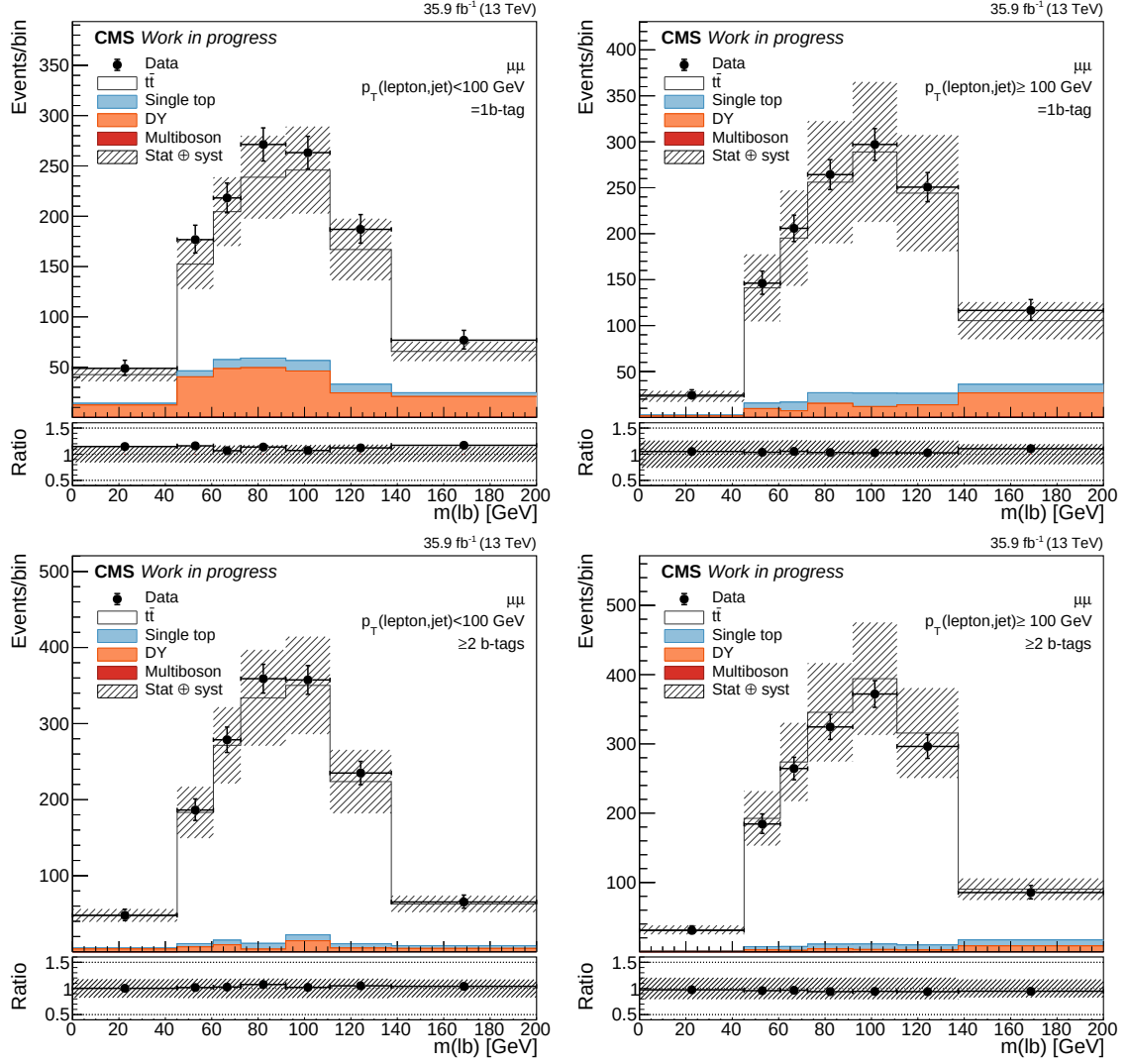


Figure 28: Similar to Fig. 27 for the $\mu\mu$ channel.

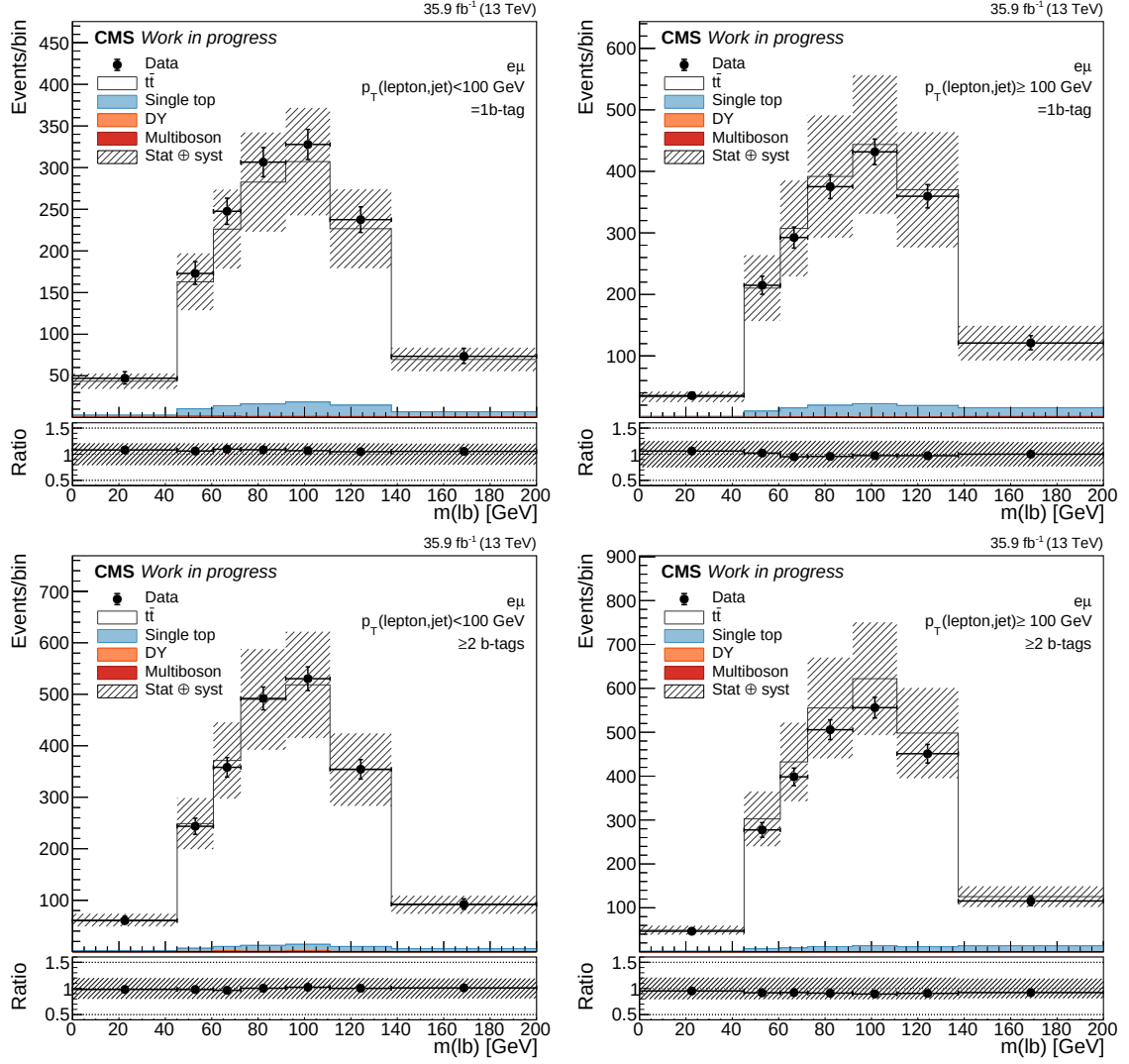


Figure 29: Similar to Fig. 27 for the $e\mu$ channel.

any effect in the endpoint of $m(\ell b)$. This is related to the fact that around the endpoint there are mainly wrong assignment lepton b-jet pairs. We assume that the effect of mass and width can be disentangled when we have sufficiently large statistics. Figure 32 and 33 show this comparison for 12 split categories that we use in final fit.

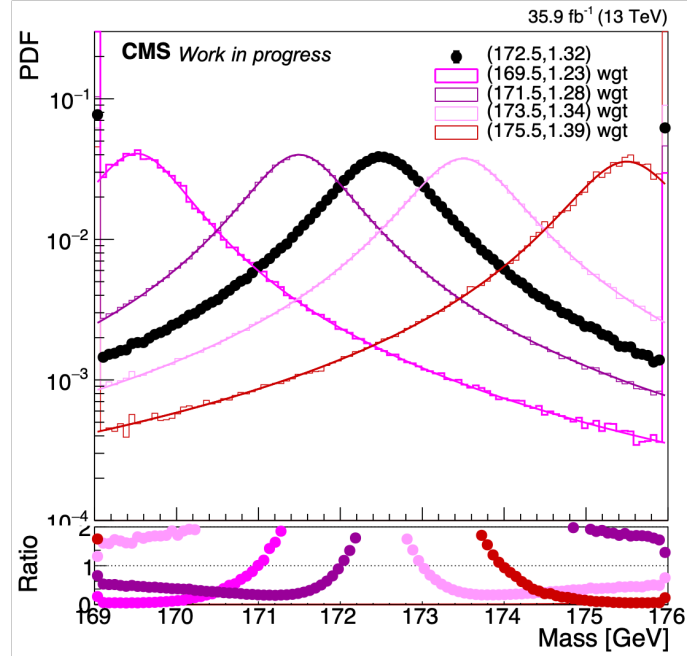


Figure 30: Generator-level distribution of the top mass before and after weighting to different m_t and Γ_t scenarios, using Eq. 4.4. For each distribution the resulting fit to a relativistic Breit-Wigner (Eq. 4.3) is superimposed.

We compared the full simulation $t\bar{t}$ sample and the re-weighted $m(\ell b)$ distributions for four (m_t, Γ_t) configurations, shown in Figure 34. The statistical tests Kolmogorov-Smirnov test and χ^2 values are included. Within statistics the distributions are compatible with each other.

Figure 35 showed a similar study comparing the private full simulation samples with the re-weighted $m(\ell b)$ distributions for various Γ_t scenarios. We especially looked at the inclusive high p_T and low p_T categories.

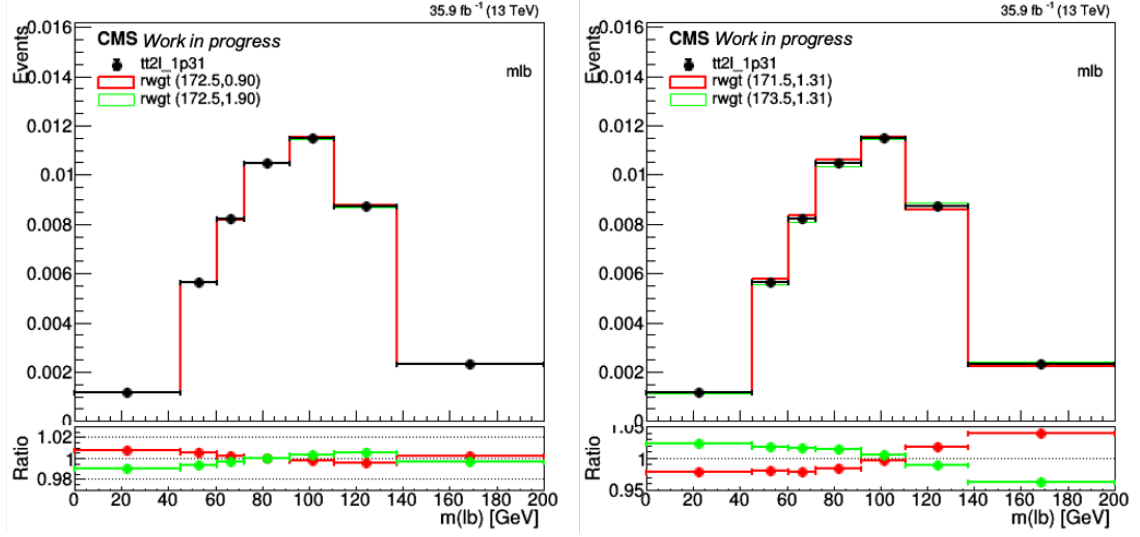


Figure 31: Comparison of the $m(\ell b)$ distributions at reconstruction level for different width scenarios at fixed mass (left), or different masses and widths, according to the SM NLO parameterization (right).

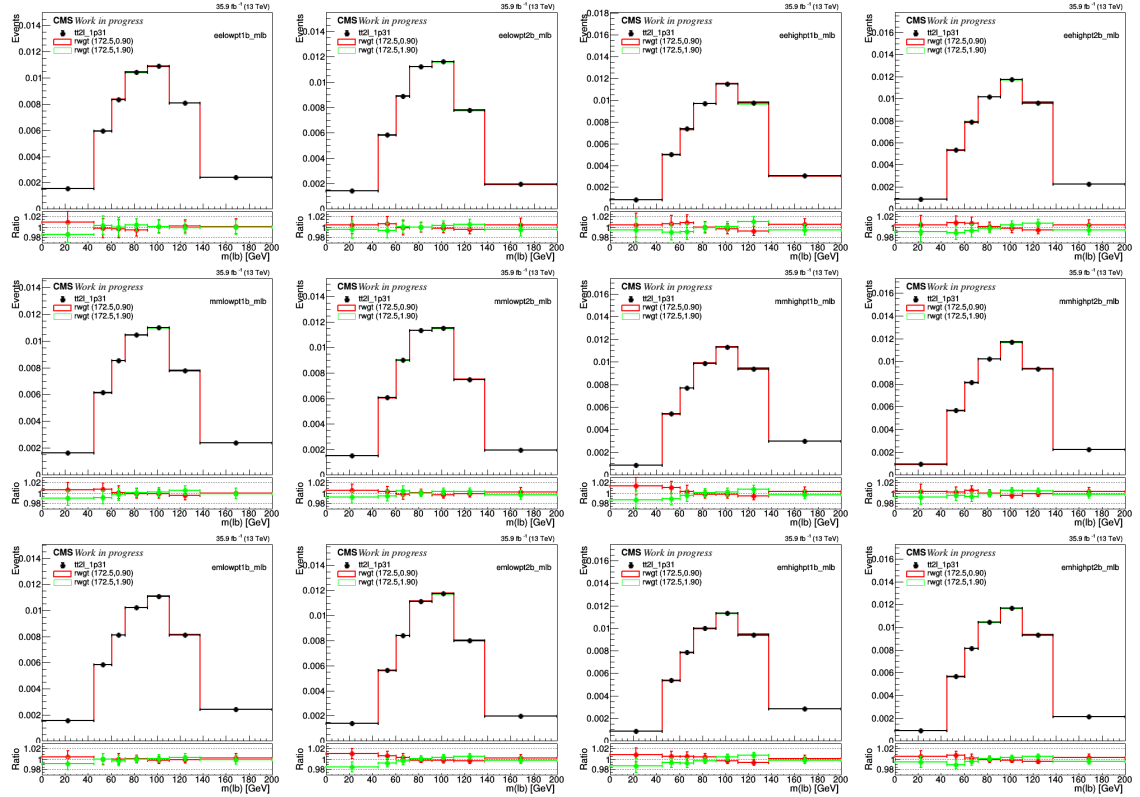


Figure 32: Comparison of the $m(\ell b)$ distributions at reconstruction level for different mass scenarios. The ee , $\mu\mu$, and $e\mu$ channels are shown on top, center and bottom. From left to right the categories correspond to low $p_T(\ell b)=1 \text{ b}$, and $\geq 2 \text{ b}$, high $p_T(\ell b)=1 \text{ b}$, and $\geq 2 \text{ b}$.

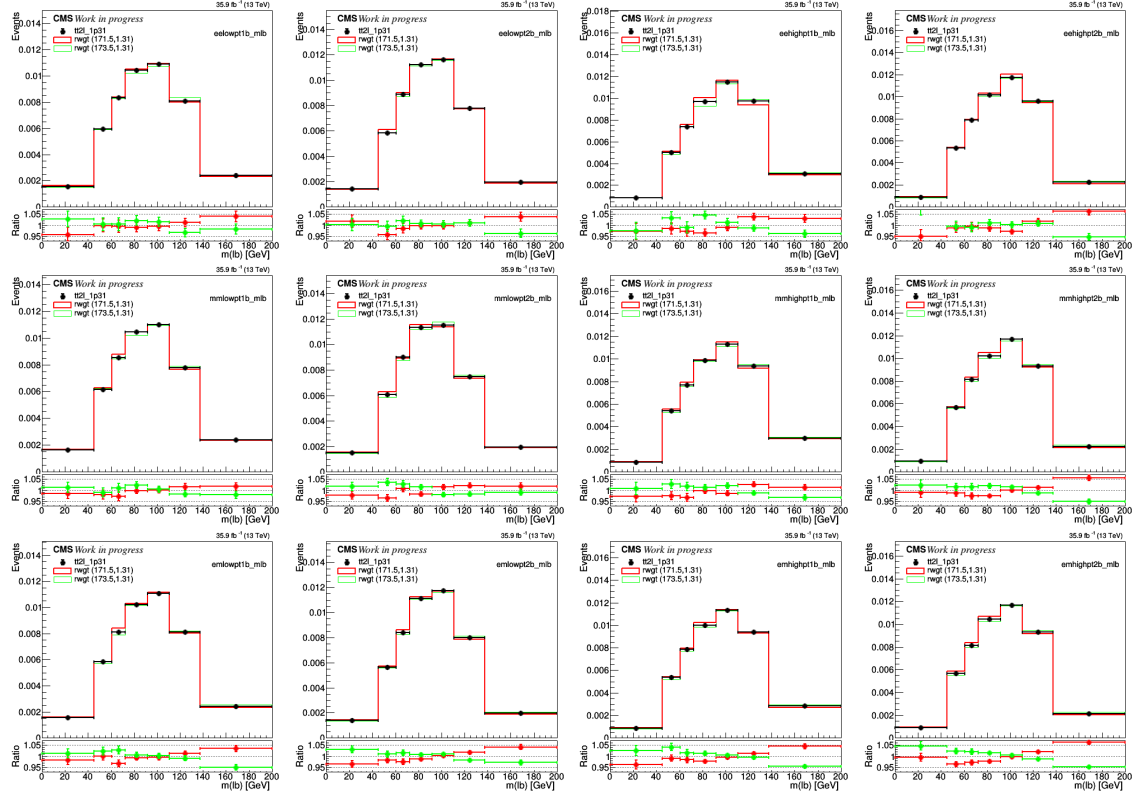


Figure 33: Comparison of the $m(\ell b)$ distributions at reconstruction level for different width scenarios. The ee , $\mu\mu$, and $e\mu$ channels are shown on top, center and bottom. From left to right the categories correspond to low $p_T(\ell b)=1b$, and $\geq 2b$, high $p_T(\ell b)=1b$, and $\geq 2b$.

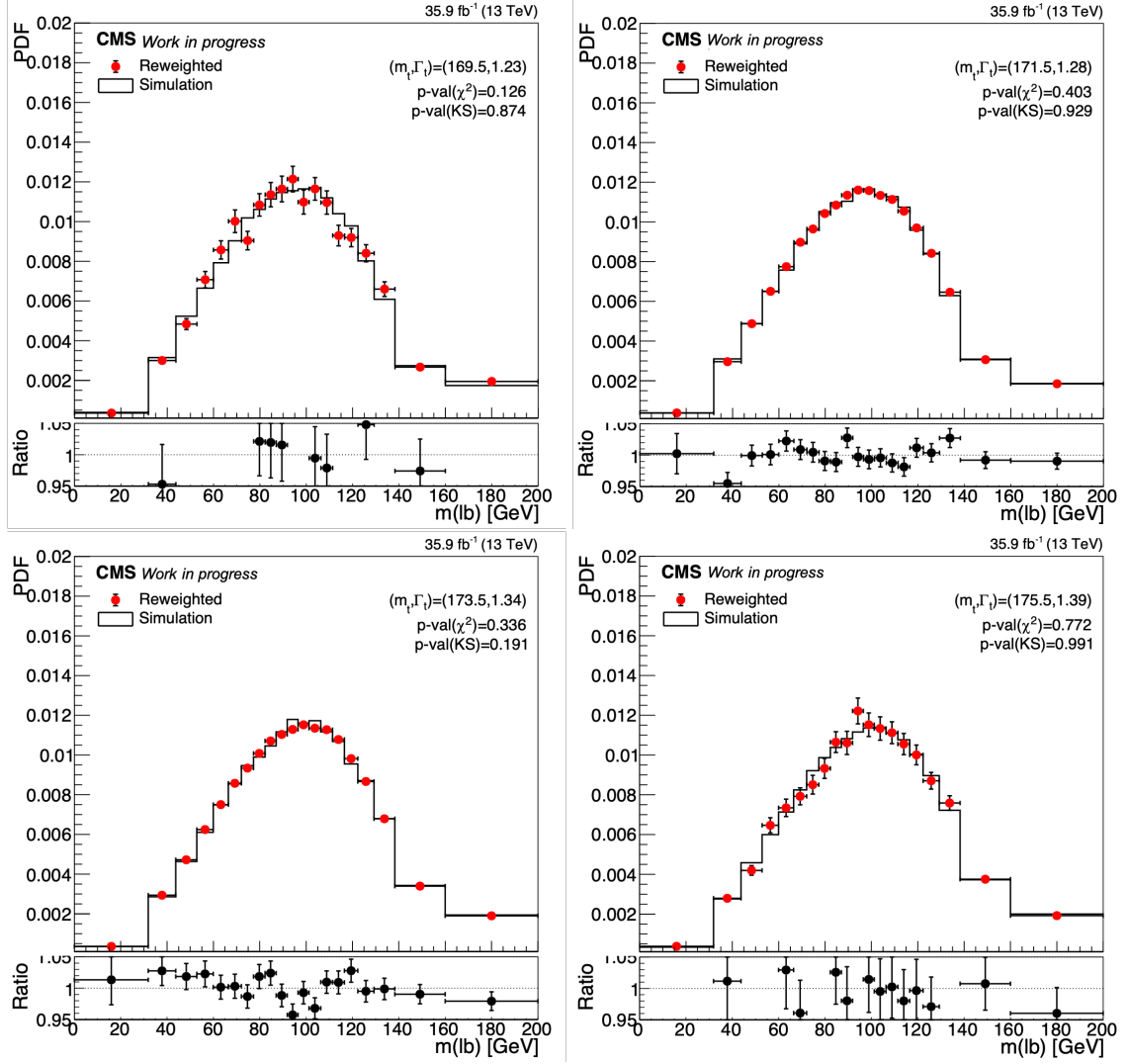


Figure 34: Comparison of the $m(\ell b)$ distribution at reconstruction level between different dedicated (m_t, Γ_t) points and the estimated distribution obtained by weighting the $(172.5, 1.31)$ GeV simulation using the procedure described in the text.

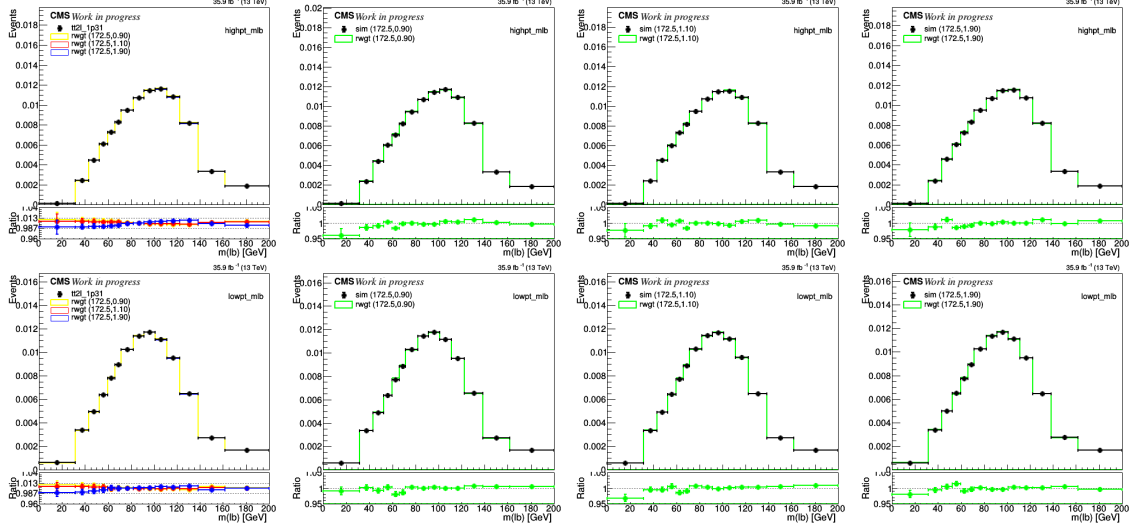


Figure 35: Private samples. The top (bottom) plots correspond to a high (low) $p_T(\ell b)$ category. The leftmost plot shows the difference in the $m(\ell b)$ shape induced by re-weighting the nominal $t\bar{t}$ sample to different width scenarios. From left to right follow the comparison between the re-weighted shape and the one obtained with dedicated samples with $\Gamma_t=0.9, 1.1$, and 1.9 GeV.

4.7. Background Estimation

The Drell Yan (DY) background is estimated by a data driven method, unlike other background processes which use their simulation samples. This data driven method is called R_{in}/R_{out} method.

The $Z \rightarrow \ell\ell$ control region is used to normalize the yields of the DY background. The control region is defined such that $76 < m_{\ell\ell} < 106$ GeV, and we call it the “peak”. The number of events outside the Z peak $N_{\ell\ell(out)}$ is estimated by an extrapolation on $m_{\ell\ell}$,

$$N_{\ell\ell(out)} = R_{\ell\ell(out/in)} \cdot [N_{\ell\ell(in)} - \frac{1}{2}N_{e\mu(in)}k_{\ell\ell'}] . \quad (4.5)$$

A detailed description can be found [41]. $N_{\ell\ell(in)}$ is number of events in the peak region,

and $N_{e\mu}(in)$ is the events only in $e\mu$ samples. $R_{\ell\ell}(out/in)$ is estimated only in DY samples

$$R_{\ell\ell}(out/in) = \frac{N_{DY\ MC}(out)}{N_{DY\ MC}(in)} \quad , \quad (4.6)$$

and $k_{\ell\ell'}$ is a factor in order to account for the different reconstruction in electron and muon.

$$k_{\ell\ell'} = \sqrt{\frac{N_{\ell\ell}(in)}{N_{\ell'\ell'}(in)}} \quad , \quad (4.7)$$

If we are to calculate the N for ee channel, here $k_{\ell\ell'}$ stands for $k_{e\mu}$. All the events count of $m_{\ell\ell}$ is based on the $m_{\ell\ell}$ after our event selections in Section 4.5. For ee or $\mu\mu$ channels, the scale factor is directly $SF_{ll} = \frac{N_{\ell\ell}(out)}{N_{DY\ MC}(out)}$, and for $e\mu$ channels,

$$SF_{e\mu} = \sqrt{SF_{ee} \cdot SF_{\mu\mu}} \quad . \quad (4.8)$$

Scale factors are summarized in Table 7.

Table 7: DY estimation for the categories of events used in our analysis. Uncertainties are of statistical nature. The breakdown of the results obtained for the different channels is given.

	ee	$\mu\mu$	$e\mu$
≥ 1 b-tagged jet			
$R_{\ell\ell}(out/in)$	0.077 ± 0.005	0.076 ± 0.004	
$k_{\ell\ell'}$	$[670.9 \pm 1.6] \times 10^{-3}$	1.491 ± 0.004	
$N_{\ell\ell}(in)$	61096	135733	
N_{out}	$[3.74 \pm 0.25] \times 10^3$	$[8.2 \pm 0.4] \times 10^3$	
SF (data/MC)	0.88 ± 0.08	1.01 ± 0.07	0.94 ± 0.06

Figure 36, 37 and 38 show the control region $Z + \geq 1$ b kinematics for leptons and jets. The agreement is good between data and MC.

Apart from DY normalization, we correct the modelling of DY shape using a data driven approach, too. We use Z regions of highpt1b or lowpt1b categories as control regions (Z-peak as $|m(\ell) - m_Z| < 15 \text{ GeV}$) to derive a scale factor bin-by-bin. $\mathcal{O}$ is the distribution

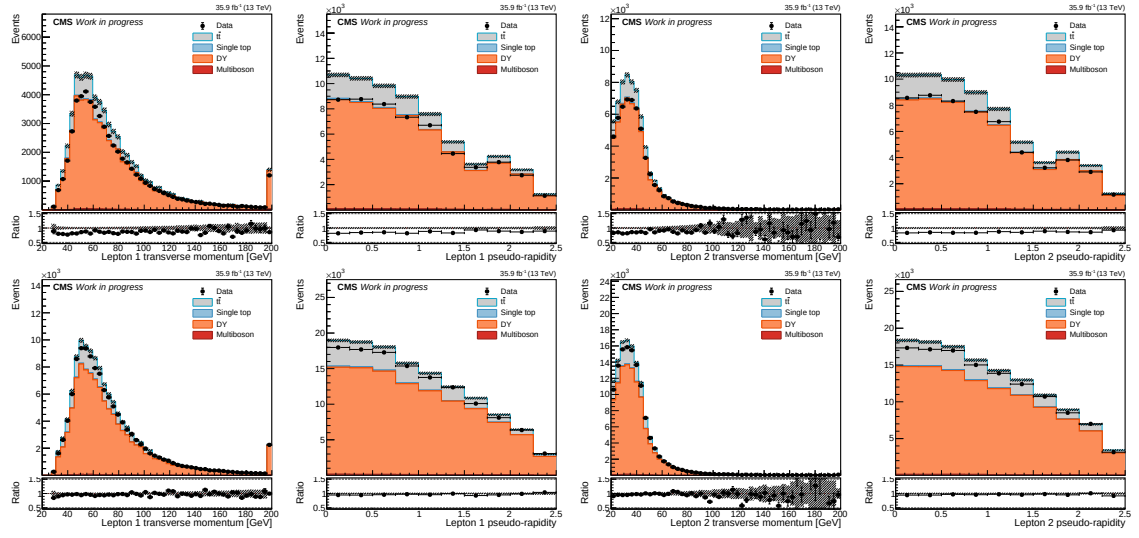


Figure 36: Lepton kinematics in the Z control region for electrons (top) and muons (bottom). From left to right the distributions are shown for leading lepton p_T and η , sub-leading lepton p_T and η . Uncertainties are of statistical nature.

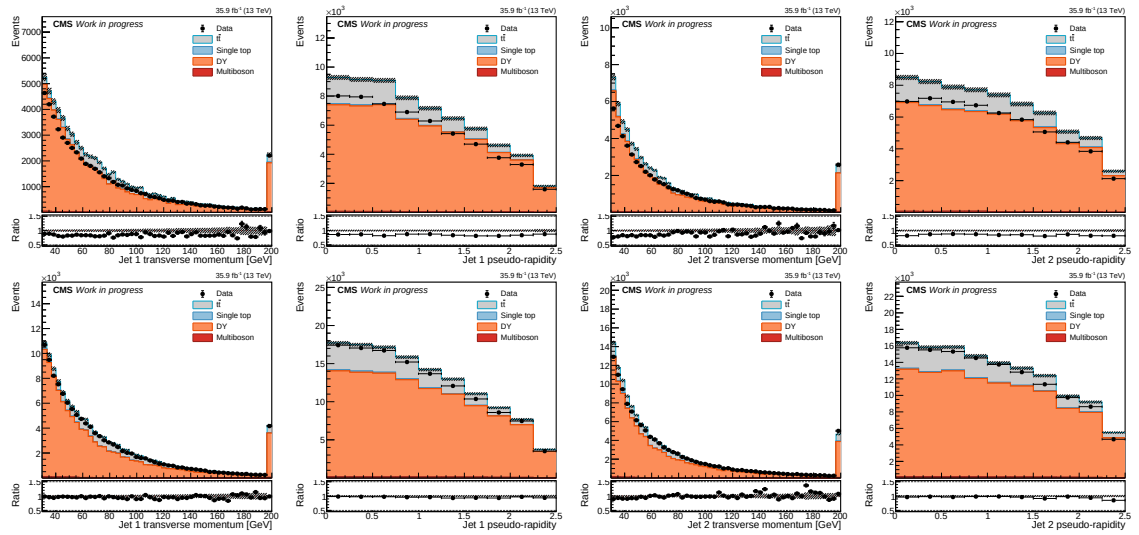


Figure 37: Similar to Fig. 36 for the jet kinematics in the Z control region. From left to right the distributions are shown for leading jet p_T and η , sub-leading jet p_T and η .

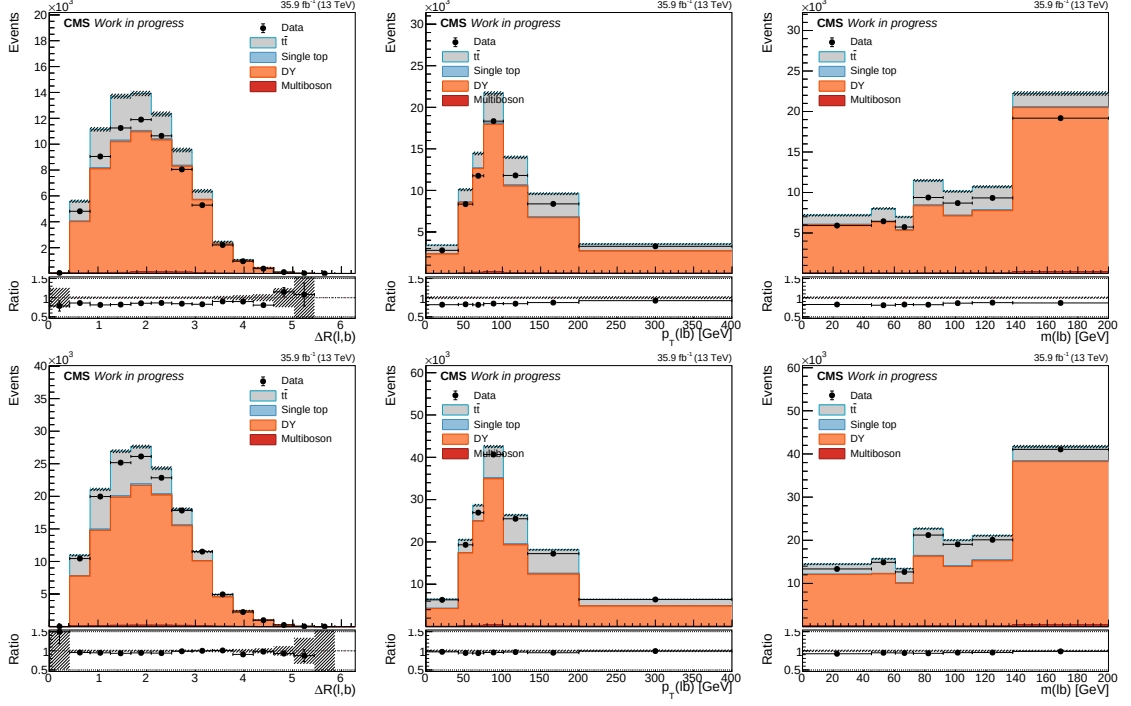


Figure 38: Similar to Fig. 36 for the kinematics of the paired ℓb . From left to right the distributions are shown for $\Delta R(\ell b)$, $m(\ell b)$ and $p_T(\ell b)$.

of interest, $m(\ell b)$ in certain event category in our case,

$$\mathcal{O} = \mathcal{O}_{\text{MC}} \cdot \left(\frac{\mathcal{O}_{\text{data,Z-peak}}}{\mathcal{O}_{\text{MC,Z-peak}}} \right) \quad (4.9)$$

where $\mathcal{O}_{\text{MC}}$ is the DY events outside Z region. Only 1b region is considered as control region because 2 b-jet regions have non-negligible $t\bar{t}$ events. The difference between corrected MC and original DY shape is used as a shape systematic uncertainty.

Figure 40 shows the DY contribution in $m(\ell b)$ shape after extrapolation. The signal region (SR) on the figures correspond to the non-Z peak region which we use in our analysis. In most bins the shape are compatible.

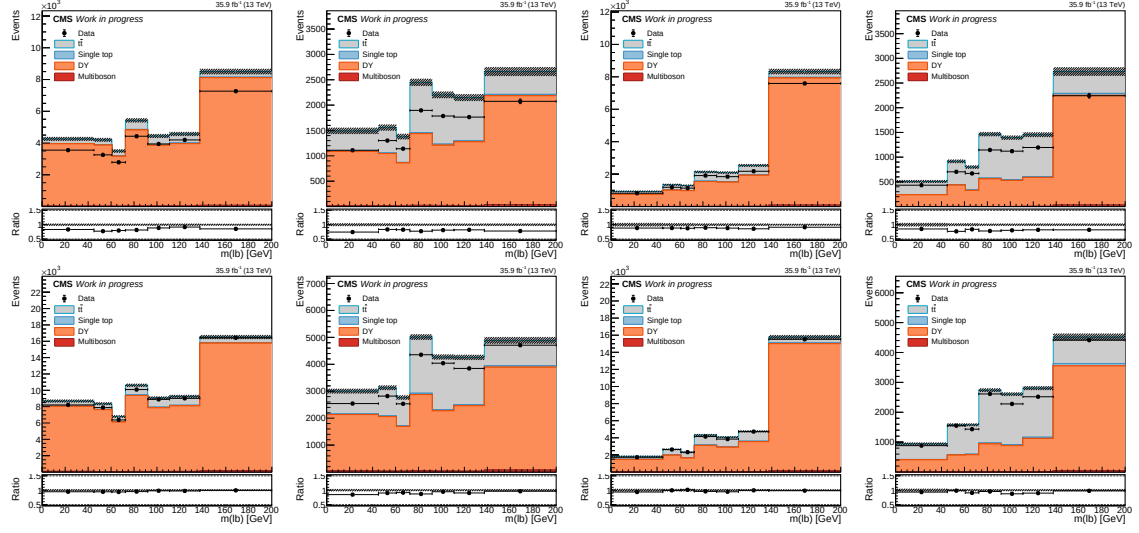


Figure 39: $m(\ell b)$ distributions in the Z control region for electrons (top) and muons (bottom). From left to right the distributions are shown for low p_T pairs in =1 b-tagged events, low p_T pairs in ≥ 2 b-tagged events, high p_T pairs in =1 b-tagged events, and high p_T pairs in ≥ 2 b-tagged events.

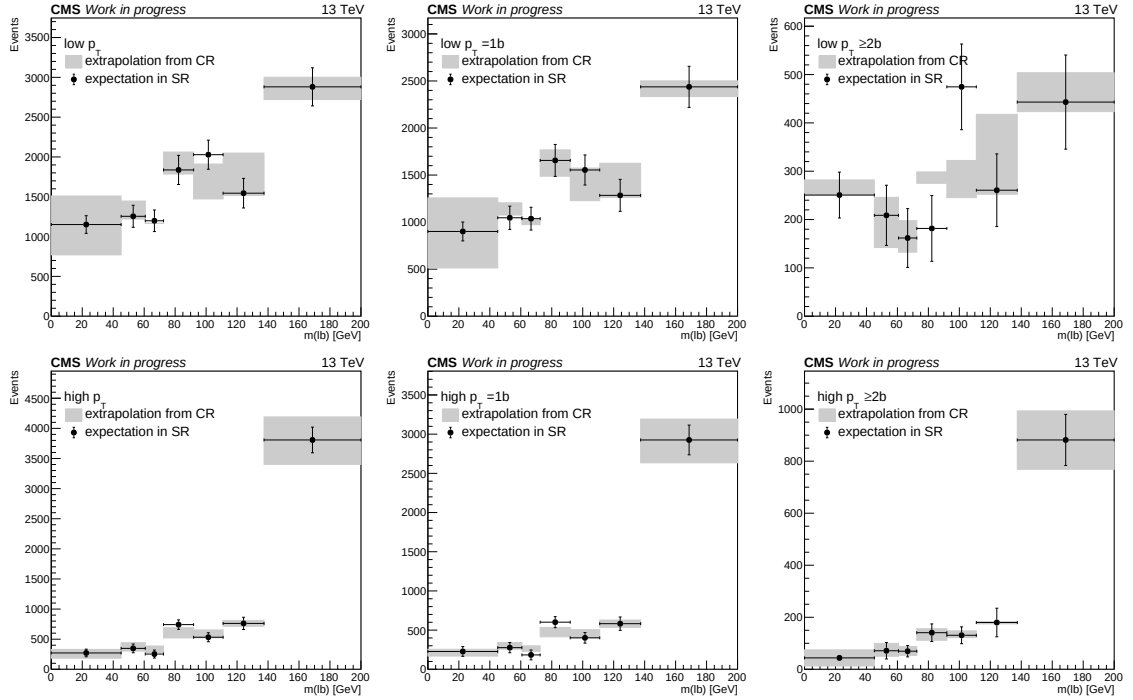


Figure 40: Comparison between the data-driven extrapolation from the Z+1 b control region, and the MC expectation in the signal region for the same-flavor channel ($ee+\mu\mu$). The top (bottom) plots refer to the low p_T (high p_T) regions. From left to right the plots are shown inclusively and then for events with =1 b and ≥ 2 b-tagged jets. With respect to Fig. 39, the yields are not divided by the bin width.

4.8. Systematic Uncertainties

Systematic uncertainties are included in the fit as nuisance parameters. In general, we separate rate effect and shape effect for each systematic source. Rate uncertainties are treated as a log-normal penalty factor in the likelihood fit, and shape uncertainties are treated as a Gaussian penalty factor.

From the discussion of the previous sections, we do not expect the rate uncertainties to influence the measurement of m_t and Γ_t . We include them because we have 12 final categories and the rate uncertainties might lead to migration of events across categories. Rate uncertainty is not considered for pileup, b-fragmentation and semi-leptonic B decay branching ratios, trigger efficiency because their rate variation is similar in each category.

We will discuss rate and shape uncertainties below and show their performance for the $m(\ell b)$ variable. The systematic uncertainties are classified as three types, experimental, theory and statistical related uncertainties. In the final fit, shape uncertainties $<1\%$ are discarded.

4.8.1. *Experimental Uncertainties*

Pileup We considered a correction to MC for pileup, and the modeling of pileup has an intrinsic uncertainty. It is accounted through a factor of 5% up and down with respect to its original estimation. This effect is fully correlated among all the event selection categories. Figure shows the effect of pileup shape uncertainty on $t\bar{t}$ signal.

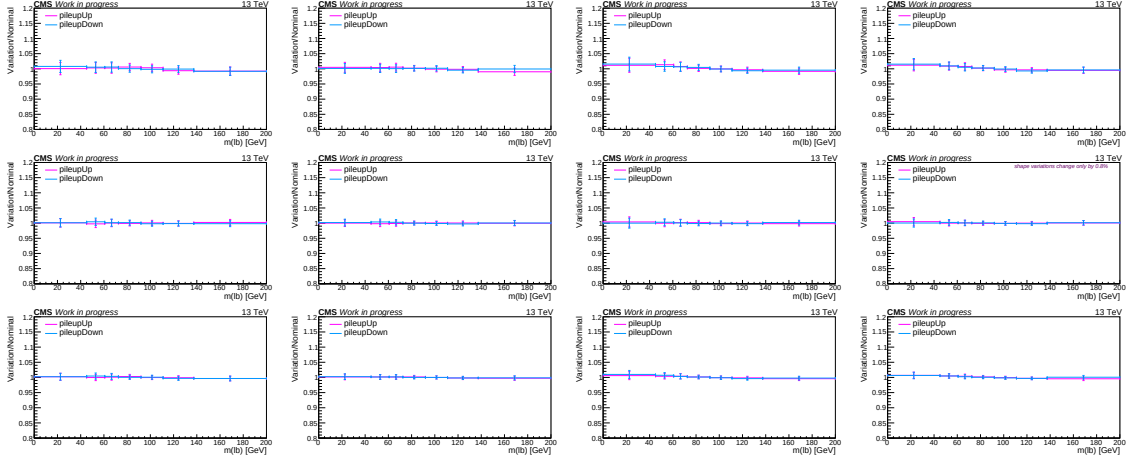


Figure 41: Ratio of the varied pileup scenarios to the nominal expectation in the different categories used in the final fit for the simulated $t\bar{t}$ sample. The ee , $\mu\mu$, and $e\mu$ channels are shown on top, center and bottom. From left to right the categories correspond to low $p_T(\ell b)=1b$, and $\geq 2b$, high $p_T(\ell b)=1b$, and $\geq 2b$.

Trigger and selection efficiency Uncertainties on trigger efficiency and lepton selections (including identification, isolation mentioned in Section 4.4) are computed by re-weighting the simulation up and down from the nominal shift. The uncertainty scale factors are found in official recommendations [42] and [43]. Figure 42, 43 and 44 show their shape variations. Note that for the rate and shape uncertainties of lepton selection, they are correlated among the lepton flavors used in the event categories. Similarly, for trigger efficiency uncertainty, correlation is made in the same di-lepton categories.

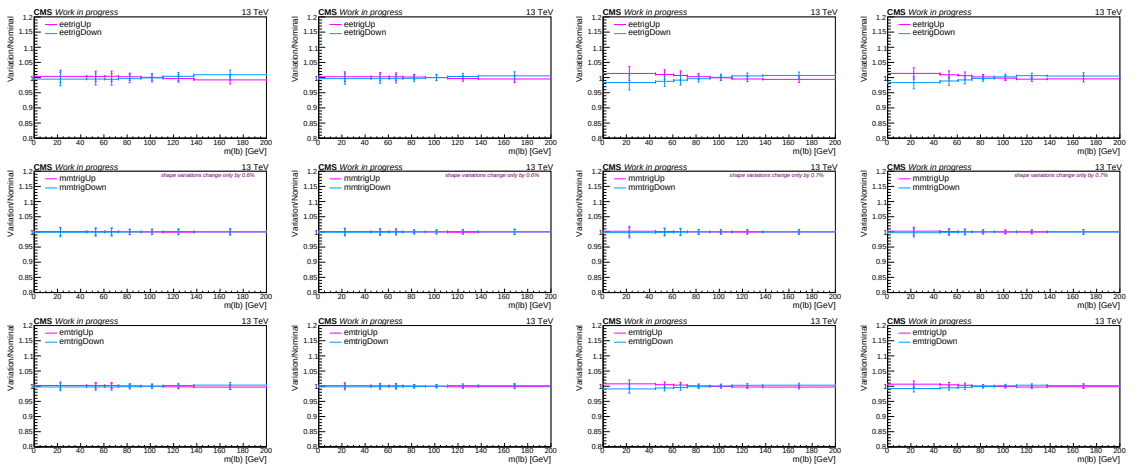


Figure 42: Similar to Fig. 41 for the trigger efficiency in the three dilepton channels.

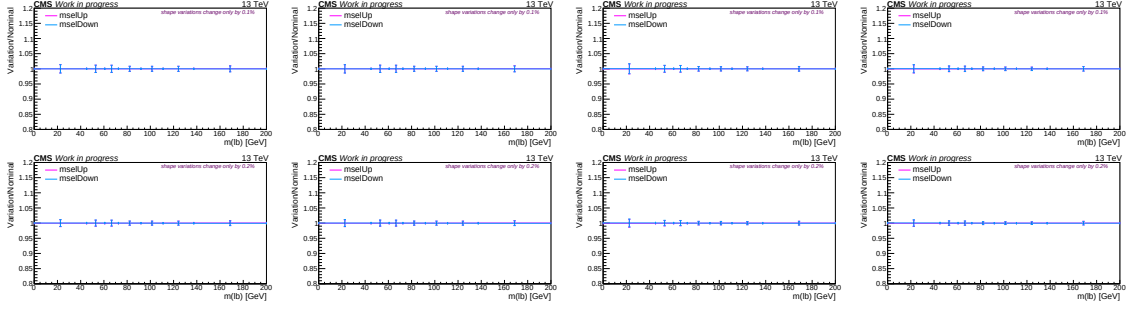


Figure 43: Similar to Fig. 41 for the muon selection efficiency in the $\mu\mu$ (top) and $e\mu$ channel (bottom).

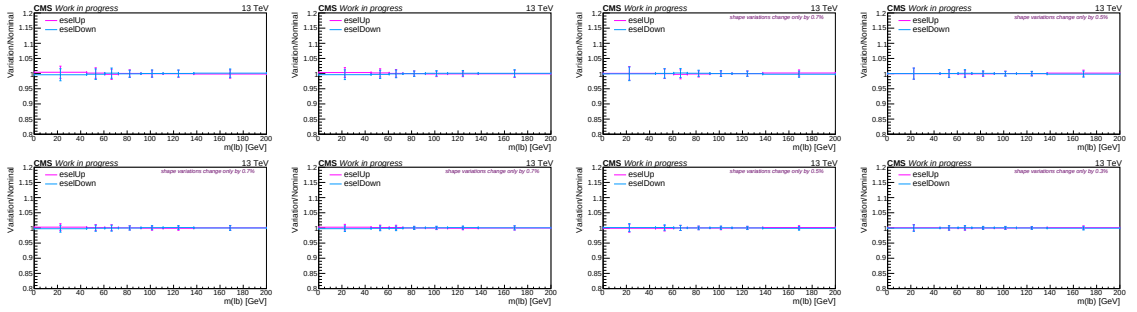


Figure 44: Similar to Fig. 41 for the muon selection efficiency in the ee (top) and $e\mu$ channel (bottom).

Uncertainty on the L1 prefire efficiency is considered as a separate source. Figure 45 illustrates the impact it is expected to have on the $m(\ell b)$ signal distribution. The effect yields some impact for 2b-jet categories and in the low $m(\ell b)$ region.

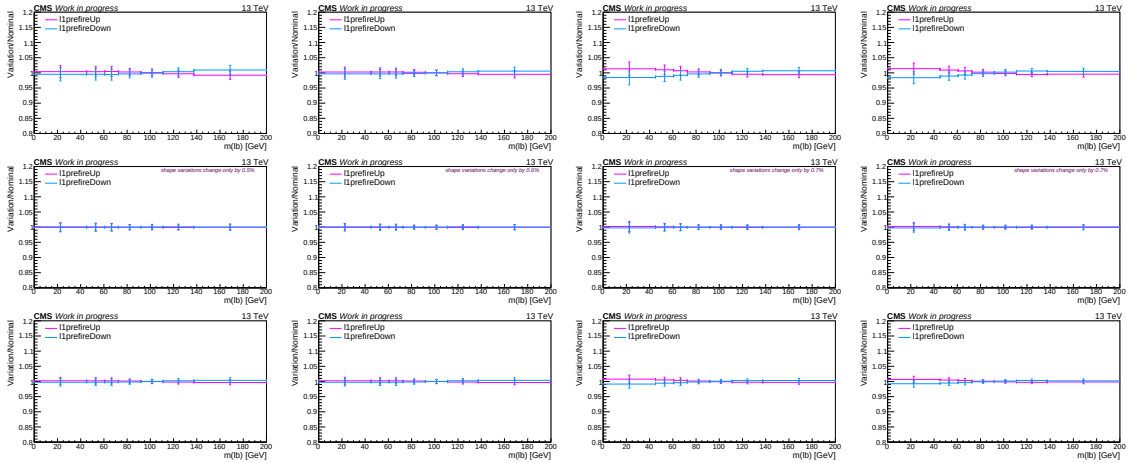


Figure 45: Similar to Fig. 41 for the L1 prefire efficiency uncertainty.

Lepton energy scale Only shape effects are considered for electron and muon energy scale.

We know that the variation in lepton energy scale would change the normalization in each

event category in the same way, and it will not affect our measurement, so only shape effects are considered. We use the break-up uncertainties following the correction recommendation. For electron, there are 7 sub-sources [44], and for muon, totally 4 sub-sources are considered. These shape variations are typically small. Examples can be found in Figure 46 to 49.

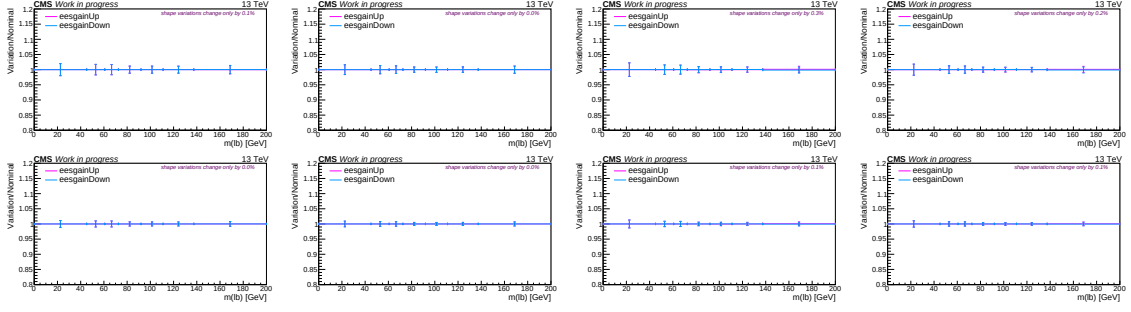


Figure 46: Similar to Fig. 41 for electron energy scale: scale gain component. Top: ee channel. Bottom: $e\mu$ channel.

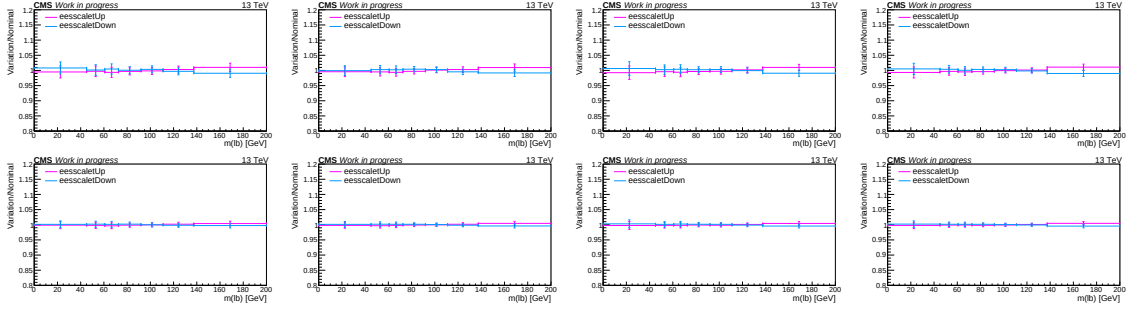


Figure 47: Similar to Fig. 46 for the scale E_T component for the electron energy scale uncertainty.

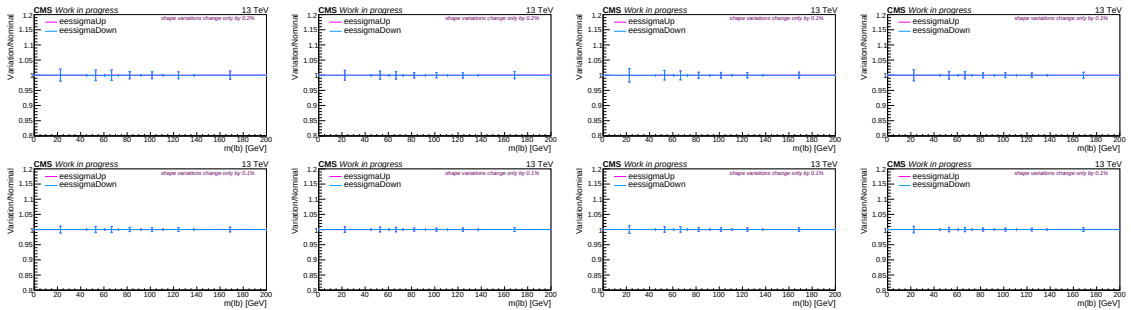


Figure 48: Similar to Fig. 46 for the sigma component for the electron energy scale uncertainty.

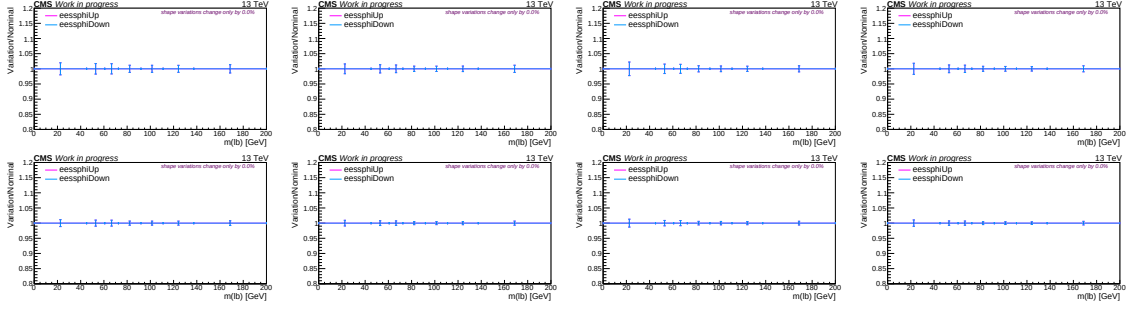


Figure 49: Similar to Fig. 46 for the sigma ϕ component for the electron energy scale uncertainty.

Jet energy scale Jet energy scale (JES) correction is applied as a function of p_T , η . We use a full breakdown of the sub-sources, 29 parameters in all [34]. From the shape variation, we found the sources which are expected to be more relevant are the FlavorPureBottomJEC (enhanced by the b-driven selection), TimePtEtaJEC, SinglePionECALJEC, and the ones related to the Absolute scale. Examples for JES uncertainties are shown in Figure 50 to 56.

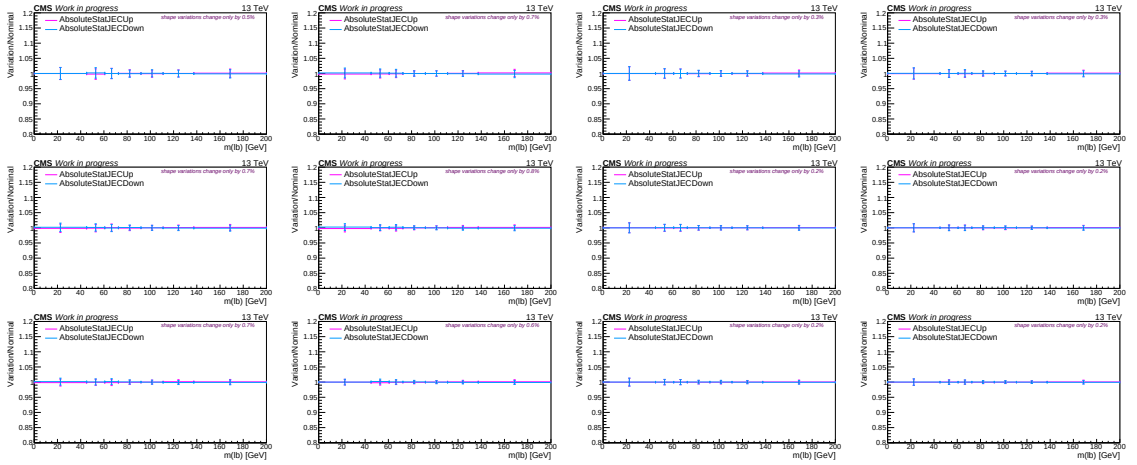


Figure 50: Similar to Fig. 41 for the AbsoluteStatJEC component of the JES uncertainty.

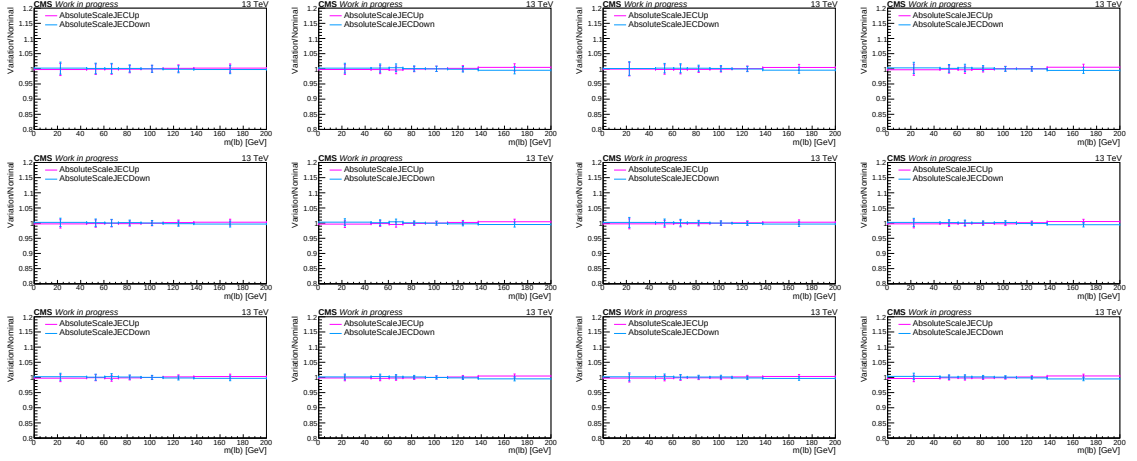


Figure 51: Similar to Fig. 41 for the AbsoluteScaleJEC component of the JES uncertainty.

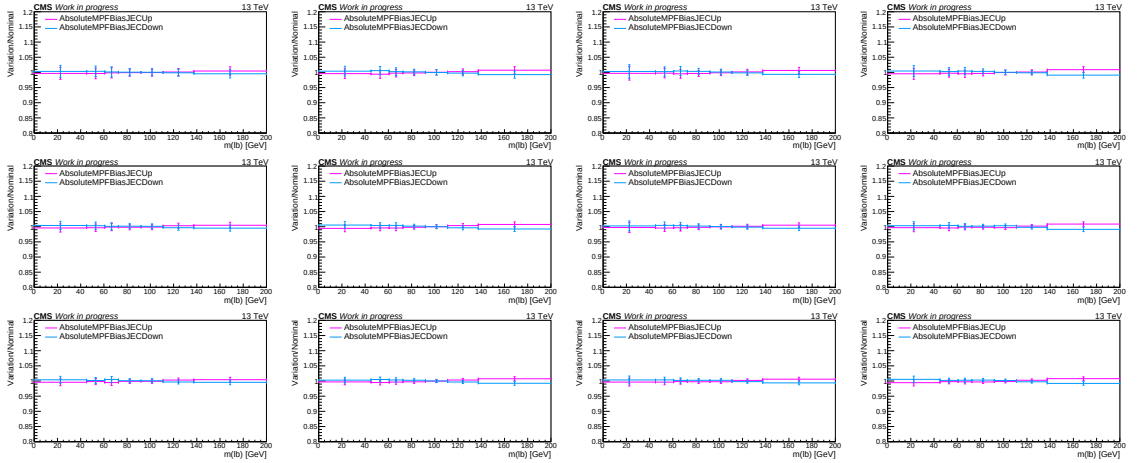


Figure 52: Similar to Fig. 41 for the AbsoluteMPFBiasJEC component of the JES uncertainty.

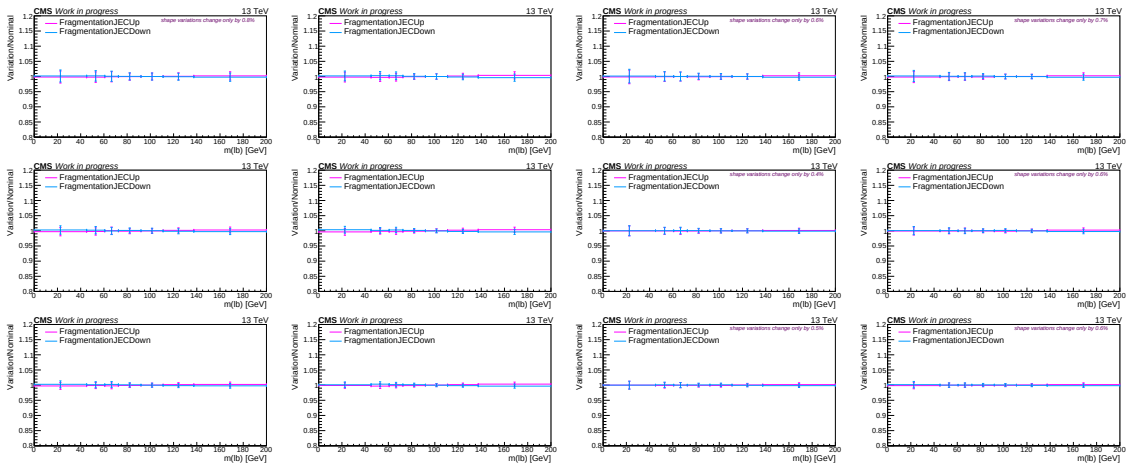


Figure 53: Similar to Fig. 41 for the FragmentationJEC component of the JES uncertainty.

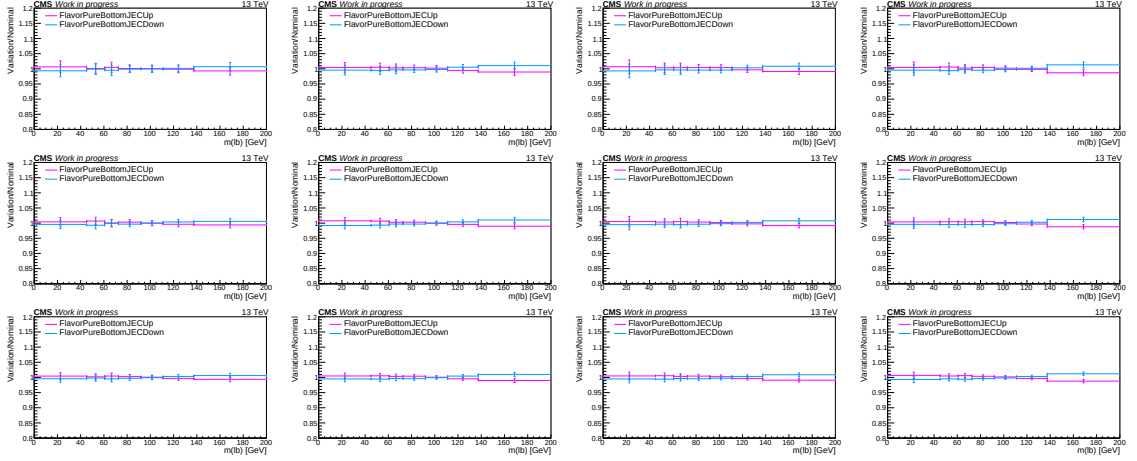


Figure 54: Similar to Fig. 41 for the FlavorPureBottomJEC component of the JES uncertainty.

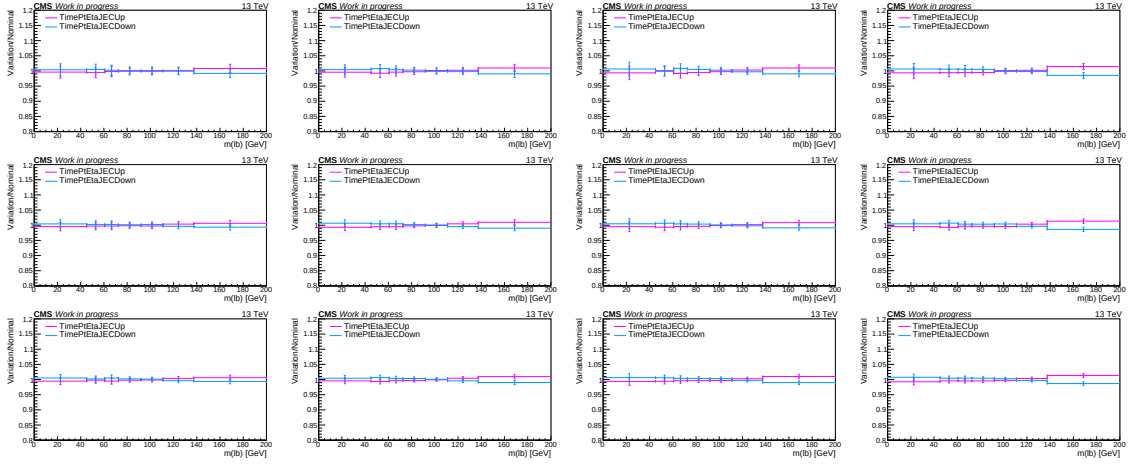


Figure 55: Similar to Fig. 41 for the TimePtEtaJEC component of the JES uncertainty.

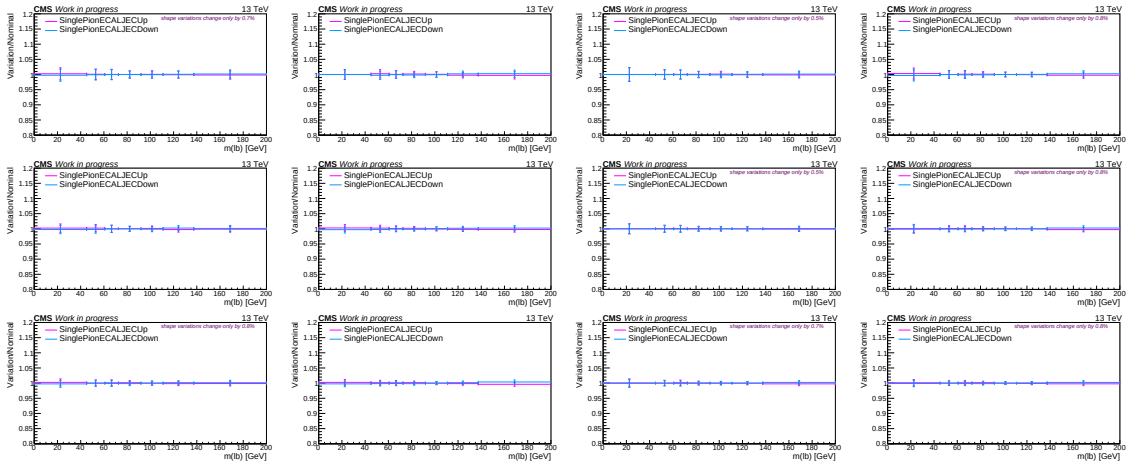


Figure 56: Similar to Fig. 41 for the SinglePionECALJEC component of the JES uncertainty.

Jet energy resolution We use the recommended jet energy resolution (JER) measurements [35]. There are 8 sub-sources considered. Figure show a few examples of JER uncertainties.

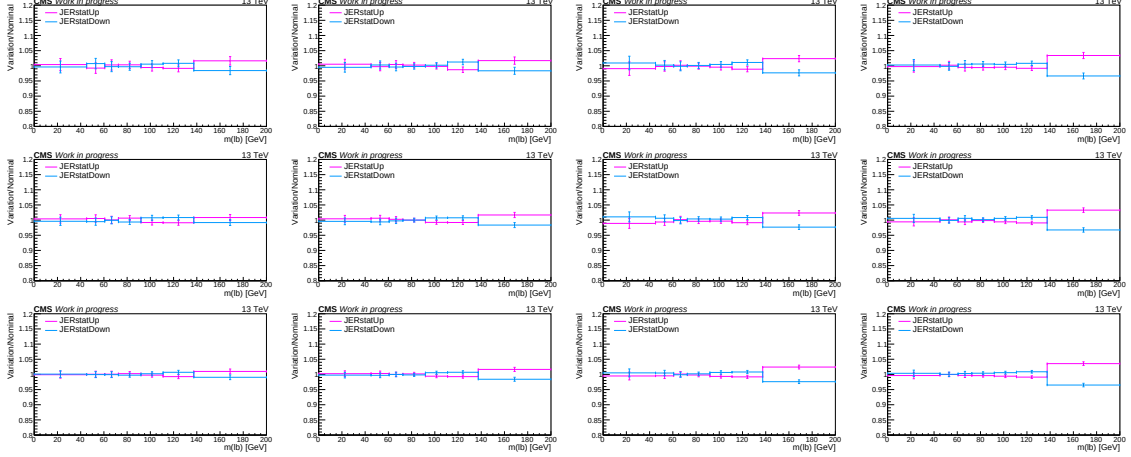


Figure 57: Similar to Fig. 41 for the JERstat component of the JER uncertainty.

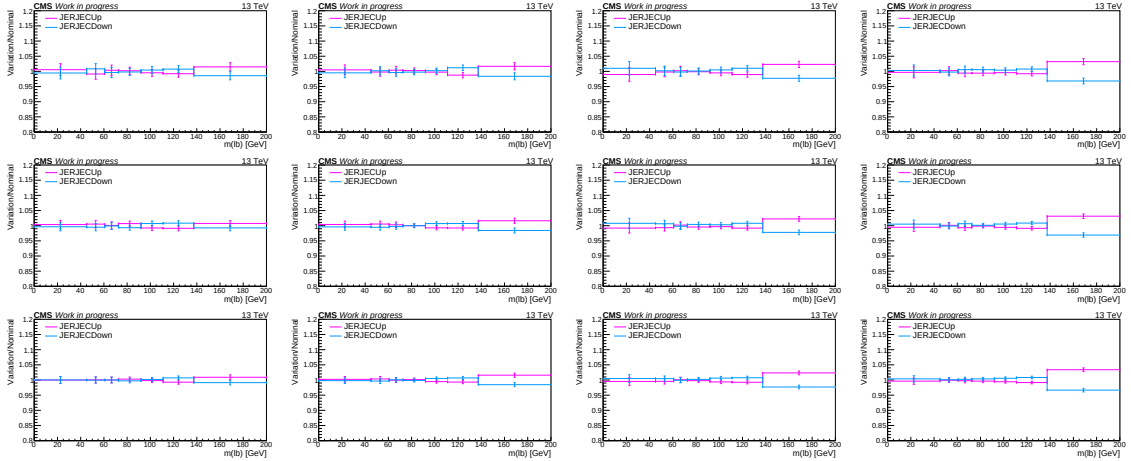


Figure 58: Similar to Fig. 41 for the JERJEC component of the JER uncertainty.

b-tagging and mis-identification efficiencies We applied scale factors for b-tagging with a deterministic probabilistic method which takes into account the generator-level flavor of the jets. Two sources of uncertainty are considered to affect this method, resulting in alternative sets of weights for light-, and heavy-(b+c) flavored jets. The effects are illustrated in Figs. 59, and 60.

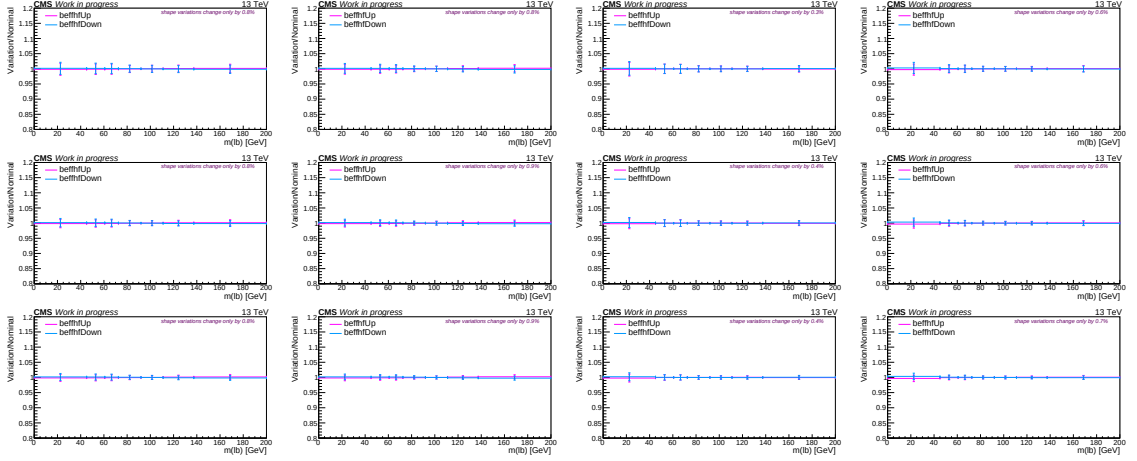


Figure 59: Similar to Fig. 41 for the uncertainty on the heavy-flavored jets efficiency (b-tagging).

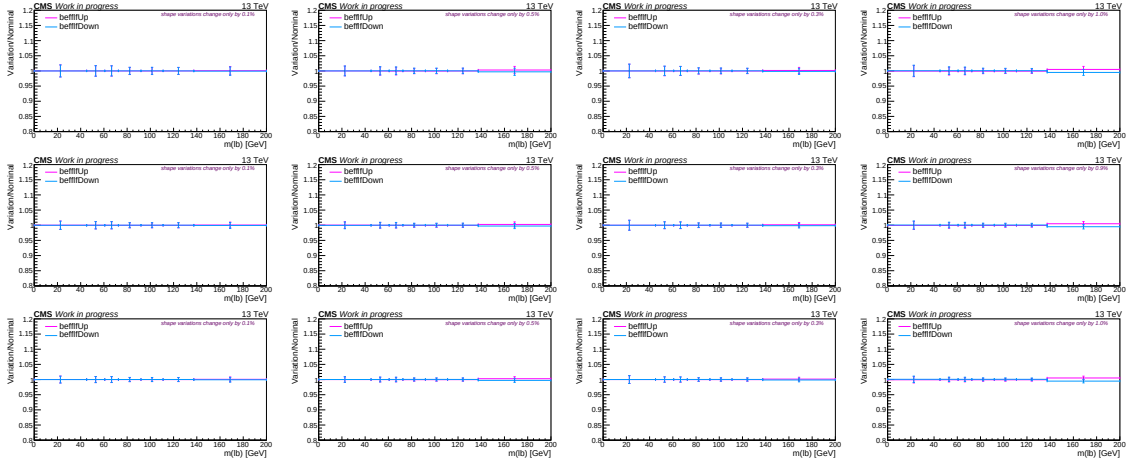


Figure 60: Similar to Fig. 41 for the light-flavored jets efficiency (b-tagging).

b-fragmentation and semi-leptonic B decay branching ratios The b-fragmentation function has its uncertainties, which is a weight applied jet-by-jet, based on the $p_T(B)/p_T(jet)$ ratio at generator level. In addition the semi-leptonic decay branching ratios of the most abundant B hadrons ($B^\pm$, B^0 , B_s^0 , Λ_b) are also varied according to their uncertainties [7]. The effects are shown in Figure 61 and 62. It is observed that b-fragmentation shape variation is relatively big.

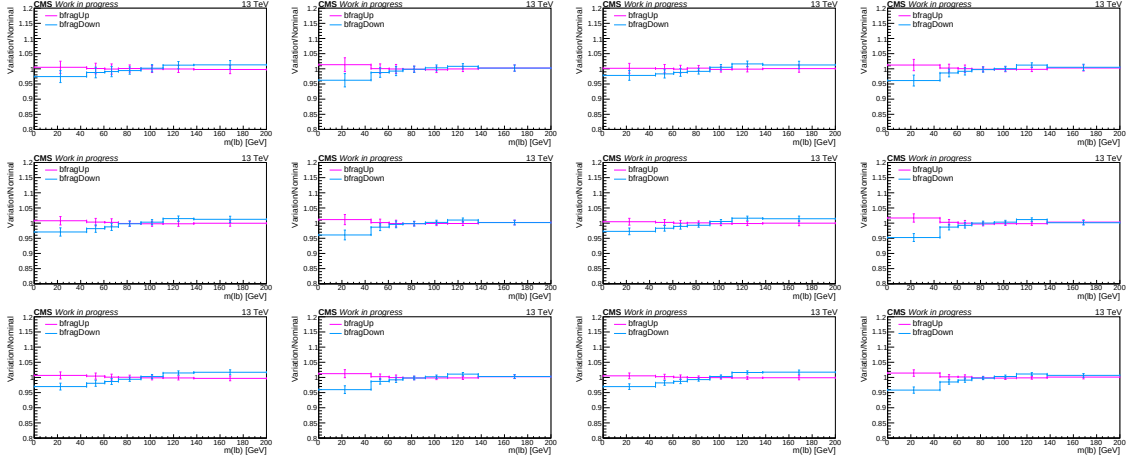


Figure 61: Similar to Fig. 41 for the b-fragmentation uncertainty.

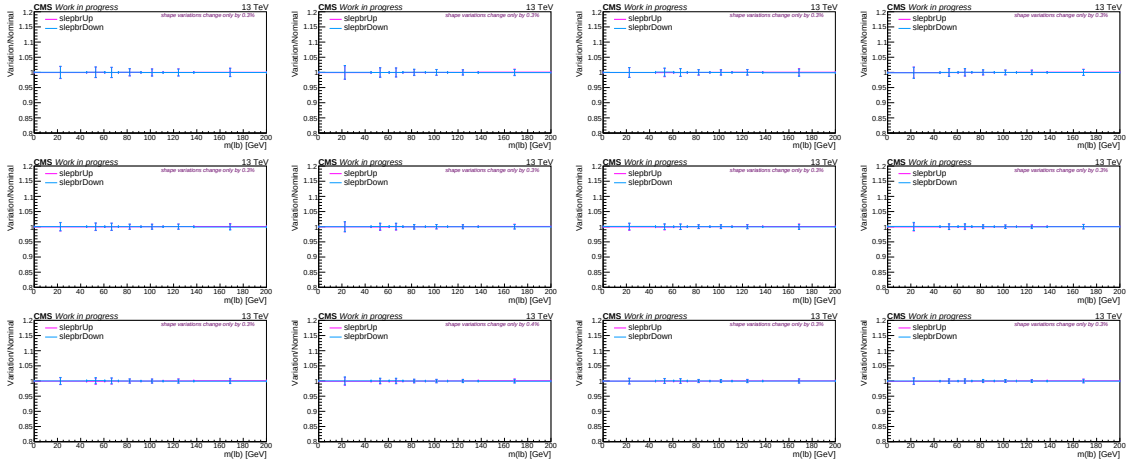


Figure 62: Similar to Fig. 41 for the uncertainty on the semi-leptonic branching ratio of B hadrons.

Drell-Yan normalization and shape We take a 30% uncertainty of the DY cross section as a rate effect. Separately, a shape uncertainty is calculated, un-correlated among event selection categories, see Figure 63. Although the shape effects are rather large, they are not expected to affect our measurement because this background does not contribute much to the total selected events.

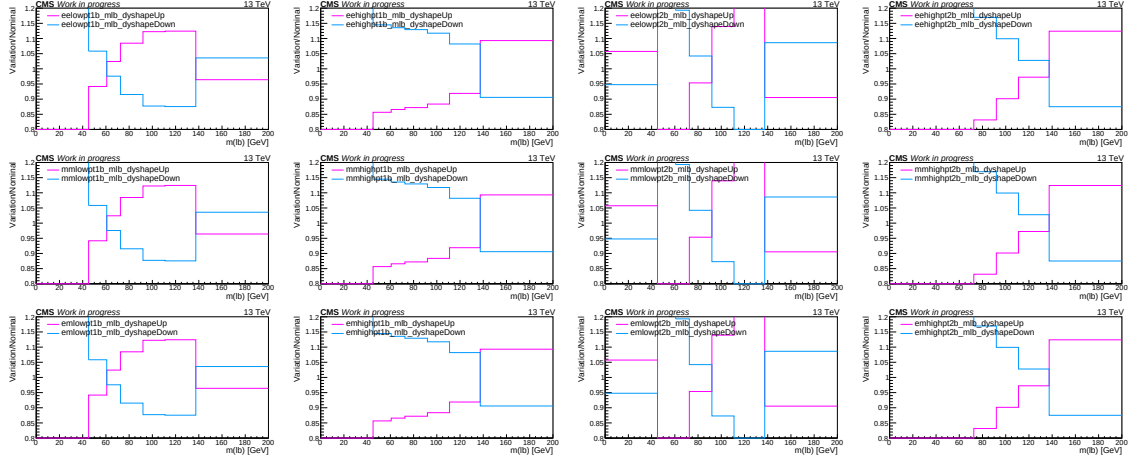


Figure 63: Similar to Fig. 41 for the DY shape uncertainty

Integrated luminosity A 2.5% uncertainty is included for the integrated luminosity [45].

This uncertainty affects the prediction for the yields of MC processes.

4.8.2. Theoretical Uncertainties

tW, vv normalization The cross section of background processes, single top (tW) and di-boson(vv) has uncertainty. The measured uncertainty for tW normalization is 14% [46]. Uncertainties on di-boson processes are 23% for WZ [47], 11% WW (same sign) [47], 5.7% for WW (opposite sign) [48]. Considering WW is more relevant, we take 20% in our analysis.

QCD scale It is assumed that in the $t\bar{t}$ MC simulation, the variation of the factorization and renormalization scales (μ_R/μ_F) are anti-correlated. In addition, the envelope of the variations is considered as another systematic source. We follow the procedure described [49]. The shape effects are shown in Figure 64-66.

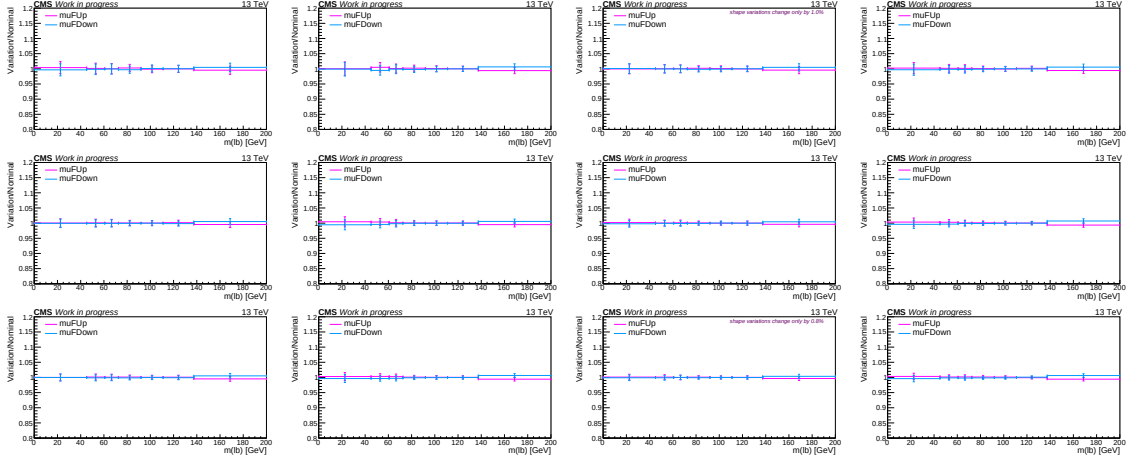


Figure 64: Similar to Fig. 41 showing the effect of varying the factorization scale, μ_F .

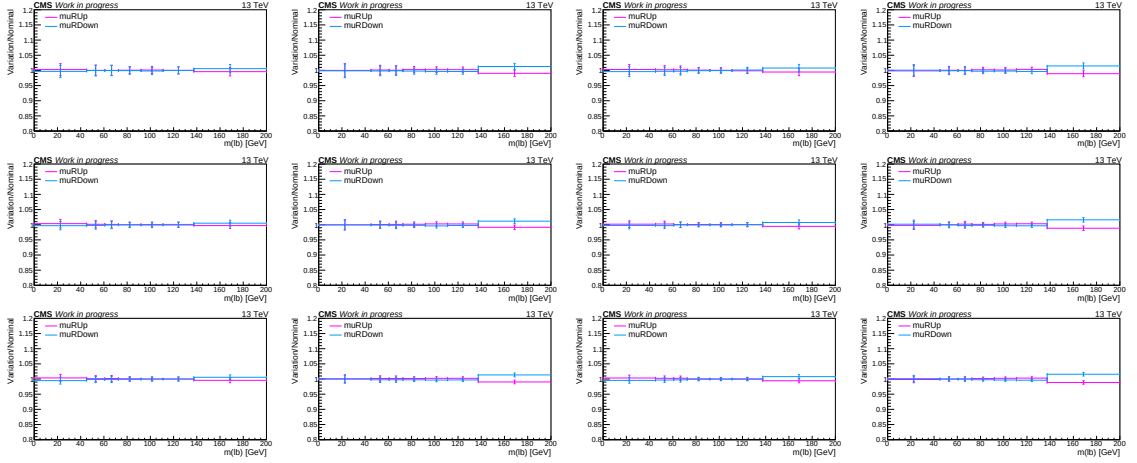


Figure 65: Similar to Fig. 41 showing the effect of varying the renormalization scale, μ_R .

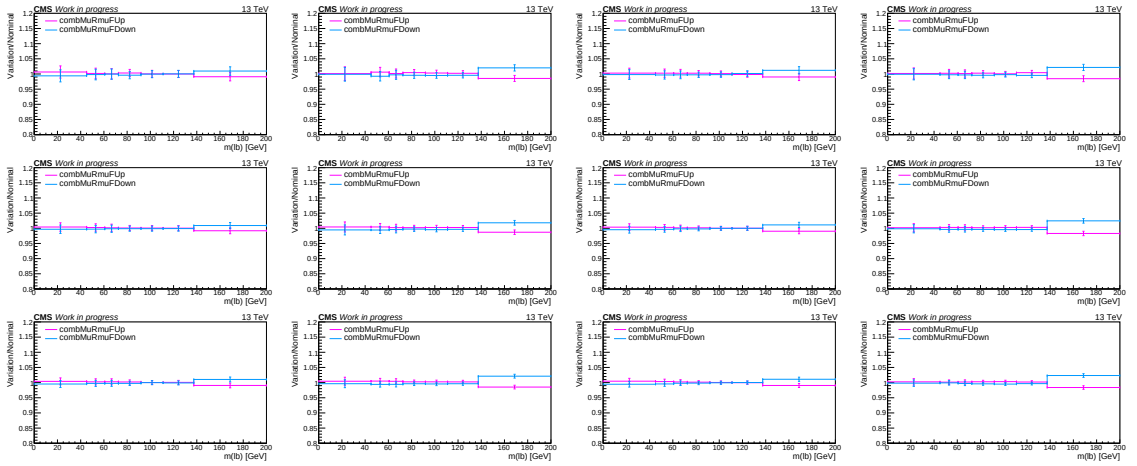


Figure 66: Similar to Fig. 41 showing the effect of a combined variation of the factorization and renormalization scales.

Parton shower scale The impact of varying α_S for initial- and final-state radiation is

evaluated decorrelating four different splitting types: $g \rightarrow gg$, $g \rightarrow q\bar{q}$, $q \rightarrow gq$, and $x \rightarrow xg$ where $x=b,t$. The different splittings occur at different scales which are hard to compute/establish from first principles in a parton shower. The splittings with same soft/collinear (singular) approximation have also different true matrix elements. Thus, by decorrelating the impact on each separately we avoid having accidental cancellations or inducing correlations between them which shouldn't exist. A total of 4 (splittings) $\times$ 2 (singular/non-singular) variations are considered for $\alpha_S(\text{ISR})$ and $\alpha_S(\text{FSR})$ separately, yielding a total of 16 nuisance parameters. These variations are implemented via event weights which are automatically computed by PYTHIA8 and stored in the event record. The weights correspond to a variation of the scale choice by factors of 0.5 and 2 independently for each of the 16 possibilities. More details can be found in [50]. Figs. 67 through 82 summarize the individual impact of these 16 nuisances on the $m(\ell b)$ shapes. The variation induced in α_S^{FSR} is expected to yield the largest source of uncertainty, in particular for $x \rightarrow xg$ and $g \rightarrow gg$ splittings. The variations of these scales are also considered for the tW background by using the weights stored in the dedicated simulations of tW.

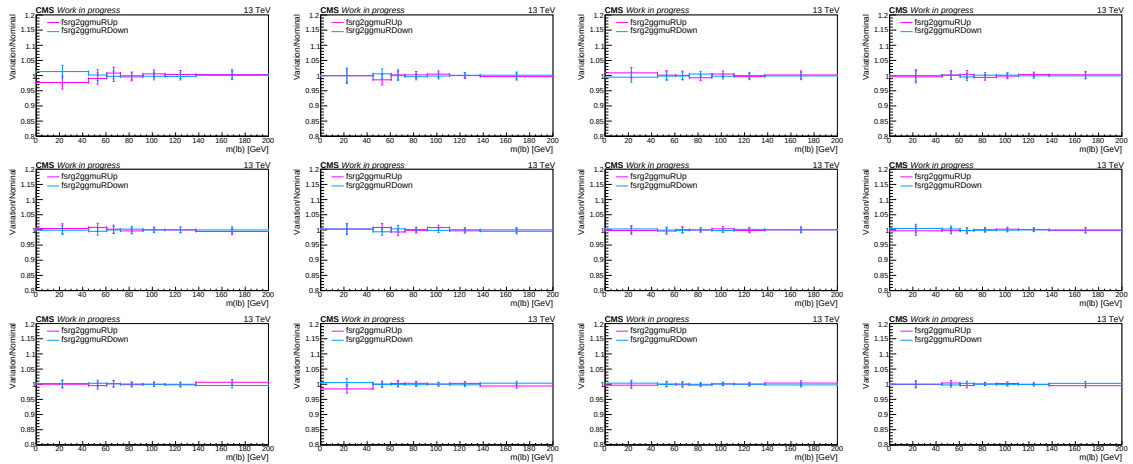


Figure 67: Similar to Fig. 41 showing the effect of varying the α_S^{FSR} scale in singular terms for $g \rightarrow gg$ splittings.

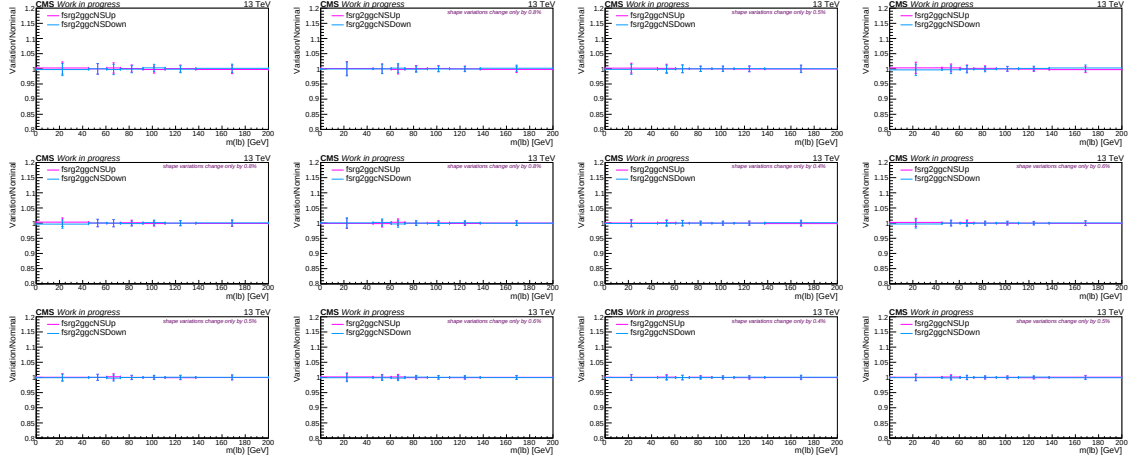


Figure 68: Similar to Fig. 41 showing the effect of varying the α_S^{FSR} scale in non-singular terms for $g \rightarrow gg$ splittings.

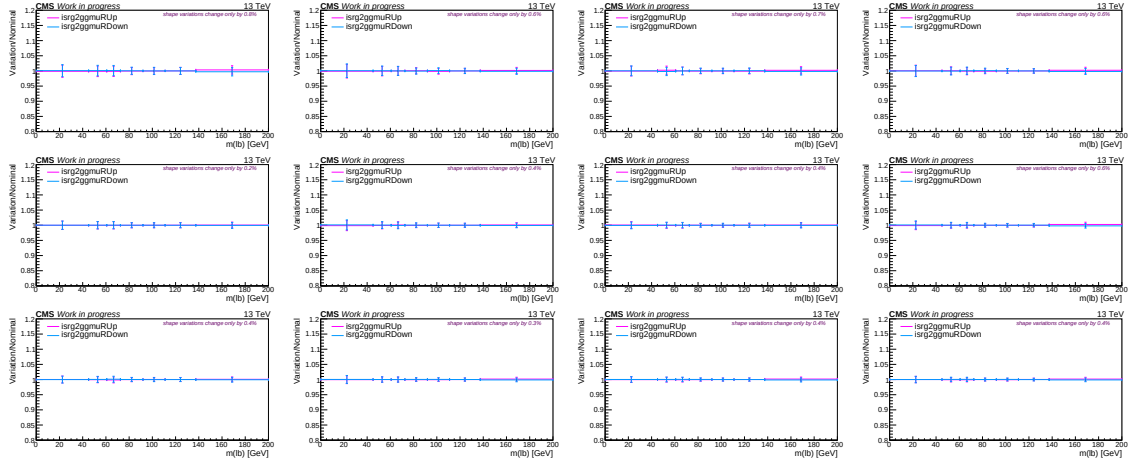


Figure 69: Similar to Fig. 41 showing the effect of varying the α_S^{ISR} scale in singular terms for $g \rightarrow gg$ splittings.

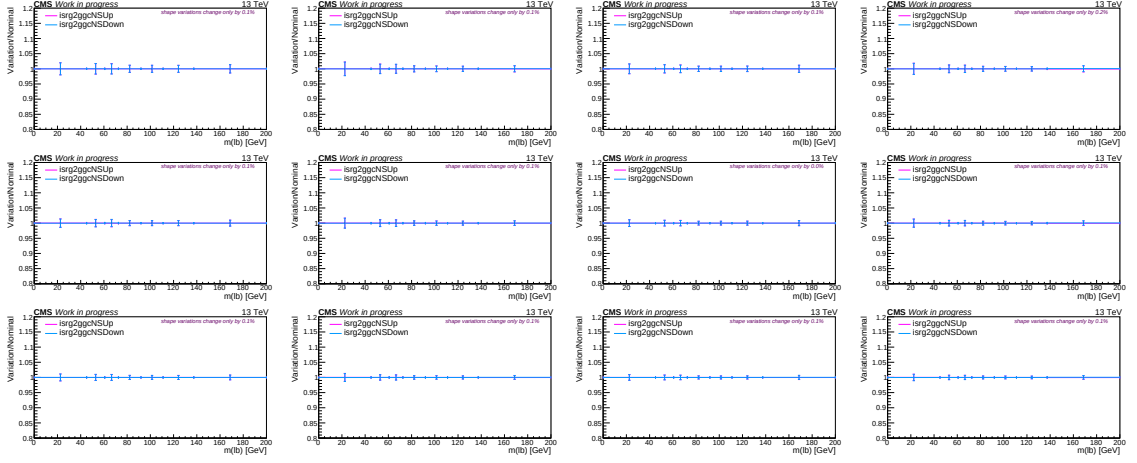


Figure 70: Similar to Fig. 41 showing the effect of varying the α_S^{ISR} scale in non-singular terms for $g \rightarrow gg$ splittings.

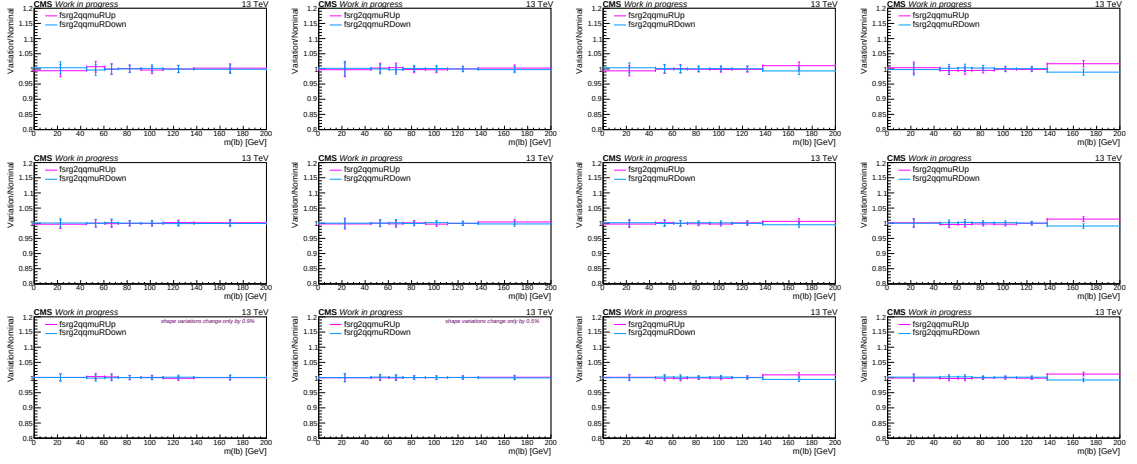


Figure 71: Similar to Fig. 41 showing the effect of varying the α_S^{FSR} scale in singular terms for $g \rightarrow q\bar{q}$ splittings.

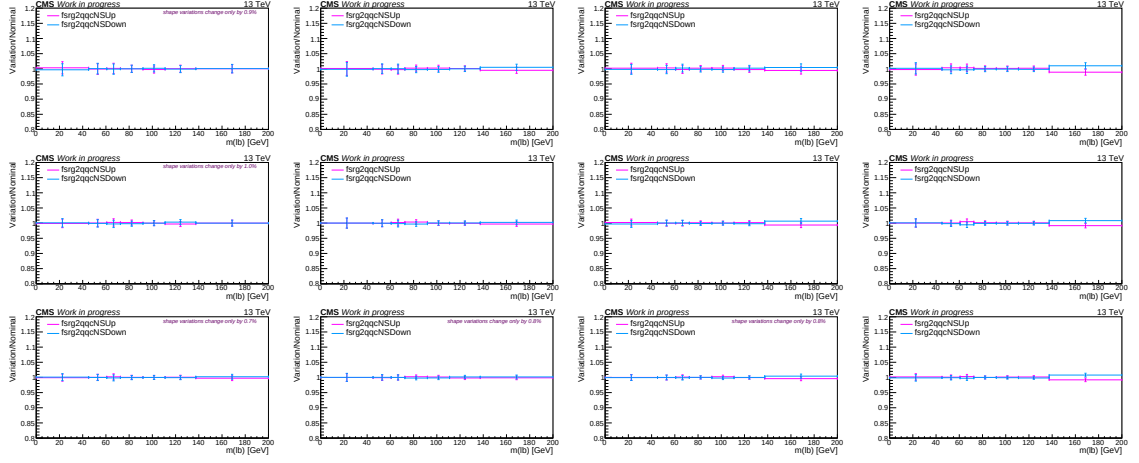


Figure 72: Similar to Fig. 41 showing the effect of varying the α_S^{FSR} scale in non-singular terms for $g \rightarrow q\bar{q}$ splittings.

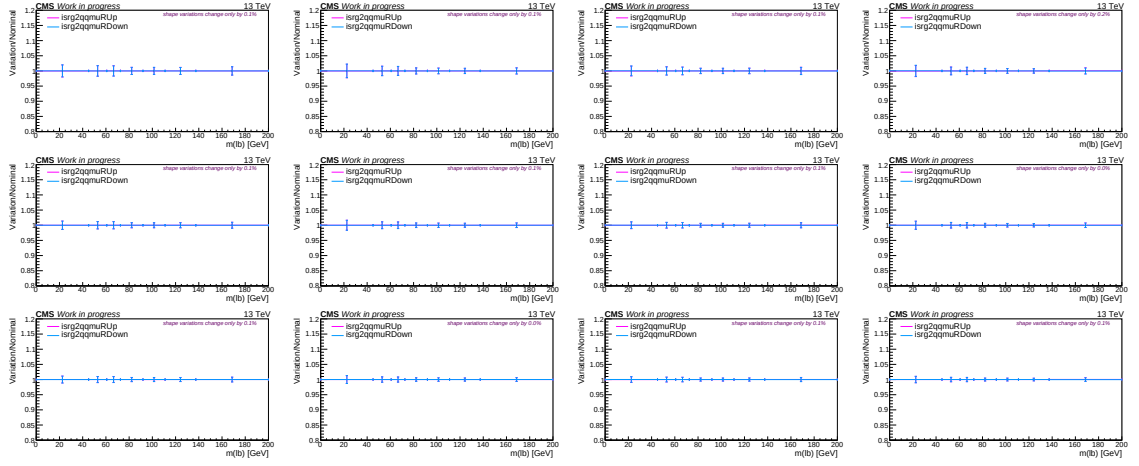


Figure 73: Similar to Fig. 41 showing the effect of varying the α_S^{ISR} scale in singular terms for $g \rightarrow q\bar{q}$ splittings.

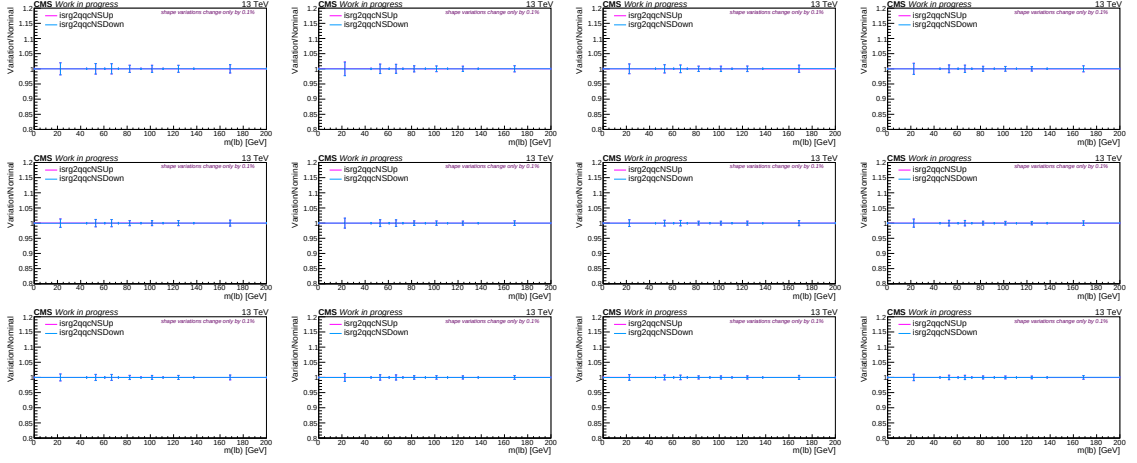


Figure 74: Similar to Fig. 41 showing the effect of varying the α_S^{ISR} scale in non-singular terms for $g \rightarrow q\bar{q}$ splittings.

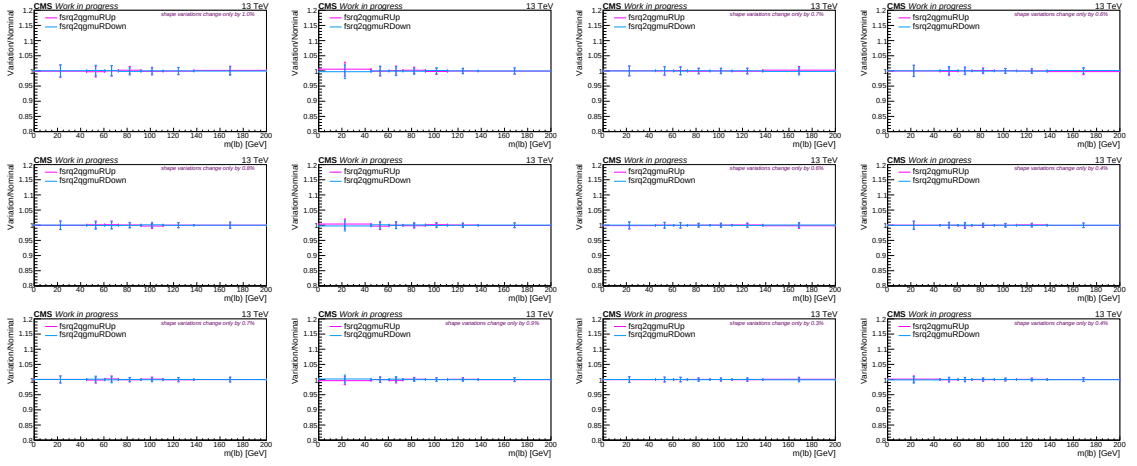


Figure 75: Similar to Fig. 41 showing the effect of varying the α_S^{FSR} scale in singular terms for $q \rightarrow gq$ splittings.

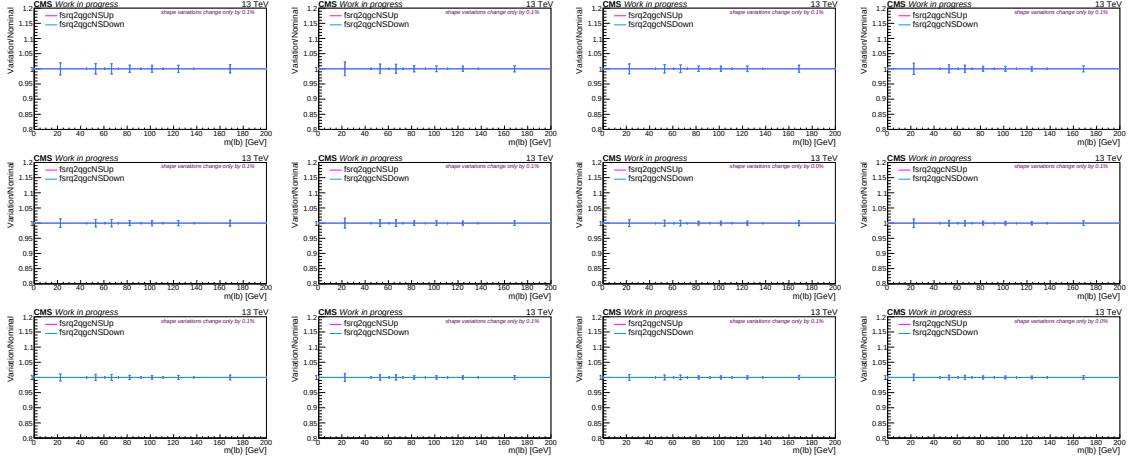


Figure 76: Similar to Fig. 41 showing the effect of varying the α_S^{FSR} scale in non-singular terms for $q \rightarrow gg$ splittings.

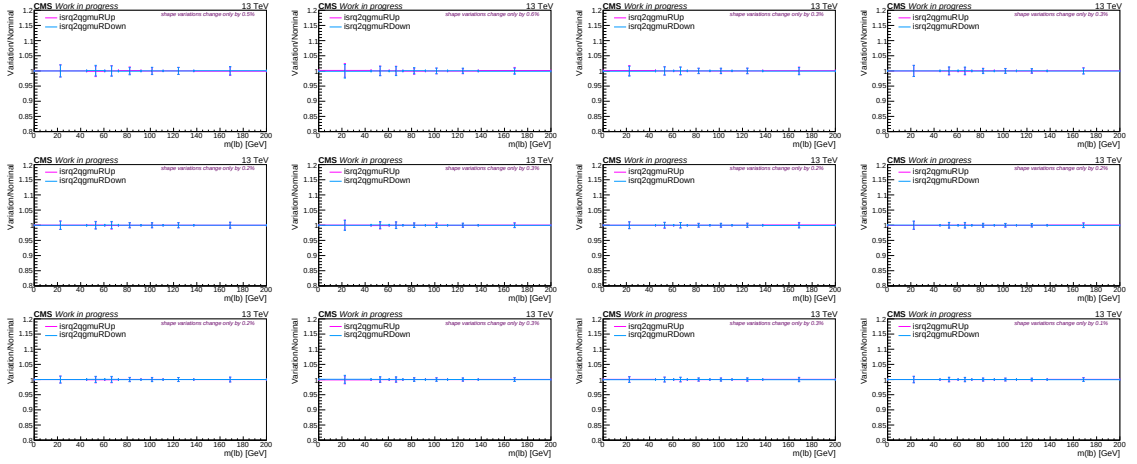


Figure 77: Similar to Fig. 41 showing the effect of varying the α_S^{ISR} scale in singular terms for $q \rightarrow gg$ splittings.

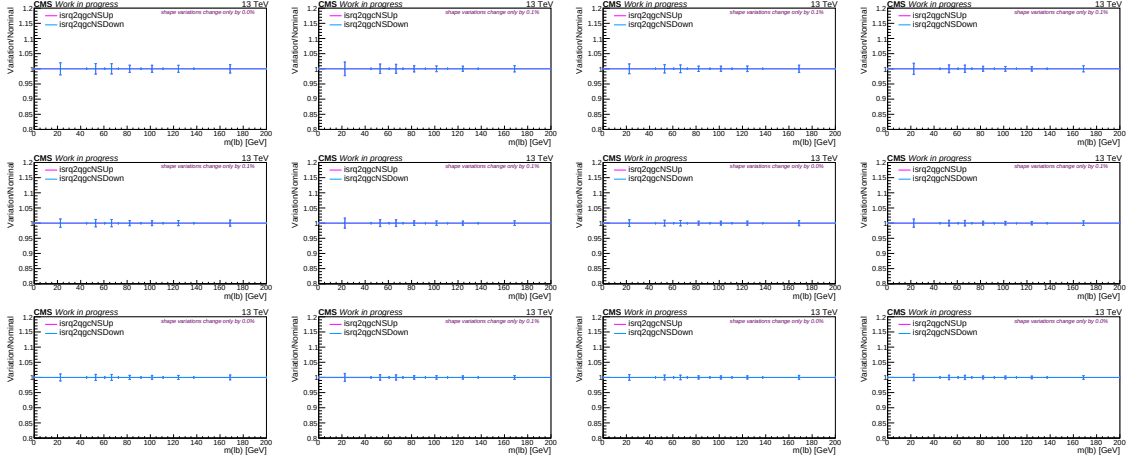


Figure 78: Similar to Fig. 41 showing the effect of varying the α_S^{ISR} scale in non-singular terms for $q \rightarrow gg$ splittings.

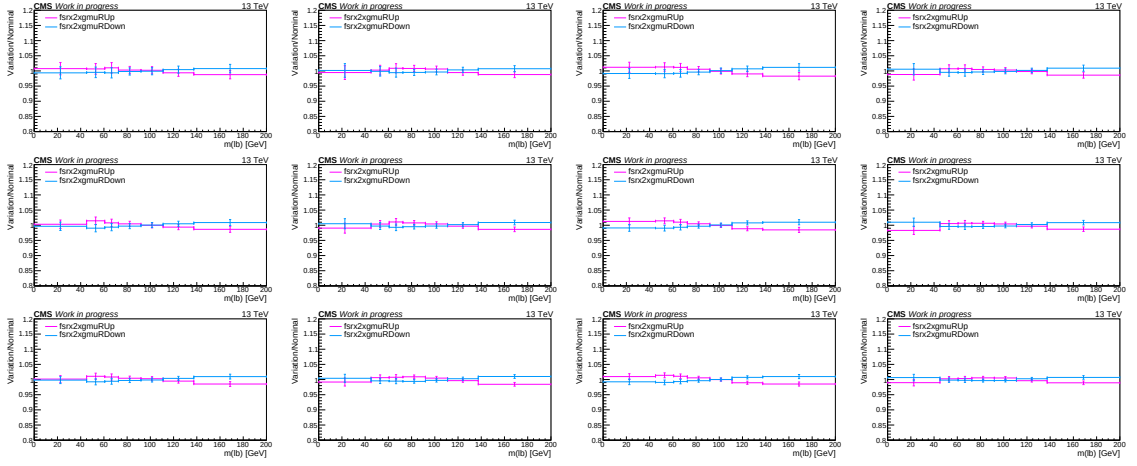


Figure 79: Similar to Fig. 41 showing the effect of varying the α_S^{FSR} scale in singular terms for $x \rightarrow gx$ splittings.

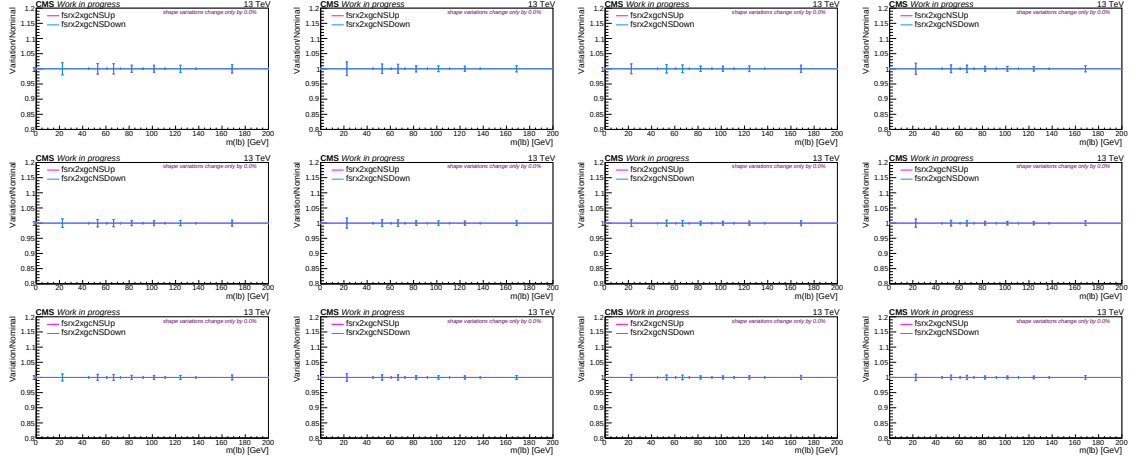


Figure 80: Similar to Fig. 41 showing the effect of varying the α_S^{FSR} scale in non-singular terms for $x \rightarrow gx$ splittings.

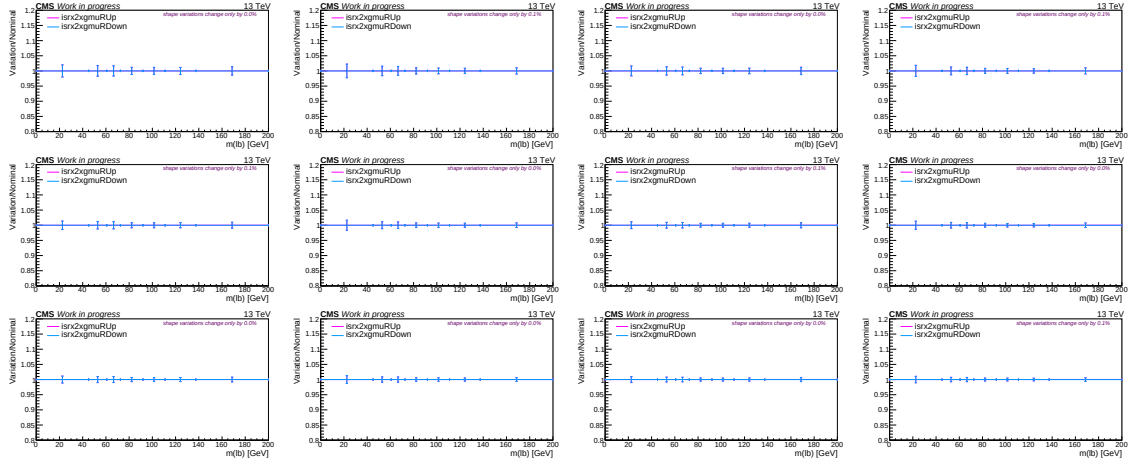


Figure 81: Similar to Fig. 41 showing the effect of varying the α_S^{ISR} scale in singular terms for $x \rightarrow gx$ splittings.

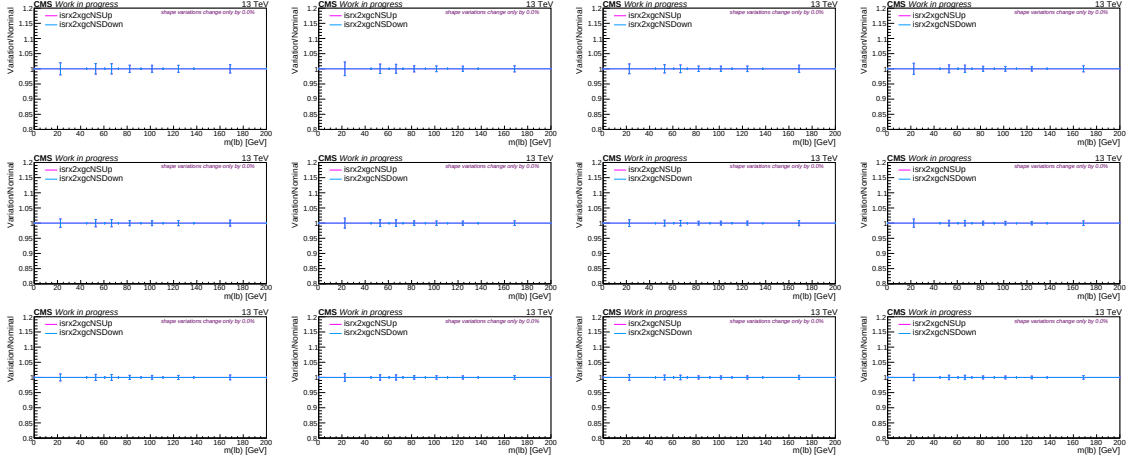


Figure 82: Similar to Fig. 41 showing the effect of varying the α_S^{ISR} scale in non-singular terms for $x \rightarrow gx$ splittings.

Top p_T The NLC QCD theory prediction of top quark p_T differs from the measurements. So we computed the uncertainty of this modeling by re-re-weighting at generator level, as the function in [51]. As shown in Figure 83, the effect is larger in high p_T categories. This is a one-side uncertainty, so we mirror the effect to get the down variation.

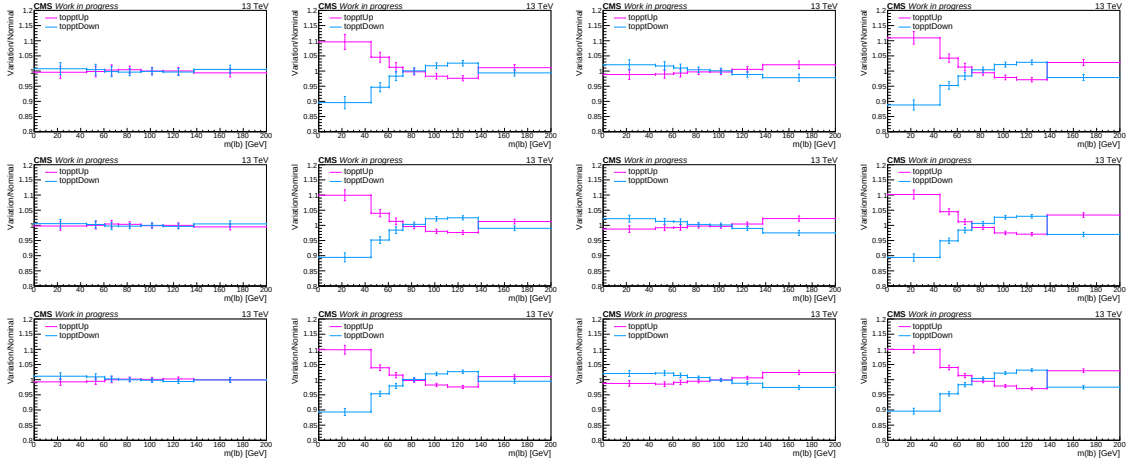


Figure 83: Similar to Fig. 41 for the variation of the top quark p_T , induced by a parton-level re-weighting.

Top mass This is a modeling uncertainty only for single top (tW) process. In this analysis we are measuring m_t , and we considered the Breit-Wigner re-weighting of m_t in $t\bar{t}$ process, but in principle, top mass in background processes also counts. The simulation of tW does not include the modeling of m_t and Γ_t . Therefore, we are not able to apply the re-weighting for it. We consider the shape variation carried by tW process m_t by using the dedicated

MC samples for $t\bar{W}$ at $m_t = 175.5$ GeV and 169.5 GeV. This would cover the scan of m_t in signal. Shape effect is shown in Figure 84.

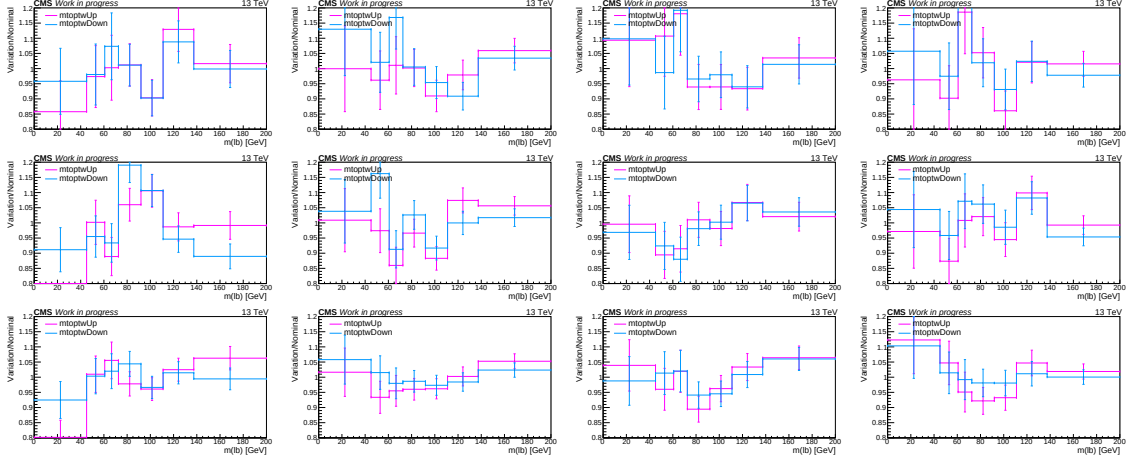


Figure 84: Similar to Fig. 41 for the variation of m_t in the simulation.

$t\bar{W}/t\bar{t}$ interference It is known that in NLO QCD, $t\bar{W}$ production interferes with $t\bar{t}$ production, due to the similar initial and final states of some diagrams. Two schemes for defining the $t\bar{W}$ signal, which distinguish it from $t\bar{t}$ production have been compared in our analysis: “diagram removal” (DR) [52], in which all doubly resonant NLO $t\bar{W}$ diagrams are removed, and “diagram subtraction” (DS) [52, 53], where a gauge-invariant subtractive term modifies the NLO $t\bar{W}$ cross section to locally cancel the contribution from $t\bar{t}$. A dedicated simulation is done to include these processes. The effect is shown in Figure 85. This is the largest source of uncertainty on the modeling of $t\bar{W}$ background. Given this is a one-sided uncertainty, the effect is mirrored bin-by-bin.

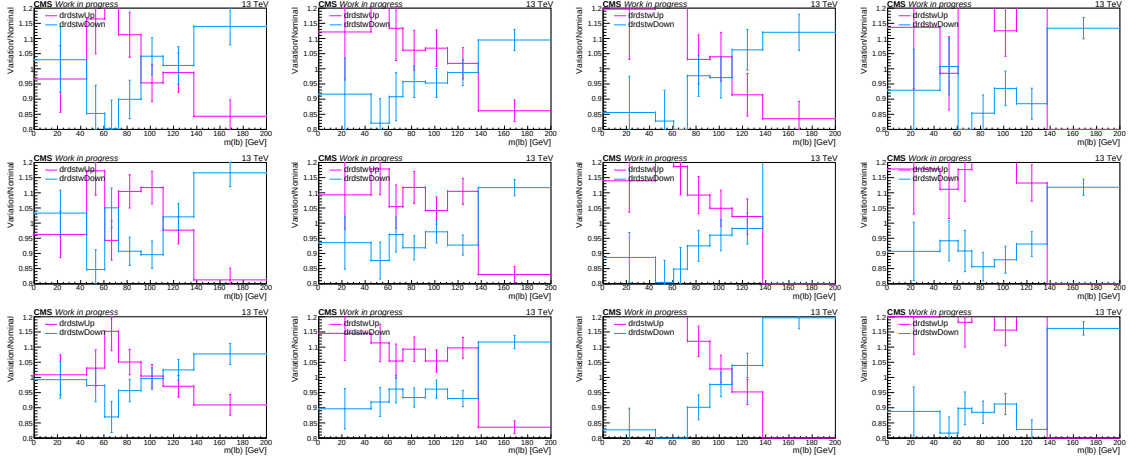


Figure 85: Similar to Fig. 41 for the variation of $tW/t\bar{t}$ interference.

PDFs 100 other PDF replicas exist for the $t\bar{t}$ simulation. Their effects are considered as a shape envelope, which takes the maximum of all the possible variations in each bin, because the effect is too small on $m(\ell b)$. The down variation is taken from mirroring the envelope. This overall effect is shown in Figure 86. A separate uncertainty of α_S in the PDF is evaluated, in Figure 87.

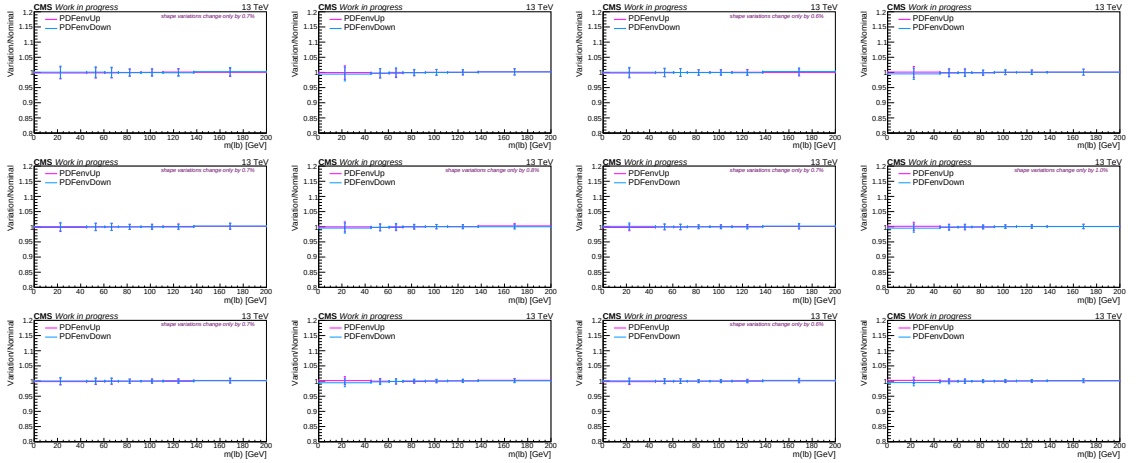


Figure 86: Similar to Fig. 41 for the envelope of PDF variations.

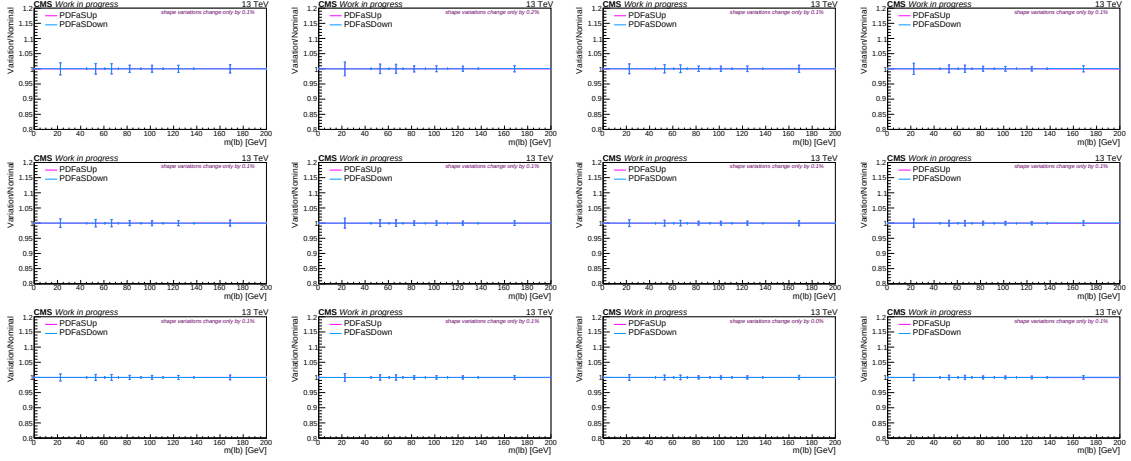


Figure 87: Similar to Fig. 41 for the variation of the α_S choice in the computation of the PDF set.

The following two types, Resummation scale and Non-perturbative QCD, total five sources of uncertainties are treated differently by only considering the shape variation on inclusive $m(\ell b)$ not in each event category, where inclusive means a sum of the 12 categories. This special treatment is designed for low statistics MC samples. The inclusive shape variation is taken from generator level shape, not reconstructed level, to avoid artificial effects coming from imperfect reconstruction. Therefore, only one shape variation is shown for each uncertainties below.

Resummation scale The h_{damp} parameter for parton shower process is to set the resummation scale, in order to complement the matrix-element computation [54]. A separate simulation that uses a h_{damp} value varied by 60% from the default value, and the effect can be found in Figure 88.

Non-perturbative QCD In the nominal $t\bar{t}$ simulation, it uses default underlying event (UE) parameters and color reconnection (CR) model. Two alternative UE tunes are simulated and build a UE uncertainty. Three different CR models are considered, gluon move [55], QCD based [56], and early resonance decays [57]. We use mirroring to build the down variation for CR shapes. Figure 88 shows their expected effects.

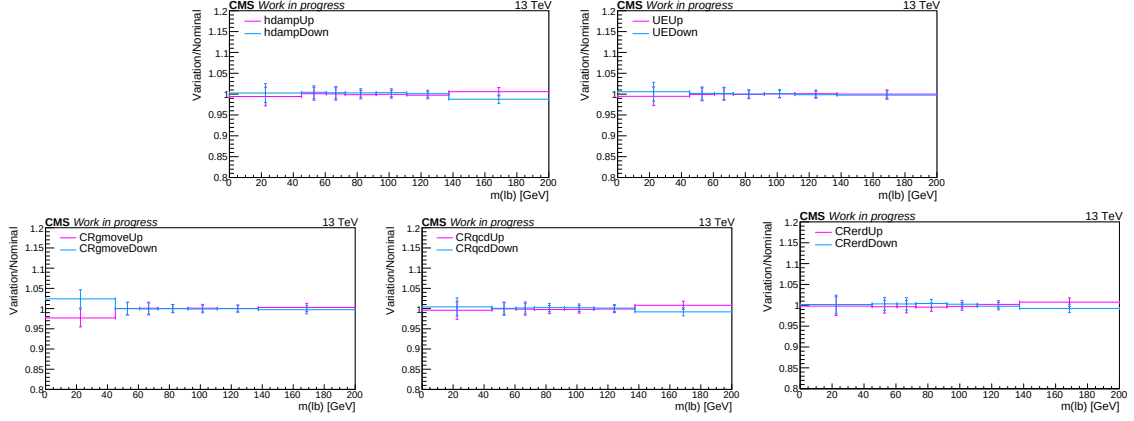


Figure 88: Systematic uncertainty shape variations, inclusive $m(\ell b)$ category, showing the effect of hdamp, UE in the first row, CR gloun move (CRgmove), CR QCD based (CRqcd) and CR early resonance decays (CRerd) in the second row.

4.8.3. MC Statistical Uncertainties

The limited statistics in the simulation may impact this analysis in an important way, given we are fitting a distribution for percent-level deformations from m_t and Γ_t . We use toy templates to evaluate the statistical uncertainties in MC. Toy templates are made by varying the un-weighted templates according to a Poisson distribution. Variations on nominal signal shape and event-weight systematic shapes are generated from the nominal templates. Variations on other systematic shapes which are modeled by dedicated MC samples are generated from those samples' templates directly. Due to time and computing power limitation, we created 400 toy sets and likelihood fit is repeated for each toy. We find the MC statistical uncertainty from the distribution of the fit results of toys. The MC statistical uncertainty result will be described in section 4.9.

4.9. Extraction of Top Mass and Width via Profile Likelihood

The results shown in this section use pseudo-data which is a combination of all the signal and background.

4.9.1. Direct Measurement of Mass and Width via Likelihood Profile Method

To find the m_t and Γ_t , we maximize a binned likelihood fit. For a given (m_t, Γ_t) hypothesis, the likelihood has a following relationship with expected number of events and observed number of events in each $m(\ell b)$ bin

$$\mathcal{L}(\mu, m_t, \Gamma_t) = \prod_{c \in \text{categories}} \prod_{i=1}^{N_{\text{bins}}} P_{\text{oisson}}[n_{i,c} | \mu \times s_{i,c}(m_t, \Gamma_t, \Theta) + b_{i,c}(\Theta)] \times \prod_k PDF(\theta_k) \quad , \quad (4.10)$$

where $\mu = \sigma/\sigma_{th}$ is the $t\bar{t}$ signal strength, $s_{i,c}$ ($b_{i,c}$) are the number of expected events in the i -th bin, in the category c for signal(background), $n_{i,c}$ is the number of observed events, and $\Theta = (\theta_1, \theta_2, \dots, \theta_m)$ is a vector of m -nuisance parameters for the uncertainties.

In the likelihood only m_t and Γ_t are parameters of interest. Thus, for each (m_t, Γ_t) hypothesis, the likelihood is maximized for μ and the nuisance parameters, and a profile likelihood ratio method is used to marginalize all parameters except the parameters of interest:

$$\lambda(m_t, \Gamma_t) = \mathcal{L}(m_t, \Gamma_t, \bar{\mu}, \bar{\Theta}) / \mathcal{L}(\bar{m}_t, \bar{\Gamma}_t, \bar{\mu}, \bar{\Theta}) \quad , \quad (4.11)$$

there $\bar{x}$ denotes that the parameter that maximizes the likelihood function. If no $\bar{x}$ is used for

a parameter, it means it is fixed (i.e., it's a fixed point/anchor of the scan for the parameter of interest). Thus the values of (m_t, Γ_t) that maximize λ correspond to the best fit parameters. Likewise, if we perform the extraction of a single parameter (m_t), the unused parameter is also marginalized, while profiling the λ function.

Due to the large number of bins and nuisance parameters, we are not able to do a fit with the standard Higgs combination tool [58]. They meet an issue of numerical instabilities which lead to non-smooth likelihood scans and spurious local minima. We finally use a tensorflow version of the likelihood minimization [59].

Results in this section are extracted from 1D scan. At $m_t = 172.5$ GeV, we scan the width points

$$\Gamma_t \in \{0.7, 0.8, 0.9, 1.0, 1.05, 1.1, 1.15, 1.2, 1.23, 1.25, 1.28, 1.3, 1.31, 1.32, 1.34, 1.36, 1.38, 1.39, 1.4, 1.45, 1.5, 1.55, 1.6, 1.65, 1.7, 1.75, 1.85, 1.9, 1.95, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.5, 4.0, 5.0\}$$

to find the best fit Γ_t . Then at $\Gamma_t = 1.31$ GeV, we scan

$$m_t \in \{169.5, 170.5, 171, 171.5, 171.75, 172, 172.25, 172.5, 172.75, 173, 173.5, 174.5, 175.5\}$$

to find the best fit m_t . In the 1D likelihood and m_t curve, we do an interpolation to find the point corresponding to the maximum likelihood.

4.9.2. Results

Figure 90 shows the profiled likelihoods at fixed Γ_t and m_t . The uncertainty reported on the plots are a combination of systematic uncertainty and data statistical uncertainty. We can further break them and find the data statistical uncertainty by a fit without any systematic nuisance parameters included. That gives $\Delta(m_t) = 0.08$ GeV, $\Delta(\Gamma_t) = 0.20$ GeV. In this

stage, we use pseudo-data as “data” which is a sum of simulation samples.

The MC statistical uncertainties are found by toys as discussed in Section 4.8, and the result is in Figure 89. We get $\Delta(m_t) = 0.10$ GeV, $\Delta(\Gamma_t) = 0.16$ GeV.

$$m_t(\text{fit}) = 172.50_{-0.23}^{+0.23} (\text{syst} + \text{data stat.}) \pm 0.10 (\text{MC stat.}) \text{ GeV assumed } \Gamma_t = 1.31 \text{ GeV or,}$$

$$m_t(\text{fit}) = 172.50_{-0.22}^{+0.22} (\text{syst}) \pm 0.08 (\text{data stat.}) \pm 0.10 (\text{MC stat.}) \text{ GeV assumed } \Gamma_t = 1.31 \text{ GeV}$$
(4.12)

and

$$\Gamma_t(\text{fit}) = 1.32_{-0.37}^{+0.50} (\text{syst} + \text{data stat.}) \pm 0.16 (\text{MC stat.}) \text{ GeV assumed } m_t = 172.5 \text{ GeV or,}$$

$$\Gamma_t(\text{fit}) = 1.32_{-0.31}^{+0.45} (\text{syst}) \pm 0.20 (\text{data stat.}) \pm 0.16 (\text{MC stat.}) \text{ GeV assumed } m_t = 172.5 \text{ GeV}$$
(4.13)

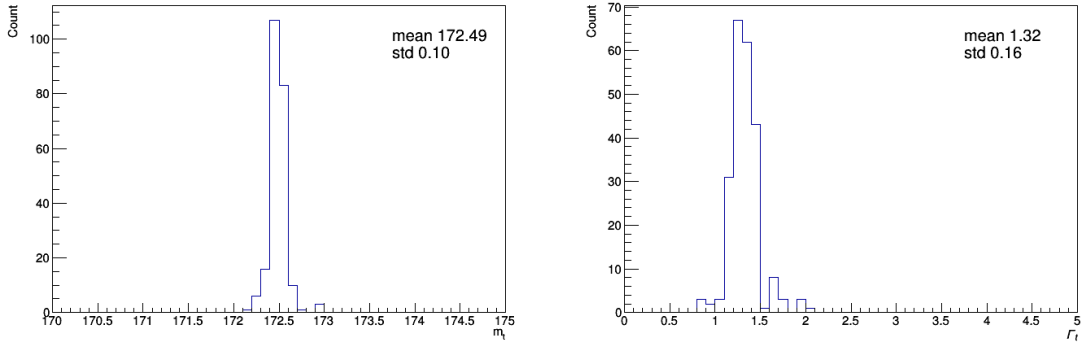


Figure 89: MC statistical uncertainty of m_t (left), and Γ_t (right).

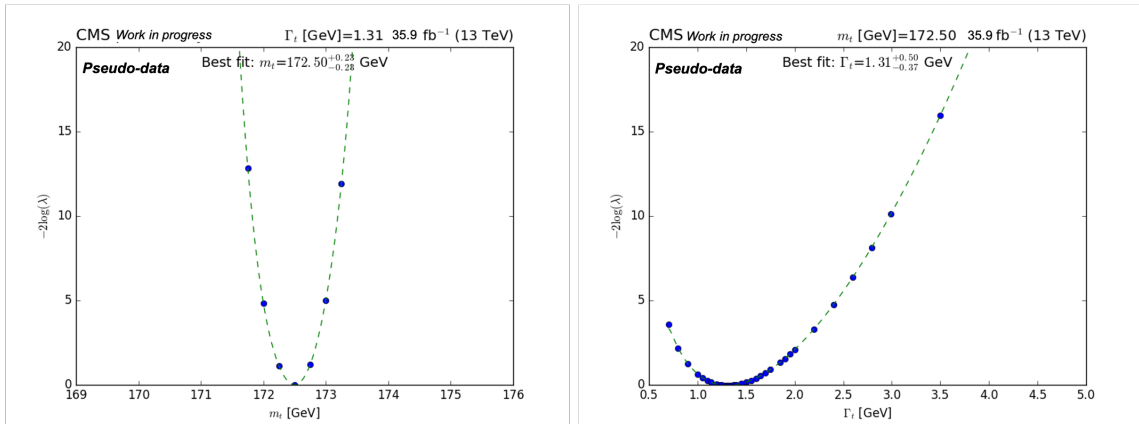


Figure 90: Likelihood profiles as function of m_t (left), and Γ_t (right).

We repeated the fit for various groups of nuisances to determine the uncertainty from dif-

ferent sources. Results can be found in Table 8.

Table 8: Expected contribution to the total uncertainty in the extraction of m_t and Γ_t .

Uncertainty source	δm_t [GeV]	$\delta \Gamma_t$ [GeV]
Selection (trigger, id, L1 pre-fire)	+0.10 / -0.10	+0.26 / -0.24
Jet energy resolution	+0.13 / -0.12	+0.32 / -0.26
Jet energy scale	+0.18 / -0.19	+0.22 / -0.24
Lepton energy scale	+0.10 / -0.10	+0.22 / -0.21
b-tagging	+0.09 / -0.09	+0.22 / -0.21
b-fragmentation/B BRs	+0.10 / -0.11	+0.31 / -0.24
ISR	+0.09 / -0.09	+0.21 / -0.20
FSR	+0.14 / -0.13	+0.23 / -0.22
hdamp	+0.03 / -0.00	+0.08 / -0.11
qcd scale	+0.17 / -0.16	+0.28 / -0.24
top p_T	+0.09 / -0.09	+0.28 / -0.25
tW	+0.15 / -0.14	+0.27 / -0.22
Color reconnection (plus UE)	+0.15 / -0.13	+0.35 / -0.27
PDF $+\alpha_S$	+0.09 / -0.09	+0.22 / -0.20

4.9.3. Post-Fit Nuisance Parameters

The uncertainty of some nuisances changes after fit. In the figures one can observe that the uncertainties which have their post-fit uncertainty more severely reduced are related to the DY normalization in the different categories, top p_T and the ones estimated with alternative $t\bar{t}$ samples: UE and CR.

4.10. Conclusion

This a combined measurement of the mass and the decay width of the top quark in dileptonic $t\bar{t}$ decay events resulting from proton-proton collisions at $\sqrt{s} = 13$ TeV. Data were collected with the CMS detector during Run 2 of the CERN LHC in 2016. After categorizing the events by lepton flavor, b-quark jet multiplicity, and the transverse momentum of the system composed by the visible decay products of the top quark, the $m(\ell b)$ variable is examined and compared to different m_t and Γ_t hypothesis. A profile likelihood method is

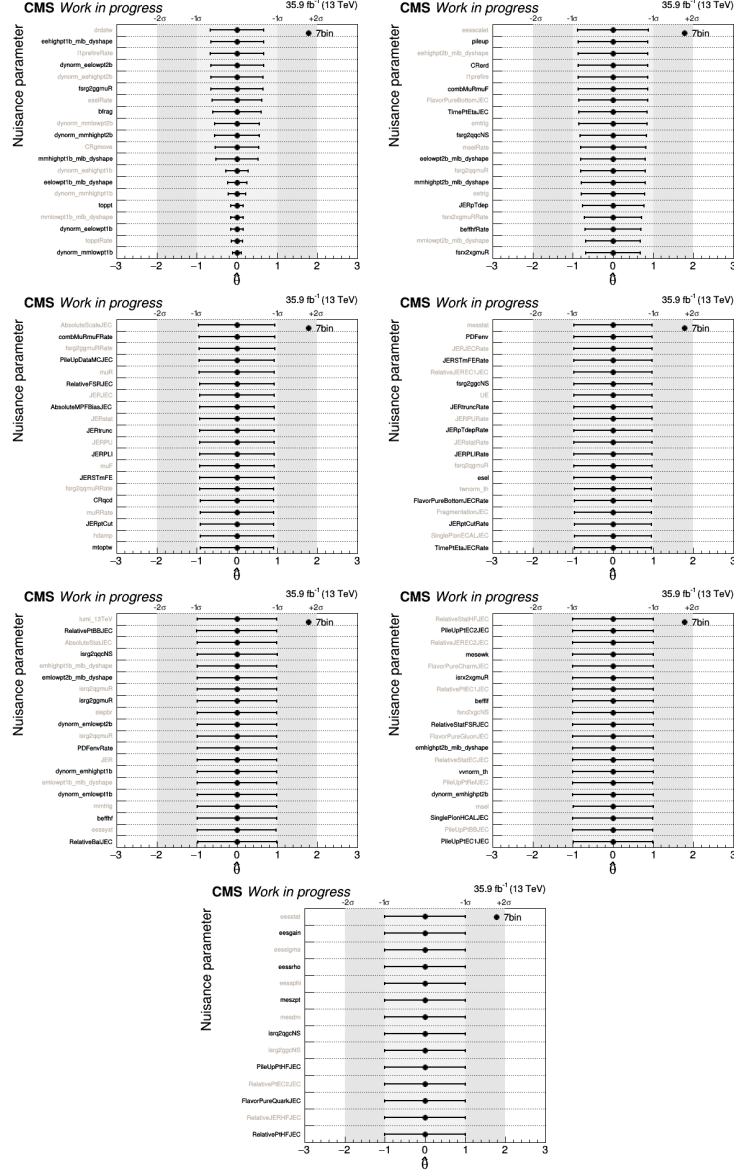


Figure 91: Comparison between pre-fit and post-fit nuisance values. For each nuisance (running on the vertical axis), the points represent the post-fit value, while the error bar represents the post-fit uncertainty. The ordering in the vertical axis is chosen by increasing post-fit uncertainty.

employed to measure simultaneously m_t and Γ_t . We expect to measure $\Gamma_t = 1.32^{+0.50}_{-0.37}$ (syst + data stat) ± 0.16 (MC stat) GeV and $m_t = 172.50^{+0.23}_{-0.23}$ (syst + data stat) ± 0.10 (MC stat) GeV.

CHAPTER 5

Four Top Quark Production Search in Single-lepton Final State

5.1. Introduction to Four Top Quark Production Search

The four top quark production is a very rare standard model process. The predicted cross section at NLO QCD and electroweak correction is 12.0 ± 2.2 fb at $\sqrt{s} = 13$ TeV [60]. Assuming $m_t = 173$ GeV, when four top quarks are produced in one event, the final state has a mass of about 700 GeV, which will be the heaviest particle final state to be observed at the LHC. Its cross section is sensitive to top Yukawa coupling in the SM lagrangian [61], and some SM extensions, like gluino pair production [62].

Figure 92 shows the production process of four tops from proton-proton collision. Four top quark production has various final states depending on the number of leptons, as shown in Figure 93. The contribution is calculated by considering W decay branch ratio and the different leptonic/hadronic combinations of the 4 top quarks. In CMS, physicists are working on a combined analysis for di-lepton, lepton plus jets and all-jets final states with

Run 2 data.

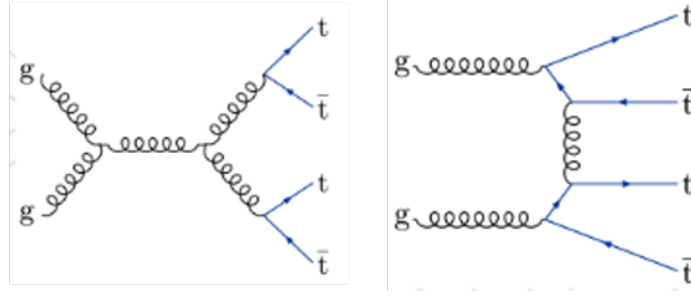


Figure 92: Four top production diagrams.

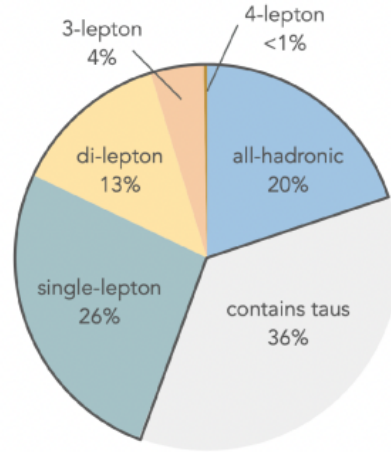


Figure 93: Four top production final states.

There are many past measurements on four top quark cross section. The most recent result published result is from ATLAS experiment, reported 4.3σ observed significance [63] using same sign di-lepton (SSDL) and multilepton (ML) final states with full Run 2 data of integrated luminosity 139 fb^{-1} . At CMS, the most recent results comes from SSDL and ML final states with Run 2 data, and it gets an observed significance of 2.6σ [64].

In this analysis, we study the lepton plus jets final state only. In this case one of the top quarks decays leptonically, and the other three decay hadronically. Therefore, the final state has a high jet multiplicity, including at least four jets from b quark hadronization. There is also a contribution of missing transverse momentum from a neutrino. We consider two

approaches using different variables to fit. The baseline study uses H_T as the discriminating variable where H_T is the scale sum of jet p_T in selected events. The improved study uses a variable BDT which is produced by the multivariate analysis (MVA).

5.2. Data and Simulation Samples

This analysis uses the full Run 2 data taken in 2016, 2017 and 2018. All the data and MC samples are produced using CMSSW version 10_2_16_UL. Official MiniAOD samples of the following campaigns are used for MC. RunIISummer16MiniAODv3-PUMoriond17 for 2016, RunIIFall17-MiniAODv2-PU2017 for 2016, and RunII-Autumn18MiniAOD-102X_upgrade2018 for 2018. Data samples are listed in Table 9. Integrated luminosity for 2016 is 35.87 fb^{-1} , and 41.53 fb^{-1} in 2017, 59.97 fb^{-1} in 2018. MC samples, generators and cross section values are listed in Table 10.

Table 9: 2016, 2017, and 2018 data in four top analysis.

Primary Dataset	Reconstruction Group
SingleMuon(Electron)	Run2016B-17Jul2018_ver2-v1
SingleMuon(Electron)	Run2016C-17Jul2018-v1
SingleMuon(Electron)	Run2016D-17Jul2018-v1
SingleMuon(Electron)	Run2016E-17Jul2018-v1
SingleMuon(Electron)	Run2016F-17Jul2018-v1
SingleMuon(Electron)	Run2016G-17Jul2018-v1
SingleMuon(Electron)	Run2016H-17Jul2018-v1
SingleMuon(Electron)	Run2017B-31Mar2018-v1
SingleMuon(Electron)	Run2017C-31Mar2018-v1
SingleMuon(Electron)	Run2017D-31Mar2018-v1
SingleMuon(Electron)	Run2017E-31Mar2018-v1
SingleMuon(Electron)	Run2017F-31Mar2018-v1
SingleMuon(Electron)	Run2018A-17Sep2018-v2
SingleMuon(Electron)	Run2018B-17Sep2018-v1
SingleMuon(Electron)	Run2018C-17Sep2018-v1
SingleMuon(Electron)	Run2018D-PromptReco-v2

In this analysis, we do not use the inclusive $t\bar{t}$ samples as in Chapter 4, but use separate samples for three decay modes, single lepton, di-lepton and all hadronic. Since these $t\bar{t}$

samples do not have sufficient statistics in the high jet multiplicity, high H_T region, we added additional samples. They are $t\bar{t}$ to single lepton events, generated with ≥ 9 jets of $p_T > 30 \text{ GeV}$ and $H_T > 500 \text{ GeV}$, where H_T is the scalar sum of the generated jet p_T . Figure 94 shows the H_T distributions in various n(jets), n(b-jets) categories before and after adding additional high jet samples, after the pre-selection in Section 5.4. n(jets) is the AK4 jet multiplicity and n(b-jets) is the b-tagged jet multiplicity.

5.3. Object Reconstruction

5.3.1. Triggers

We use the same trigger configuration for 2016 data and MC as the CMS published analysis on the single lepton final state [71]. For 2017, 2018 data and MC, a dedicated study has been done [72] in order to select more events in low p_T region for leptons because they are expected to provide better sensitivity. The triggers are summarized in Table 11. In each lepton flavor channel, different triggers are combined by OR logic. The efficiencies of these triggers are close to 1 in $p_T(\text{lepton}) > 50 \text{ GeV}$ region, and in lower p_T region, we use an average scale factor 0.98 to account for the difference of efficiencies between data and MC. The uncertainty in the efficiency is 3%. Note that the efficiencies vary for data/MC and vary by lepton flavor and η , details can be found in [72].

5.3.2. Event Filters and Pileup Correction

All events have to pass the following MET filters

- Good primary vertex: $z < 24.0 \text{ cm}$, $\rho < 2.0 \text{ cm}$, 4 or more degrees of freedom
- HBHE noise filter

Table 10: Four top analysis MC samples. The $t\bar{t}$ high jet multiplicity and H_T bin sample include a filtering coefficient to their cross section as given in the parenthesis.

Sample	Generators	Cross section [pb]
TTTT	amcatnlo-pythia8	$0.012^{+18\%}_{-21\%}$ [60]
TTTo2L2Nu	powheg-pythia8	832^{+40}_{-46} ($\times 0.10$) [65]
TTToSemiLeptonic	powheg-pythia8	832^{+40}_{-46} ($\times 0.44$) [65]
TTToHadronic	powheg-pythia8	832^{+40}_{-46} ($\times 0.46$) [65]
TTToSemiLepton_HT500Njet9	powheg-pythia8	832^{+40}_{-46} ($\times 0.44 \times 0.006$) [65]
ST_t-channel_top_4f_InclusiveDecays	powheg-pythia8	$136.0^{+5.5}_{-4.7}$ [66]
ST_t-channel_antitop_4f_InclusiveDecays	powheg-pythia8	$80.9^{+4.1}_{-3.7}$ [66]
ST_s-channel_top_leptonDecays	powheg-pythia8	$6.35^{+0.23}_{-0.21}$ ($\times 0.3259$) [66]
ST_s-channel_antitop_leptonDecays	powheg-pythia8	$3.97^{+0.19}_{-0.17}$ ($\times 0.3259$) [66]
ST_s-channel_4f_leptonDecays	madgraph-pythia8	$10.32^{+0.40}_{-0.36}$ ($\times 0.3259$) [66]
ST_tW_top_5f_inclusiveDecays	powheg-pythia8	35.85 ± 1.9 [67]
ST_tW_antitop_5f_inclusiveDecays	powheg-pythia8	35.85 ± 1.9 [67]
TTWJetsToLNu	amcatnloFFFX-madspin-pythia8	$0.55^{+0.14}_{-0.09}$ ($\times 0.3259$) [68]
TTZToLLNuNu_M-10	amcatnlo-pythia8	$0.86^{+0.08}_{-0.09}$ ($\times 3 \times (0.0337 + 0.0667)$) [68]
TTZToLL_M-1to10	amcatnlo-pythia8	0.053 [McM]
ttHTobb_M125	powheg-pythia8	$0.293^{+0.032}_{-0.039}$ [65]
ttHTNonbb_M125	powheg-pythia8	$0.215^{+0.023}_{-0.028}$ [65]
TTWW	madgraph-pythia8	0.01150 [69]
TTWZ	madgraph-pythia8	0.00388 [69]
TTZZ	madgraph-pythia8	0.00198 [69]
TTWH	madgraph-pythia8	0.00158 [69]
TTZH	madgraph-pythia8	0.00153 [69]
TTHH	madgraph-pythia8	0.00076 [69]
TTTW	madgraph-pythia8	0.00073 [McM]
TTTJ	madgraph-pythia8	0.00047 [McM]
DYJetsToLL_M-50_HT-200to400	madgraphMLM-pythia8	54.951
DYJetsToLL_M-50_HT-400to600	madgraphMLM-pythia8	7.862
DYJetsToLL_M-50_HT-600to800	madgraphMLM-pythia8	1.977
DYJetsToLL_M-50_HT-800to1200	madgraphMLM-pythia8	0.858
DYJetsToLL_M-50_HT-1200to2500	madgraphMLM-pythia8	0.191
DYJetsToLL_M-50_HT-2500toInf	madgraphMLM-pythia8	0.004
WJetsToLNu_HT-200to400	madgraphMLM-pythia8	359.7 ± 0.2 ($\times 1.21$) [65]
WJetsToLNu_HT-400to600	madgraphMLM-pythia8	48.910 ± 0.072 ($\times 1.21$) [65]
WJetsToLNu_HT-600to800	madgraphMLM-pythia8	12.050 ± 0.007 ($\times 1.21$) [65]
WJetsToLNu_HT-800to1200	madgraphMLM-pythia8	5.501 ± 0.017 ($\times 1.21$) [65]
WJetsToLNu_HT-1200to2500	madgraphMLM-pythia8	1.329 ± 0.002 ($\times 1.21$) [65]
WJetsToLNu_HT-2500toInf	madgraphMLM-pythia8	0.0322 ± 0.0001 ($\times 1.21$) [65]
WW	pythia8	$118.7^{+3.0}_{-2.6}$ [70]
WZ	pythia8	47.1 [65]
ZZ	pythia8	16.5 [65]
QCD_HT-200to300	madgraphMLM-pythia8	1712000 ± 380 [65]
QCD_HT-300to500	madgraphMLM-pythia8	347700 ± 75 [65]
QCD_HT-500to700	madgraphMLM-pythia8	32100 ± 7 [65]
QCD_HT-700to1000	madgraphMLM-pythia8	6831 ± 1.7 [65]
QCD_HT-1000to1500	madgraphMLM-pythia8	1207 ± 0.5 [65]
QCD_HT-1500to2000	madgraphMLM-pythia8	119.9 ± 0.06 [65]
QCD_HT-2000toInf	madgraphMLM-pythia8	25.24 ± 0.02 [65]

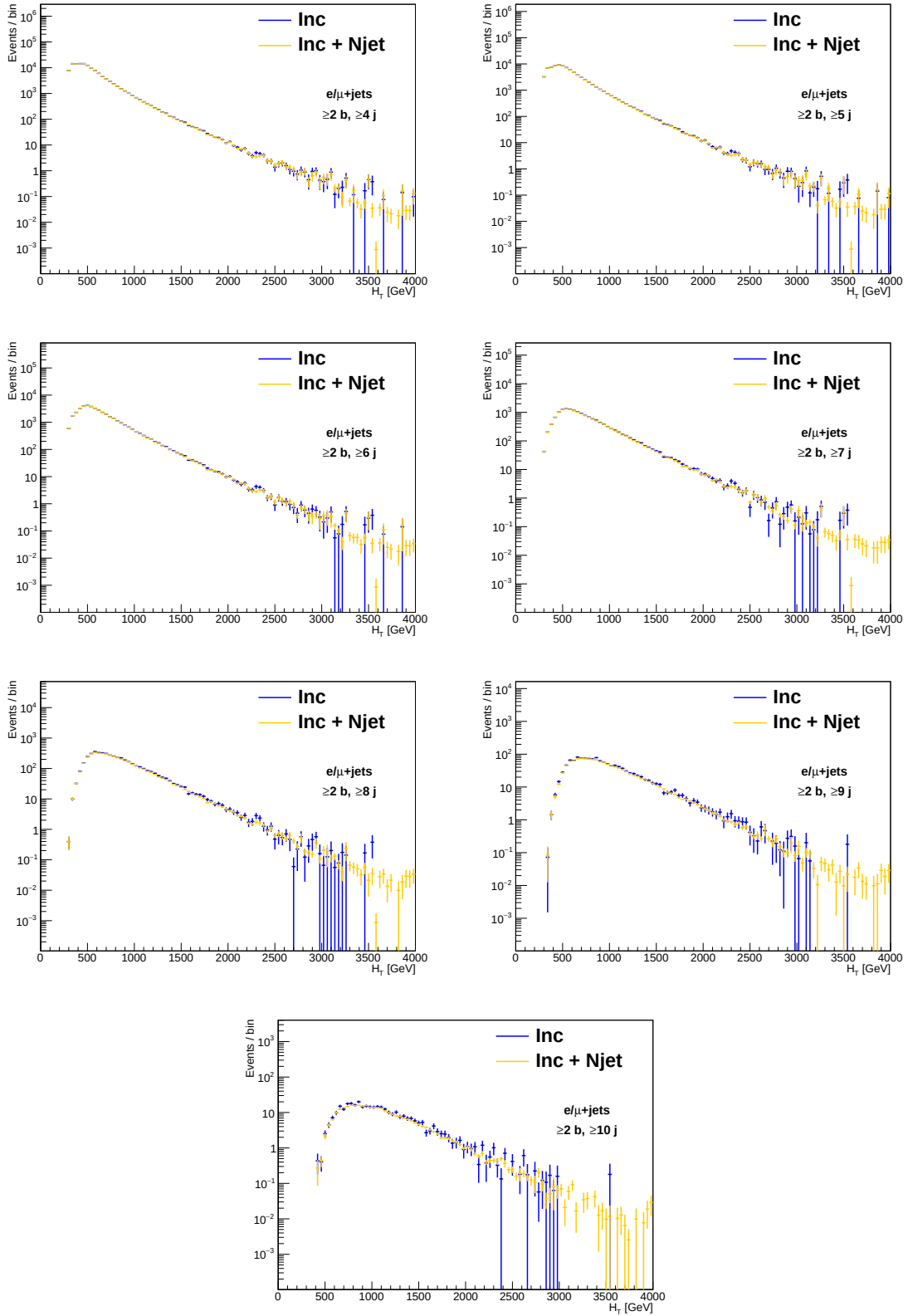


Figure 94: Comparison of inclusive $t\bar{t}$ sample distributions (Inc) to those produced including the high jet multiplicity bin samples (Inc+Njet), in distributions of H_T in various jet multiplicity categories with combined electron and muon channels, after baseline event selections described later.

Table 11: Summary of triggers. The triggers are used as a logical “or” combination in each channel.

Year	Electron	Muon
2016	HLT_Ele32_eta2p1_WPTight_Gsf_v*	HLT_IsoMu24_v*
		HLT_IsoTkMu24_v*
2017	HLT_Ele15_IsoVVVL_PFHT450_v*	HLT_Mu15_IsoVVVL_PFHT450_v*
	HLT_Ele50_IsoVVVL_PFHT450_v*	HLT_Mu50_IsoVVVL_PFHT450_v*
	HLT_Ele15_IsoVVVL_PFHT600_v*	HLT_Mu15_IsoVVVL_PFHT600_v*
	HLT_Ele35_WPTight_Gsf_v*	HLT_Mu50_v*
	HLT_Ele38_WPTight_Gsf_v*	
2018	HLT_Ele15_IsoVVVL_PFHT450_v*	HLT_Mu15_IsoVVVL_PFHT450_v*
	HLT_Ele50_IsoVVVL_PFHT450_v*	HLT_Mu50_IsoVVVL_PFHT450_v*
	HLT_Ele15_IsoVVVL_PFHT600_v*	HLT_Mu15_IsoVVVL_PFHT600_v*
	HLT_Ele15_IsoVVVL_PFHT450_PFMET50_v*	HLT_Mu15_IsoVVVL_PFHT450_PFMET50_v*
	HLT_Ele35_WPTight_Gsf_v*	HLT_Mu50_v*
	HLT_Ele38_WPTight_Gsf_v*	HLT_TkMu50_v*

- HBHE isolated noise filter
- Global tight halo 2016 filter
- Bad EE supercrystal filter (only on data)
- ECAL dead cell trigger primitive filter
- Bad charged hadron filter
- Bad muon filter

In order to compare the pileup performance in data and MC, we first produce the distribution of mean number of interactions per bunch crossing. Then MC events are weighted using minimum bias cross section of 69.2 mb.

Particle flow algorithm is used to reconstruction the leptons (electron or muon), jets, and missing transverse momentum (p_T^{miss}).

5.3.3. *Electrons*

Electron selection Tight or Loose is based on an MVA ID provided by CMS EGamma POG [73]. A Tight electron has a signal efficiency of around 90%, and a Loose electron has a signal efficiency of about 98%. We define a tight electron in our analysis as an electron tight ID, and $p_T > 20$ and $|\eta| < 2.5$. A loose electron in our analysis has loose ID, and has $p_T > 15$ and $|\eta| < 2.5$. We do not take electrons in ECAL barrel endcap gap $1.4442 < |\eta| < 1.566$.

We also set a requirement on mini-isolation (miniIso) variable. It is used to measure the isolation of an electron, defined as the sum of energy around the electron in a cone size divided by p_T of the electron. Relative isolation is the sum of particle flow candidates within a fixed cone around the electron, correcting the pileup effects. The mini-isolation criterion uses a p_T dependent cone size so that one can achieve higher efficiency at higher energy. We ask miniIso < 0.1 for tight electron and miniIso < 0.4 for loose electron. There is a correction scale factor applied to miniIso for MC following recommendation in [73].

5.3.4. *Muons*

There are official Tight and Loose muons defined by Muon POG [74]. Tight muon has a signal efficiency about 97% and loose muon has a signal efficiency of about 100%. In our analysis, we require that a tight muon has Tight ID, and $p_T > 20$ GeV, $|\eta| < 2.4$, miniIso < 0.1 . Loose muon has loose ID, $p_T > 15$ and $|\eta| < 2.4$, miniIso < 0.4 . Similarly, a correction scale factor is applied for muon reconstruction.

5.3.5. Jets

We use AK4 jets in this analysis. AK4 stands for the jet clustering algorithm anti-KT, with a distance size 0.4. Jets pass the particle flow loose ID [75], with $p_T > 30$ GeV and $|\eta| < 2.4$. Jet energy scale and resolution corrections are applied, shown in Table 12.

Correction	2016	2017	2018
JER	Summer16_25nsV1	Fall17_V3	Autumn18_V7
JES	Summer16_07Aug2017_V11	Fall17_17Nov2017_V32	Autumn18_V19

We use DeepCSV algorithm to define the b-tagged jet in our analysis. A jet is b-tagged if the DeepCSV discriminator $> 0.6321(2016)$ *or* $0.4941(2017)$ *or* $0.4184(2018)$ which is medium working point with a rate of mis-identification of b-quarks of the order of 1% (or called “fake rate”). A correction to the b-tagging efficiency is applied. We use the jet-by-jet update method, where the tagging status of a jet is upgraded or downgraded depending of the scale factor $>$ or $<$ 1. Figure 95 shows the tagging efficiency for b, c or light flavor jets as a function of jet p_T . The average b-tagging efficiency is about 60%.

In BDT training described in Section 5.5, DeepCSV discriminators are used as input variables. Therefore, we do not apply the scale factor discussed above, but apply a different correction scale factor, DeepCSV reshaping weight [76]. This weight will correct the whole b-tagging discriminant distribution in MC to match that in data. The number of events before and after applying reshaping weights should be identical. So a re-normalization weight is further applied. The re-normalization weight is calculated with all the event selection in Section 5.4 except for b-jet requirement for each signal and background processes in different categories based on lepton flavor (e, μ) and the number of AK4 jets (4, 5, ≥ 6). The H_T original distribution, after applying CSV reshaping weights, and after reshaping plus re-normalization scale factor are shown in Fig. 96.

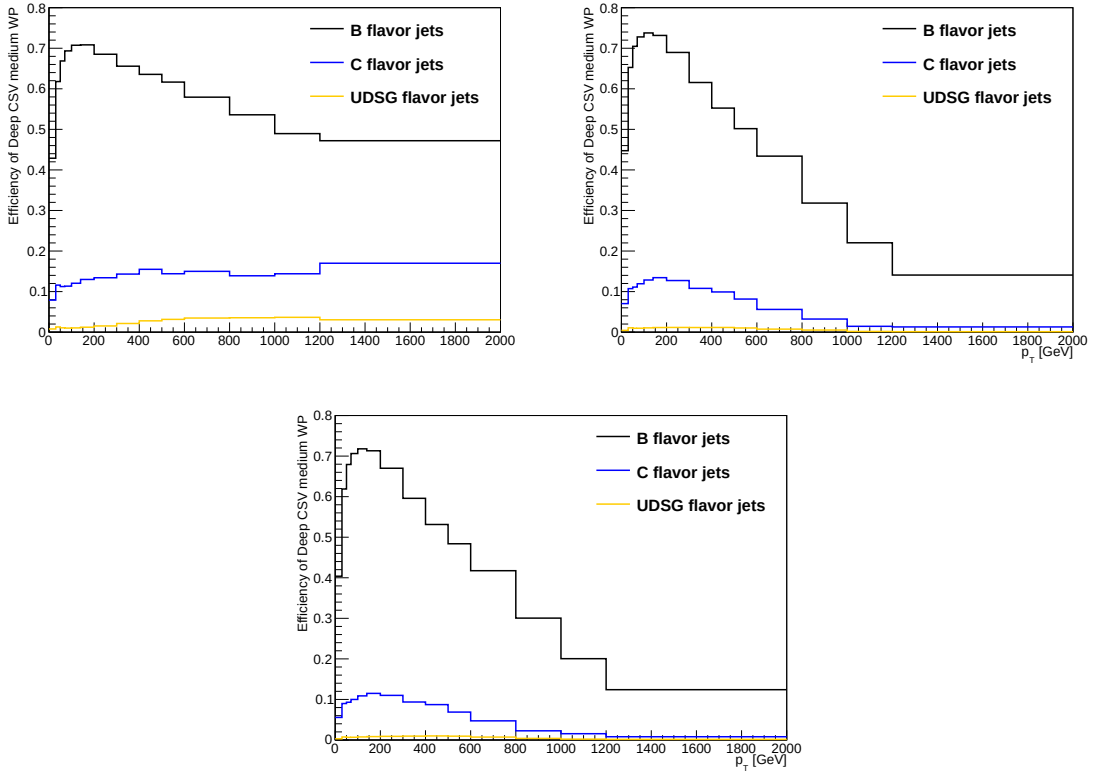


Figure 95: Distributions of efficiency of tagging a jet with b, c, or light flavor using the Deep CSV medium working point for (left) 2016, (right) 2017, and (lower) 2018 dataset.

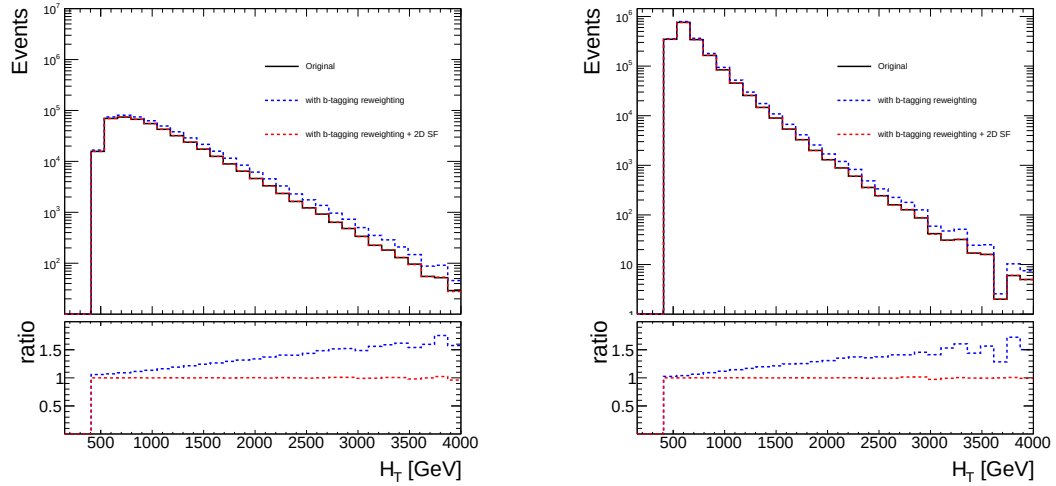


Figure 96: Validation of H_T distribution of $tttt$ (left) and $ttjj$ (right): original distribution, after applying CSV reshaping weights, and after reshaping plus re-normalization scale factor Run 2017.

5.3.6. Missing Transverse Momentum p_T^{miss}

Missing transverse momentum represents a measure of the energy of neutrino. It is defined as the negative vector sum of p_T of all the objects in the event. We use particle flow p_T^{miss} with type 1 corrections which transfer JEC effects to p_T^{miss} .

5.3.7. Resolved Top Quark

We mentioned that in single lepton final state, we have three top quarks decay hadronically into jets. They are mostly low p_T AK4 jets and they may be separated far away, unlike boosted top quarks. The commonly used AK8 jet tagging algorithm is therefore not sufficient for these resolved top quarks. A different top-tagging algorithm, called “Resolved top-tagging” algorithm, or “HOT tagger” [77] is used for low p_T top quarks. HOT tagger is an algorithm based on neural network. It considers all the three-jet combinations in an event and build top candidates. Combinations that do not come from a top quark or overlap with another candidate are removed. Other top quark candidates are considered as reconstructed top quarks. The signal tri-jets are taken from semileptonic $t\bar{t}$ sample, and background tri-jets are taken from $t\bar{t}$ and QCD samples. In our analysis, we use tight working point, of 1% fake rate.

Resolved top tagging efficiencies in MC are corrected by scale factors [78]. The efficiencies are determined for different samples, $t\bar{t}$, single top, $t\bar{t}$ V, $t\bar{t}$ XY and signal sample. Other background processes do not have resolved top quarks. In MC samples, we consider those reconstructed top quarks that are matched to a generator level hadronically decayed top spatially, with two or more of its daughters are matched to AK4 jets spatially. Scale factors are applied with the jet-by-jet update method, like that for b-tagging scale factor.

5.4. Event Selection

The pre-selection criteria is as follows:

- 1 tight, isolated electron (or muon) with $p_T > 35$ (26) GeV and $|\eta| < 2.1$ for 2016 analysis,
- 1 tight, isolated electron (or muon) with $p_T > 20$ GeV and $|\eta| < 2.1$ for 2017 and 2018 analyses,
- 0 additional loose electrons (or muons) with $p_T > 15$ GeV and $|\eta| < 2.5$ (2.4),
- 4 or more AK4 jets with $p_T > 30$ GeV and $|\eta| < 2.4$,
- At least 2 of the AK4 jets are b-tagged,
- $H_T > 500$ GeV,
- $p_T^{miss} > 60$ GeV,
- Transverse mass of the lepton-neutrino system, $M_T > 60$ GeV,
- ΔR (lepton, closest jet) > 0.4 .

We applied the same event selection for 2016 data as the published CMS analysis [71]. We use lower p_T cut on leptons for 2017 and 2018 data in order to gain more sensitivity. After selections, we achieved signal efficiencies of about 2.4(3.5), 3.3 (4.0), and 3.4 (4.2)% for electron (muon) channels in Run 2016, 2017 and 2018. The selection ΔR (lepton, closest jet) > 0.4 is an extra cut in order to remove the QCD events where more likely jets overlap with the lepton.

Figures 97 to 103 show some examples of variable distributions after above selection. Overall the agreement between data and simulation is good and the discrepancy can be covered

by uncertainties. On the distribution plots, we split the events into the following parts:

$t\bar{t} + b\bar{b}$, and $t\bar{t} + !b\bar{b}$ will be explained in **Heavy flavor correction** below;

$t\bar{t} + H$ processes;

TOP includes single top processes, $t\bar{t} V$ and $t\bar{t} XY$ processes;

EWK includes W + jets, Z + jets and diboson events;

QCD events.

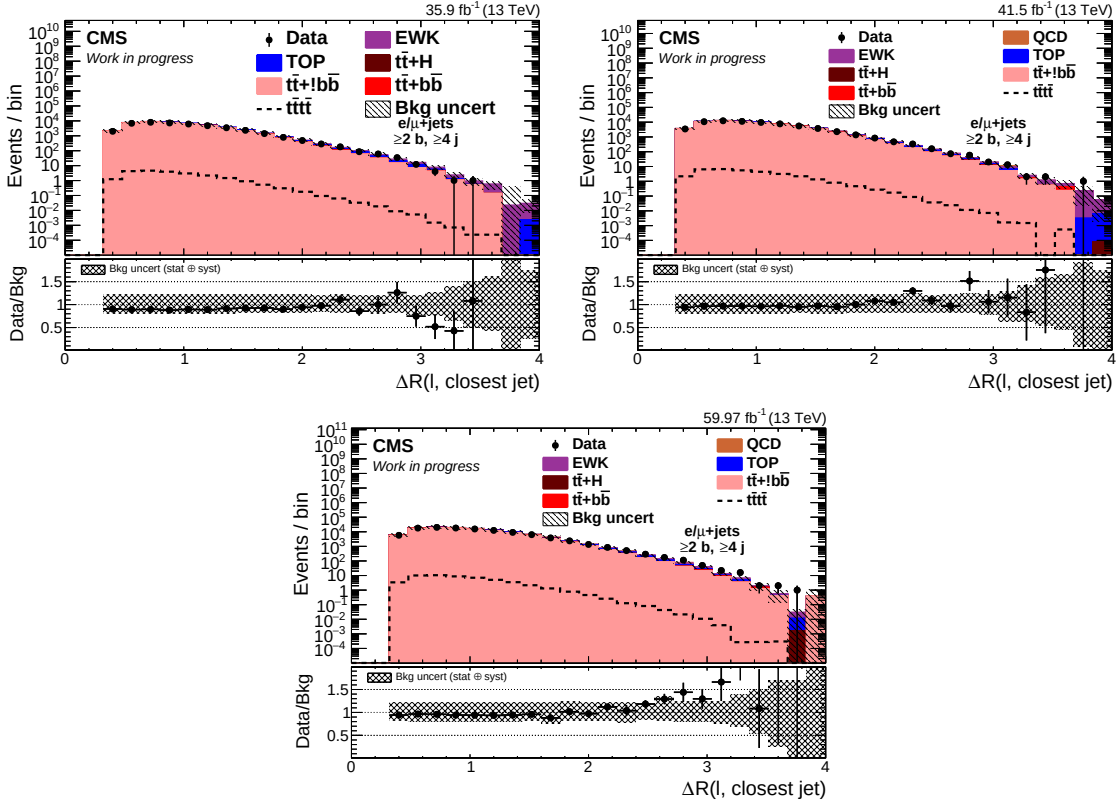


Figure 97: Distributions of ΔR (lepton, closest jet) in data and MC after initial selection in (left) 2016, (right) 2017, and (lower) 2018 data set. Background uncertainties include all statistical and systematic components. The total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin.

Heavy flavor correction The dominant background process in our analysis is the standard model $t\bar{t}$ process. It is verified that in all the event selection categories, which will be discussed in Section 5.7 $t\bar{t}$ events take over 90%. Considering the different $t\bar{t}$ decays would generate different number of jets, we split them into the following categories depending on

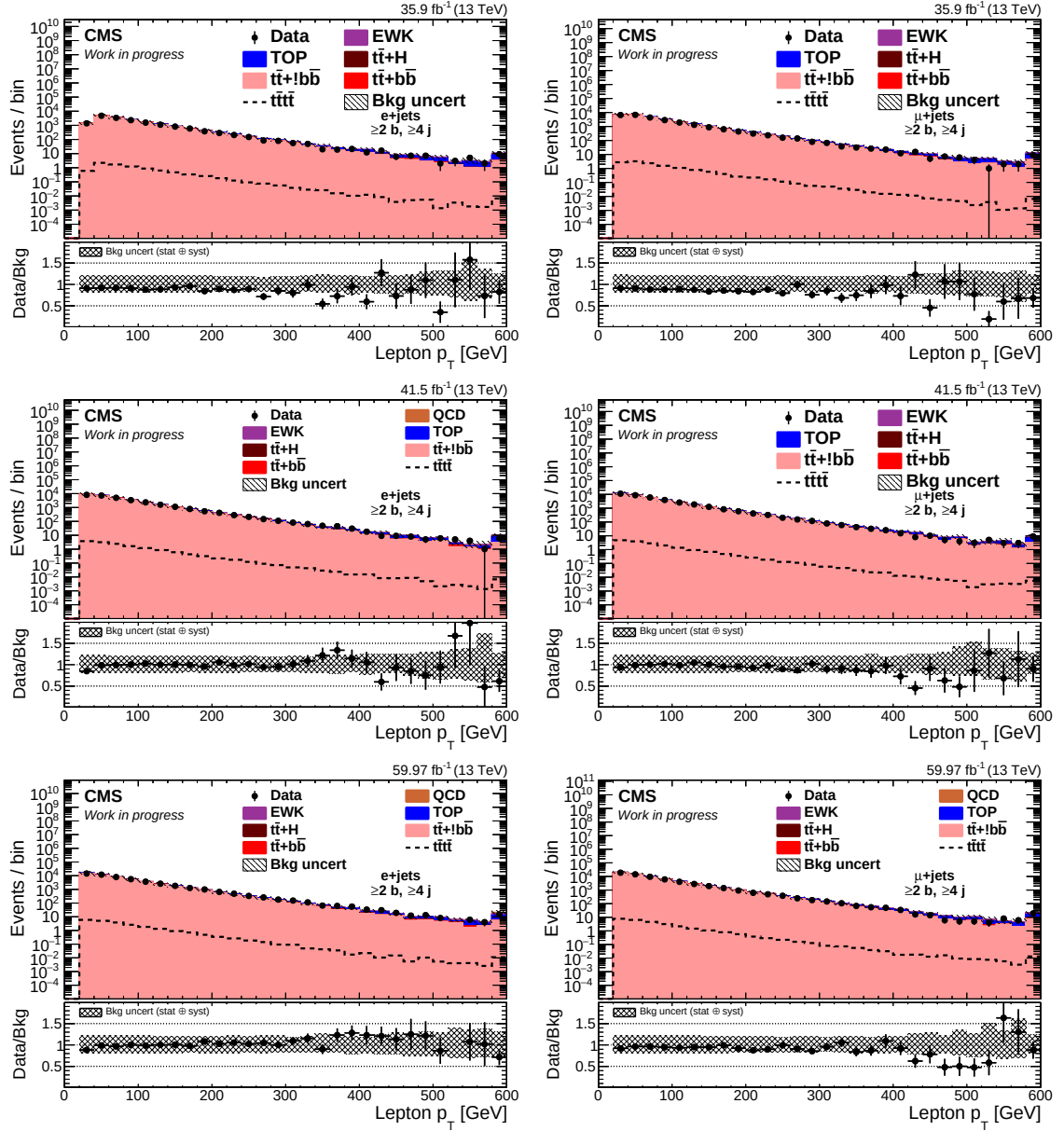


Figure 98: Distributions of (left) electron and (right) muon p_T in data and MC after initial selection in (from top to bottom) 2016, 2017, and 2018 data set. Background uncertainties include all statistical and systematic components. The total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin.

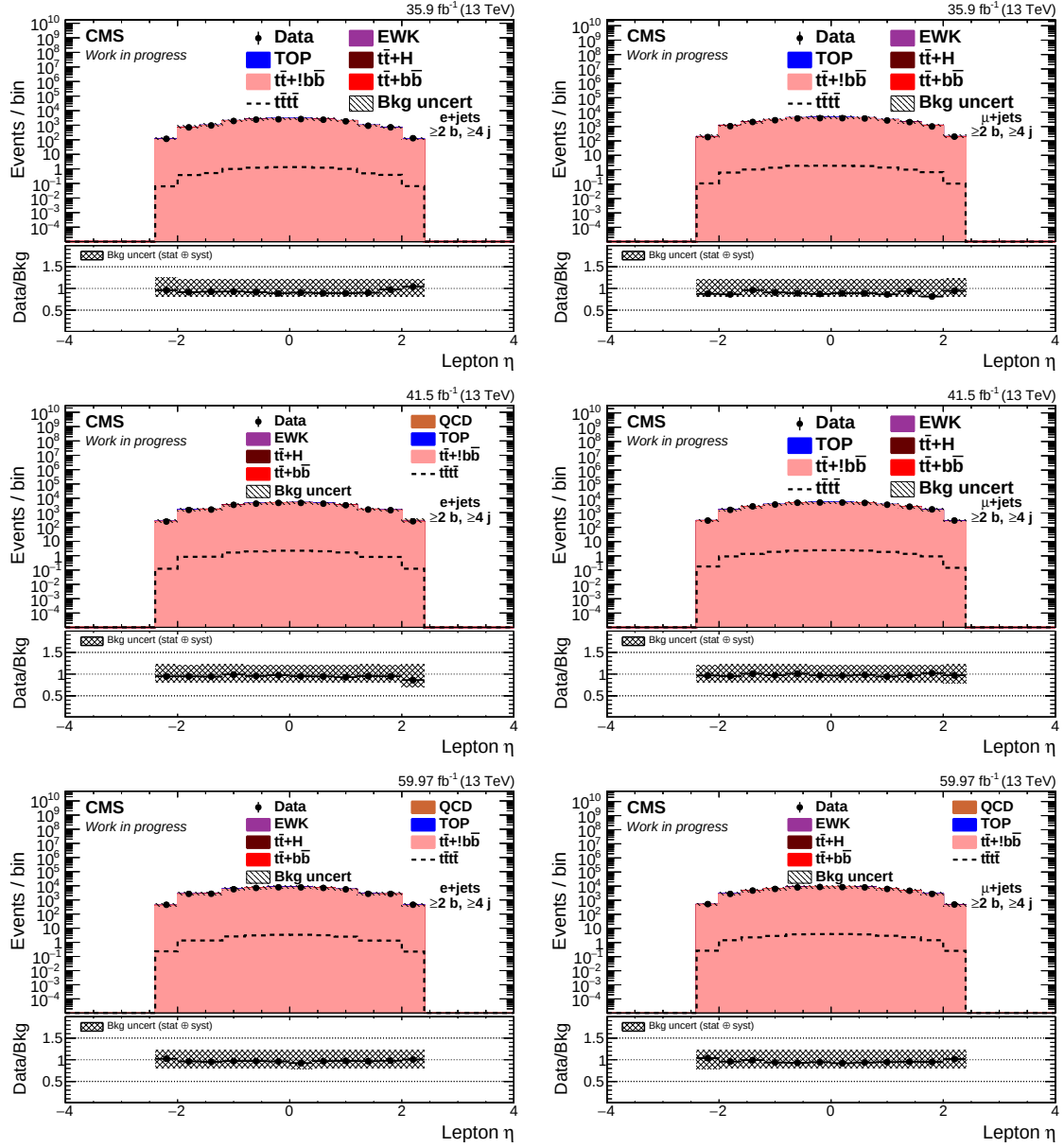


Figure 99: Distributions of (left) electron and (right) muon $|\eta|$ in data and MC after initial selection in (from top to bottom) 2016, 2017, and 2018 data set. Background uncertainties include all statistical and systematic components. The total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin.

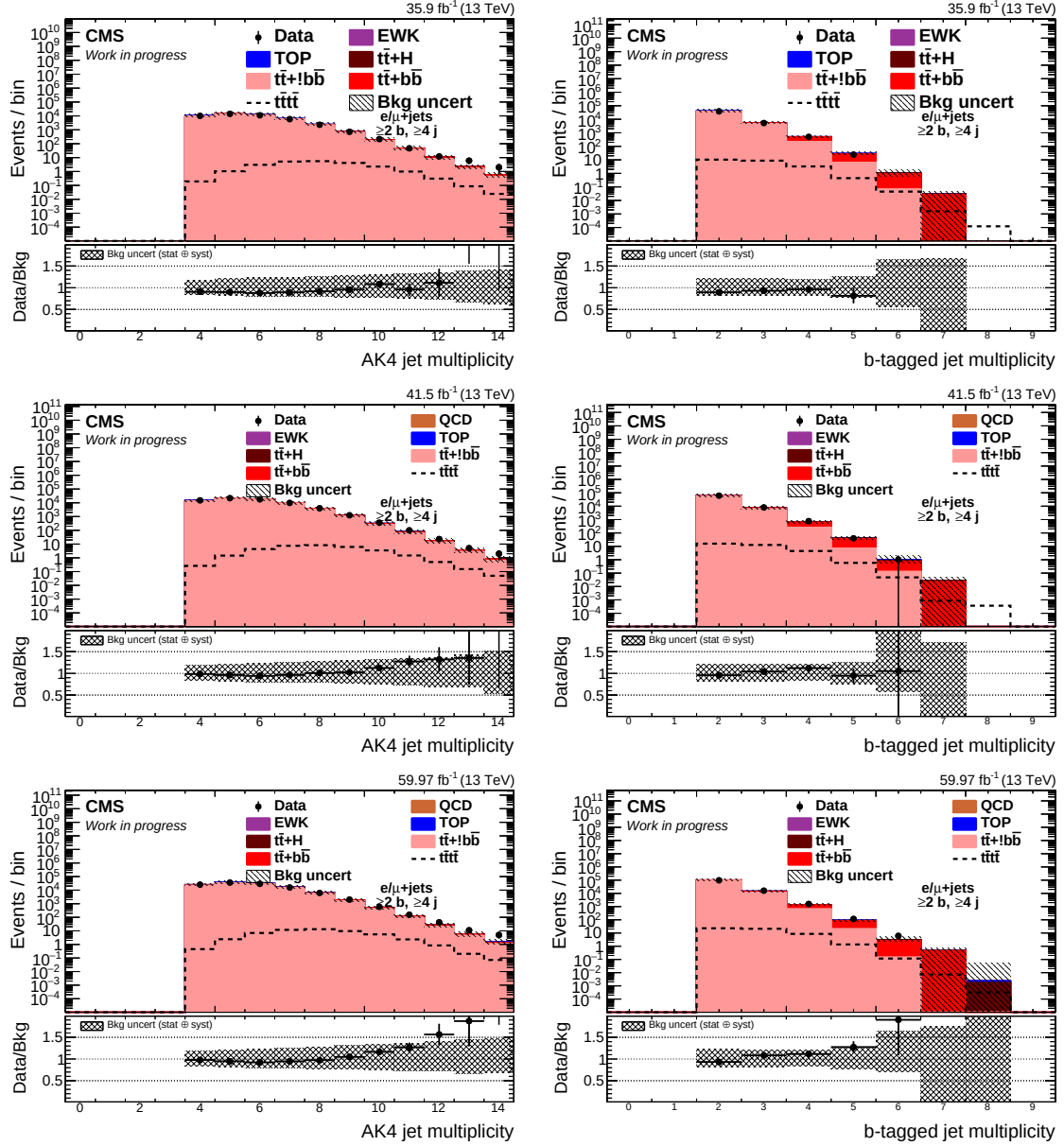


Figure 101: Distributions of (left) jet multiplicity and (right) b-tag multiplicity of all AK4 jets with $p_T > 30$ GeV in data and MC after initial selection in (from top to bottom) 2016, 2017, and 2018 data set. Background uncertainties include all statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin.

the number of additional jets from extra radiation in generator level.

- $t\bar{t} + b$: one additional b jet containing a single b hadron
- $t\bar{t} + 2b$: one additional b jet containing at least two b hadrons
- $t\bar{t} + b\bar{b}$: at least two additional b jets, independent of the number of b hadrons in each
- $t\bar{t} + c\bar{c}$: at least one additional c jet, independent of the number of c hadrons in each
- $t\bar{t} + \text{lf}$: no additional b or c jets

We use a CMS tool [79] to determine the jet parton flavor. A CMS study on $t\bar{t}$ cross section presents that the simulation of $t\bar{t} + b\bar{b}$ cross section needs a correction [80]. We apply a scale factor 1.2 on the $t\bar{t} + b\bar{b}$ events, and scale down the remaining $t\bar{t}$ events in order to maintain the total number. There is a 13% normalization uncertainty on $t\bar{t} + b\bar{b}$ applied [80]. In the plots for this analysis, we use a combination of $t\bar{t} + b$, $t\bar{t} + 2b$, $t\bar{t} + c\bar{c}$, $t\bar{t} + \text{lf}$ as one category called $t\bar{t} + !b\bar{b}$.

5.5. Multivariate Analysis

5.5.1. Introduction

In order to optimize the discrimination between signal and background, we performed a multivariate analysis using Boosted Decision Tree (BDT)-based approach. BDT discriminator is trained with $t\bar{t}t\bar{t}$ as signal and all the $t\bar{t}$ samples as background.

The samples are divided into three equally sized sub-samples, for training(1/3), testing(1/3), and application(1/3). We applied all the pre-selection cuts in Section 5.4. In addition we studied how the cut on the number of AK4 jets affect the final results which will be discussed in this section. We tried two cuts, $n(\text{jets}) \geq 4$ or $n(\text{jets}) \geq 6$.

We started with the following BDT training parameters:

- 100 decision trees
- max depth = 2

5.5.2. *Input Variable Definitions*

We made 72 variables as BDT input, and we studied various combinations of variables among them. They are listed in various groups depending on the components where they are built from.

Jet kinematics

- H_T : The scalar sum of the p_T of all the AK4 jets in an event.
- S_T : The scalar sum of H_T , p_T^{miss} and p_T of the lepton in an event.
- $H_T(\text{b jets})$: The scalar sum of p_T of b-tagged jets in an event.
- $p_T(b_1)$: Leading b-tagged jet p_T .
- $p_T(j_1)$: Leading jet p_T .
- $p_T(lep)$: Lepton p_T .
- $p_T(j_2)$: Subleading jet p_T .
- $p_T(j_5)$: Fifth leading jet p_T .
- $p_T(j_6)$: Sixth leading jet p_T .
- 5^{th} jet p_T : p_T of the fifth jet, where the ranking is defined such that first all b-tagged jets ordered by p_T and then untagged jets also ordered by p_T .

- $H_T/H_T(4 \text{ leading jets})$: The ratio between H_T and H_T of four leading jets.

Lepton and b-jet pair variables

- $\min[M(l,b)]$: The minimum mass of the lepton and b-jet pairs.
- $\Delta R(l, b)$ with $\max[p_T(l, b)]$: The separation between the lepton and b-jet with maximum lepton and b-jet pair p_T .
- $\min[\Delta R(l, b)]$: The minimum separation between the lepton and the b-jets.
- $M(l, b_1)$: The mass of lepton and the leading b-jet system.
- $M(l, b)$ with $\min[\Delta R(l, b)]$: The mass of lepton and b-jet system with minimum separation between lepton and b-jet.
- $\Delta R(l, b)$ with $\min[M(l, b)]$: The separation between lepton and b-jet with minimum lepton and b-jet pair mass.
- $\Delta\phi(l, b)$ with $\min[M(l, b)]$: The separation of ϕ between lepton and b-jet with minimum lepton and b-jet pair mass.

b-jet pair variables

- $M(b, b)$ with $\min[\Delta R(b, b)]$: The mass of b-jet pair with the minimum separation.
- $\Delta R(l, bb)$ with $\min[\Delta R(b, b)]$: The separation between the lepton and b-jet pair where the b-jet pair has minimum separation.
- $\max[\Delta\eta(b, b)]$: The maximum η separation between the b-jet pair.
- $\min[\Delta R(b, b)]$: The minimum separation between b-jet pairs.
- MT2bb: The transverse mass M_{T2} reconstructed by two leading b-jets and p_T^{miss} . The definition of this variable can be found in Ref. [81].

- $\max[M(b,b)]$: The maximum mass of b-jet pair.
- H_T without b_1 and b_2 : H_T minus p_T of two leading b-jets.
- $\text{ave}[\Delta R(b,b)]$: Average separation between all possible b-jet pairs in an event.

Space related variables

- *Centrality*: This is defined as scalar sum of p_T of all the jets divided by the sum of energy of all the jets.
- *Sphericity*: This is a measure of distribution of all the energy clusters with respect to the jet axis.
- *Aplanarity*: This is another variable that describes the directional distribution of the energy clusters in the jet system.

The construction of *Sphericity* and *Aplanarity* is from a sphericity tensor [82]

$$S^{\alpha,\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2} \quad (5.1)$$

where α, β correspond to x, y, z components of the jet's momentum. One may find three eigenvalues of $S^{\alpha,\beta}$, called λ_1, λ_2 and λ_3 . Then

$$Sphericity = \frac{3}{2}(\lambda_2 + \lambda_3), Aplanarity = \frac{3}{2}\lambda_3. \quad (5.2)$$

b-tagging discriminator CSV values

- p_T weighted CSV: p_T weighted DeepCSV value of all jets.
- $\text{DeepCSV}(j_3)$: DeepCSV value of third leading jet.
- $\text{DeepCSV}(j_4)$: DeepCSV value of fourth leading jet.

- DeepCSV(3): DeepCSV value of the jet with third leading DeepCSV value.
- DeepCSV(4): DeepCSV value of the jet with fourth leading DeepCSV value.

FW moments 1 through 6

These are defined as $H_l = \sum_{i,j} \frac{|\vec{p}_i||\vec{p}_j|}{E^2} P_l \cos(\theta_{ij})$, where θ_{ij} is the opening angle between jets i and j , E is the total energy of all the jets, the $P_l(x)$ are the Legendre polynomials. Details about the development of FW moments can be found in [83].

Trijet and dijet variables

- $M(jjj)$ with $\max[p_T(jjj)]$: The mass of trijet system where the trijet has largest p_T among all possible three jet systems in an event.
- $M(j,j)$ with $\min[\Delta R(j,j)]$, $j \neq b$: The mass of the light di-jet system with minimum separation.

Missing transverse momentum variables

- p_T^{miss} : Missing transverse momentum.
- $M_T(l, p_T^{miss})$: The transverse mass of the system constituted by the lepton and p_T^{miss} .
- Hemiout: Scalar sum of p_T of objects far from p_T^{miss} , where objects include lepton and all jets in the event. The distance in ϕ between p_T^{miss} and the object is required to be larger than $\pi/2$.

Lepton and jet pair variables

- $M(l, j_1)$: The mass of lepton and leading jet system.
- $M(l, j_2)$: The mass of lepton and subleading jet system.
- $M(l, j_3)$: The mass of lepton and third leading jet system.

- $\Delta R(l, j)$ with $\min[M(l, j)]$: The separation between lepton and jet with minimum lepton and jet pair mass.
- $\Delta\phi(l, j)$ with $\min[M(l, j)]$: The separation in ϕ between lepton and jet with minimum lepton and b-jet pair mass.

W jets

- $M(\text{all jets, leptonic W})$: The mass of all jets and leptonically decaying W system.

Trijet discriminator

- Trijet discriminator: The largest trijet discriminator in an event, found by HOTTagger.

Multiplicity variables

- AK4 jet multiplicity
- Resolved t-tag multiplicity: number of resolved top quarks in an event, calculated using 1% fake rate working point, as described in Sec. 5.3.
- Boosted t-tag multiplicity: number of AK8 jets, which have $p_T > 400$, soft-drop mass between $105 < m_{SD} < 220$, and N-subjettiness $\tau_3/\tau_2 < 0.8$.
- Boosted W-tag multiplicity: number of AK8 jets, which have $p_T > 200$, soft-drop mass between $65 < m_{SD} < 105$, and N-subjettiness $\tau_2/\tau_1 < 0.45$.
- b-tag multiplicity: number of b-tagged jets with DeepCSV medium working point, as described in Sec. 5.3.

HOT tagger related variables

HOTGoodTrijet1 corresponds to the resolved t-tagged trijet with 1% fake rate working point (discriminator value greater than 0.95) with the biggest discriminator value.

- HOTGoodTrijet1_mass: The trijet mass reconstructed from its three daughters.
- HOTGoodTrijet1_dijetmass: The mass of dijet with minimum separation among the three daughters of trijet.
- HOTGoodTrijet1_pT_ratio: The ratio of three daughters' vector sum p_T and scalar sum p_T .
- HOTGoodTrijet1_dRtridijet: The ΔR separation between trijet and dijet with minimum separation.
- HOTGoodTrijet1_dRtrijetJetnotdijet: The ΔR separation between trijet and the jet that is not in dijet with minimum separation.
- HOTGoodTrijet1_csvJetnotdijet: The DeepCSV discriminator value of the jet that is not in dijet with minimum separation.

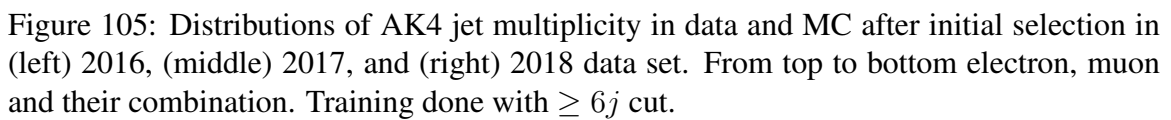
5.5.3. *BDT Input Variables in Data and MC*

Figures 104 and 106 show the distributions of AK4 jet multiplicity and fourth largest DeepCSV value, top two variables based on separation ranking shown later, in data and MC.

5.5.4. *Variable Ranking by Separation*

The BDT input variables are ranked by the separation, defined as [84]. This is not a training method specific ranking. It only shows the behaviors of the input variables.

$$\langle S^2 \rangle = \frac{1}{2} \int \frac{(\hat{y}_S(y) - \hat{y}_B(y))^2}{\hat{y}_S(y) + \hat{y}_B(y)} dy \quad (5.3)$$



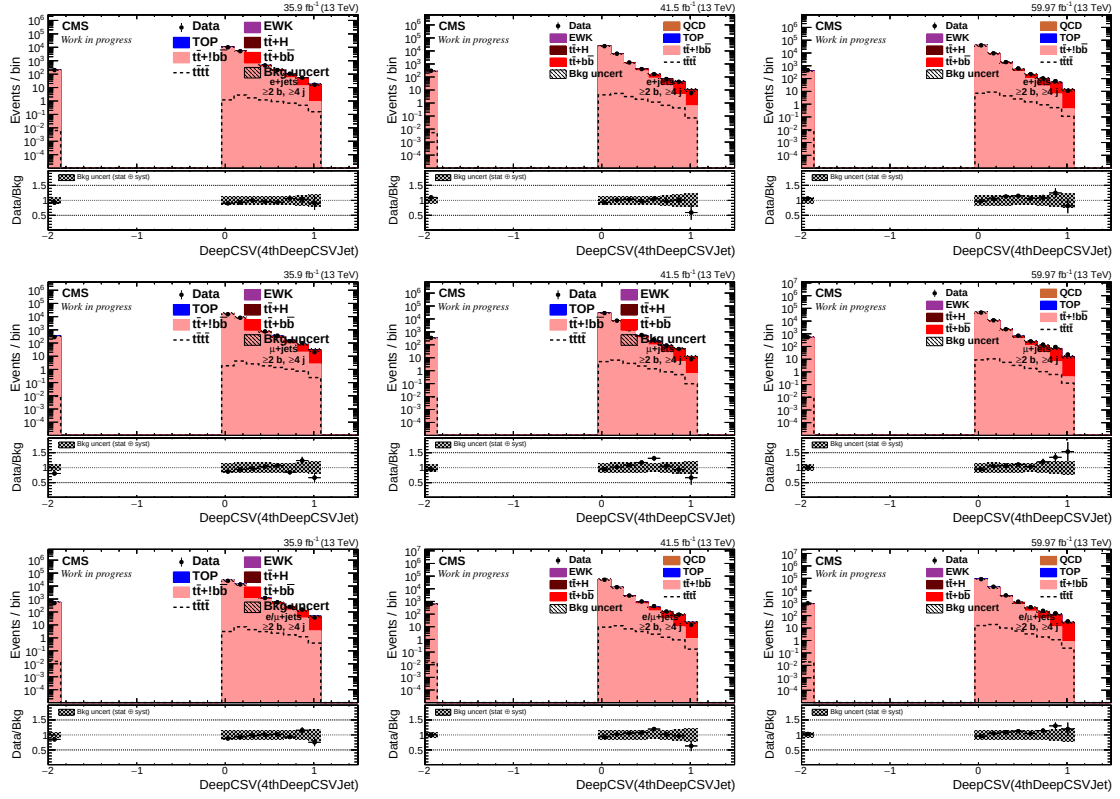


Figure 106: Distributions of fourth largest DeepCSV value in data and MC after initial selection in (left) 2016, (middle) 2017, and (right) 2018 data set. From top to bottom electron, muon and their combination. Training with $\geq 4j$ cut.

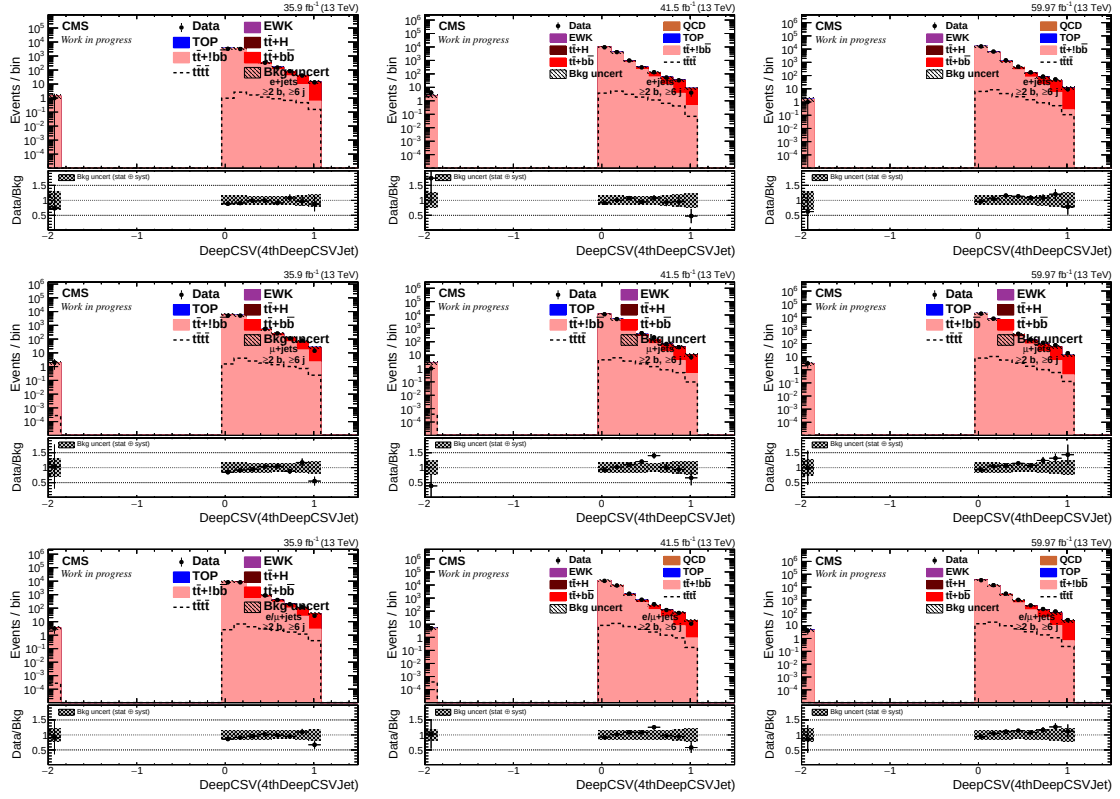


Figure 107: Distributions of fourth largest DeepCSV value in data and MC after initial selection in (left) 2016, (middle) 2017, and (right) 2018 data set. From top to bottom electron, muon and their combination. Training with $\geq 6j$ cut.

where $\hat{y}_S(y)$ is the signal PDF of variable y , $\hat{y}_B(y)$ is that for background.

In Table 13 we show the separation ranking of training with 40 variables, corresponding to 2017 data set and the number of jets ≥ 6 .

5.5.5. *BDT Performance and Validation*

Figure 108 to 110 show the BDT distributions after pre-selections mentioned in Section 5.4; while two different $n(\text{jets})$ cuts are considered.

We noticed that not all variables contribute to the final result significance after fit which will be discussed in Section 5.7. Figure 111 shows the AUC value and significance as a function of input variables in the training. We finally decide to use top 40 variables in separation ranking.

We confirmed that there is not significant over-fitting by comparing the training and test ROC curves in Figure 112 and AUC values in Table 14.

5.5.6. *BDT Shape Correction*

We observed that discrepancies between BDT distributions in data and MC exist. Although the shape disagreement can be mostly covered by uncertainties ranges, there is a slope in the data/MC ratio as a function of BDT value from -1 to 1. Therefore, we decide to derive a scale factor for such a slope. Given that $n(\text{b-jets}) = 2$ is not likely to contain signal events, we use the inclusive 2 b-jet category as a control region to do a linear fit and find the fit coefficients. Inclusive means we do not split lepton flavor, number of resolved tops. Figures 113 to 115 show this procedure. They are derived for each data taking year and separately for $n(\text{jets}) = 6, 7$, or ≥ 8 cases, based on their different trends. Shape correction factors and uncertainties are listed in Table 15.

Table 13: BDT input variable ranking by separation, corresponding to training with 40 variables, 2017 dataset and number of jets ≥ 6 .

Rank	Variable	Separation
0	AK4 jet multiplicity	3.316e-01
2	DeepCSV(4thDeepCSVJet)	2.415e-01
3	DeepCSV(3rdDeepCSVJet)	2.407e-01
4	$p_T(j_6)$	2.197e-01
5	HT/HT(4 leading jets)	2.131e-01
6	trijet2 discriminator	2.049e-01
7	bjet multiplicity	1.770e-01
8	S_T	1.719e-01
9	$p_T(j_5)$	1.647e-01
10	H_T	1.630e-01
11	$5^{th} jet p_T$	1.536e-01
12	Hemiout	1.475e-01
13	trijet3 discriminator	1.413e-01
14	HTwoTwoPtBjets	1.257e-01
15	HT(bjets)	9.475e-02
16	M(allJets, leptoninc W)	9.141e-02
17	6^{th} FW moment	6.380e-02
18	$M_T(lep, E_T^{miss})$	6.151e-02
19	$M(l, b_1)$	5.156e-02
20	resolvedTop multiplicity	5.080e-02
21	$p_T(j_2)$	4.504e-02
22	top multiplicity	4.370e-02
23	HOTGoodTrijet2_dijetmass	4.284e-02
24	HOTGoodTrijet2_pTratio	4.282e-02
25	HOTGoodTrijet2_dRtrijetJetnotdijet	4.280e-02
26	HOTGoodTrijet2_mass	4.280e-02
27	Aplanarity	4.253e-02
28	$\min[\Delta R(b, b)]$	4.222e-02
29	HOTGoodTrijet2_dRtridijet	4.154e-02
30	trijet1 discriminator	4.079e-02
31	$\max[M(b, b)]$	3.945e-02
32	$p_T(b_1)$	3.509e-02
33	HOTGoodTrijet2.csvJetnotdijet	3.410e-02
34	M(l,b) with $\min[\Delta R(l, b)]$	3.374e-02
35	E_T^{miss}	3.313e-02
36	Sphericity	2.902e-02
37	$\text{ave}[\Delta R(b, b)]$	2.052e-02
38	Centrality	1.834e-02
39	$\max[\Delta \eta(b, b)]$	1.440e-02
40	MT2bb	8.664e-03

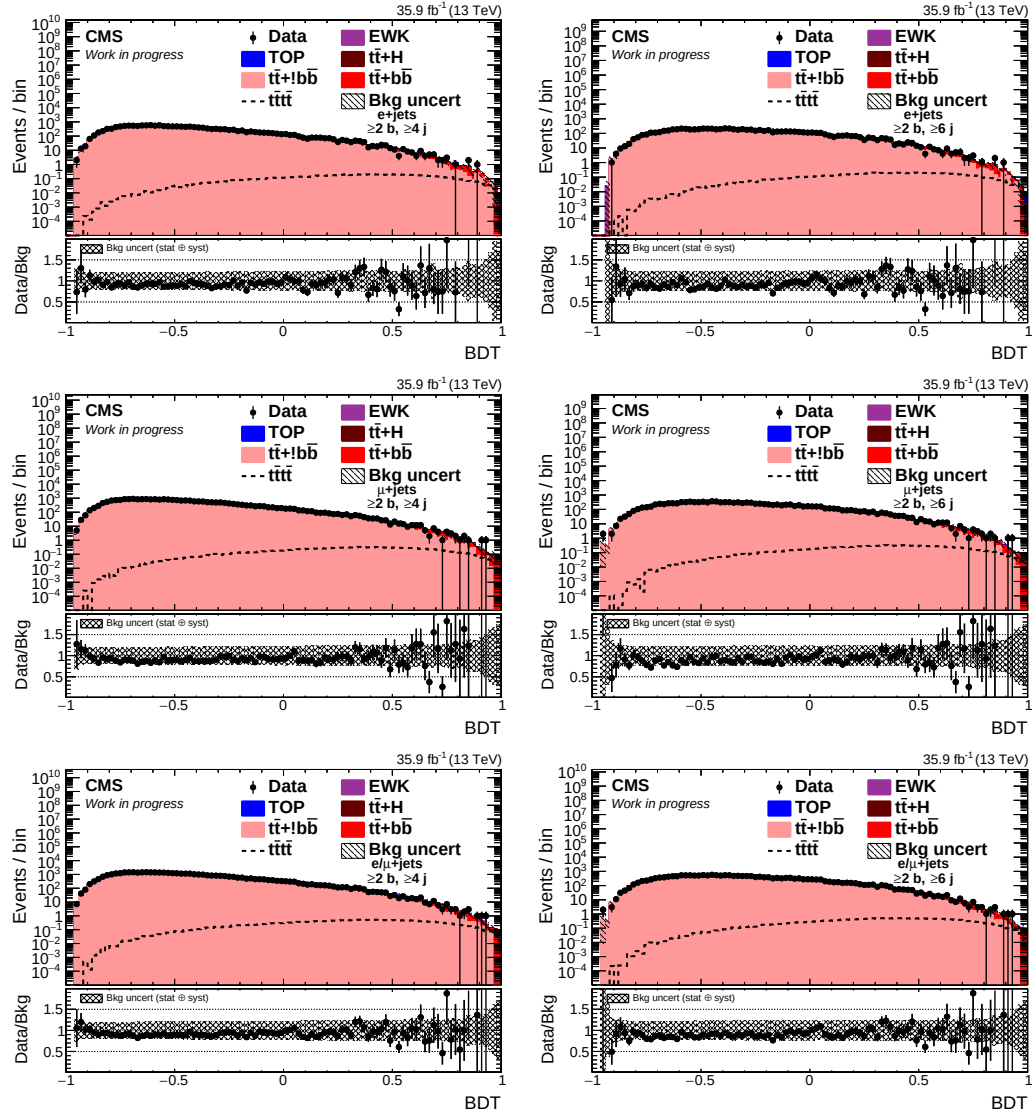


Figure 108: Distributions of BDT in data and MC after preselection with (left) ≥ 4 and (right) ≥ 6 jets for (upper) electron, (middle) muon, and (lower) combined lepton channels, corresponding to 2016 dataset and training with 40 variables.

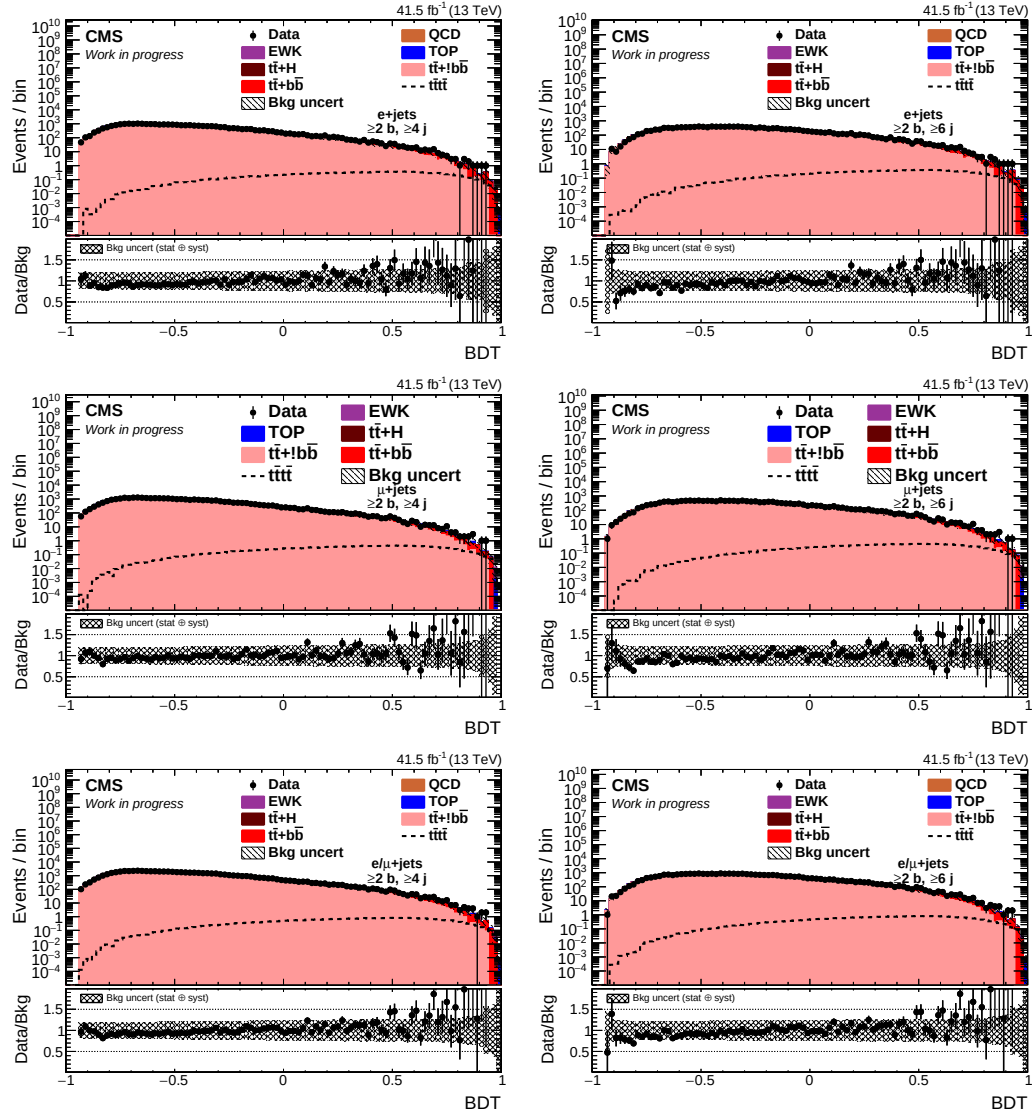


Figure 109: Distributions of BDT in data and MC after preselection with (left) ≥ 4 and (right) ≥ 6 jets for (upper) electron, (middle) muon, and (lower) combined lepton channels, corresponding to 2017 dataset and training with 40 variables.

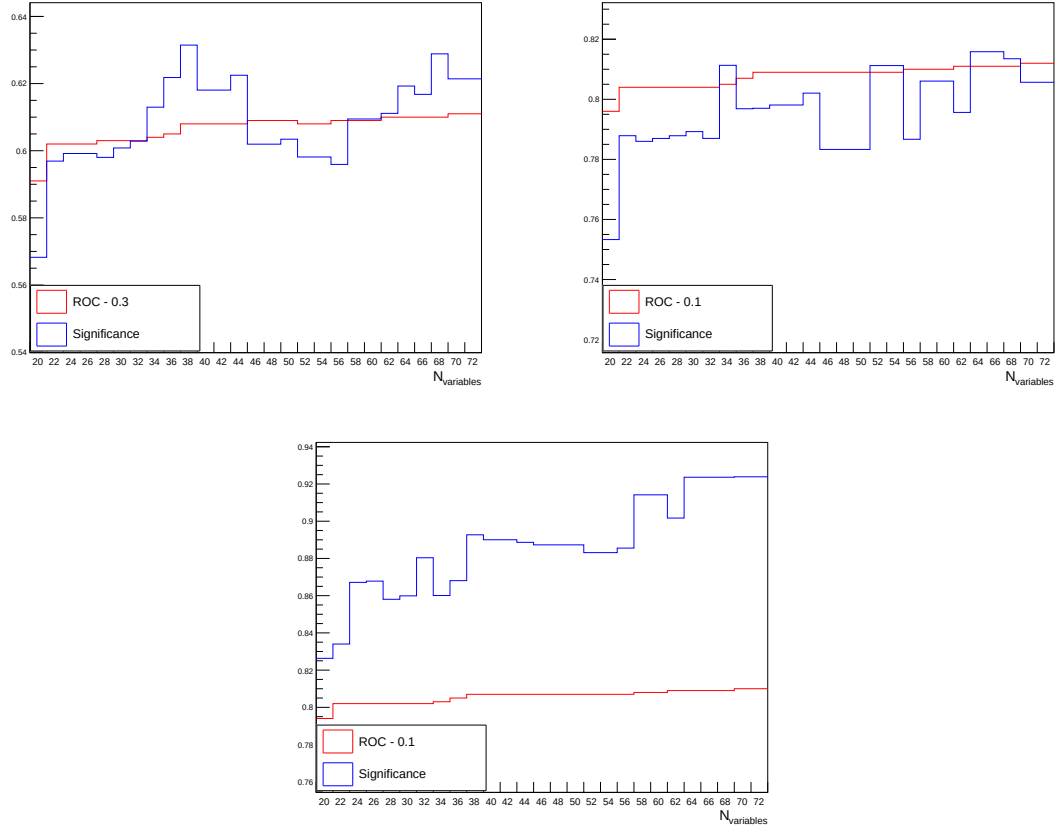


Figure 111: ROC AUC score and significance of the BDT in function of the number of input variables used in (left) 2016, (right) 2017, (lower) 2018 data set.

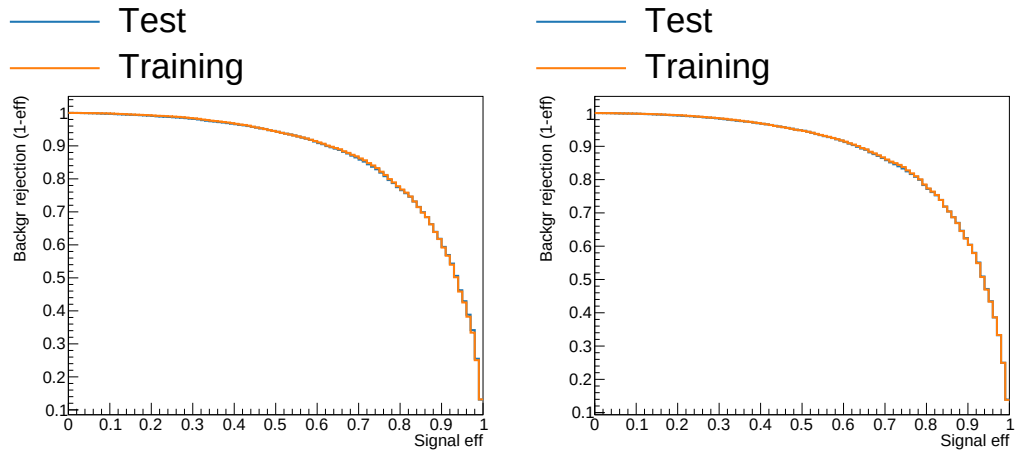


Figure 112: Comparison of ROC curves for the BDT in the different training scenarios considered (upper), and comparison of the ROC curve for the training and validation datasets (lower) in (left) 2017 and (right) 2018 data set.

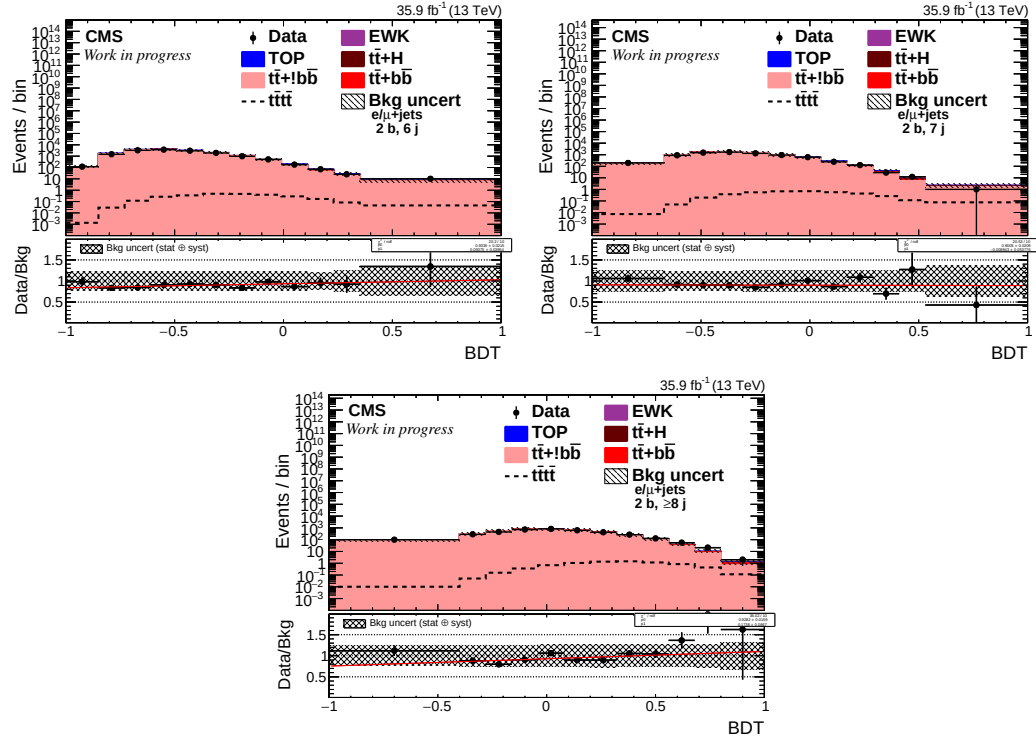


Figure 113: Distributions of BDT in data and MC with 2 b-tag and (left) 6 jet, (right) 7 jet, and (lower) ≥ 8 jets for combined lepton channels of 2016 data set. The solid red line in the lower panels show the first order polynomial fit to data to background ratio. The background uncertainties include all statistical and systematic components, where the total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin.

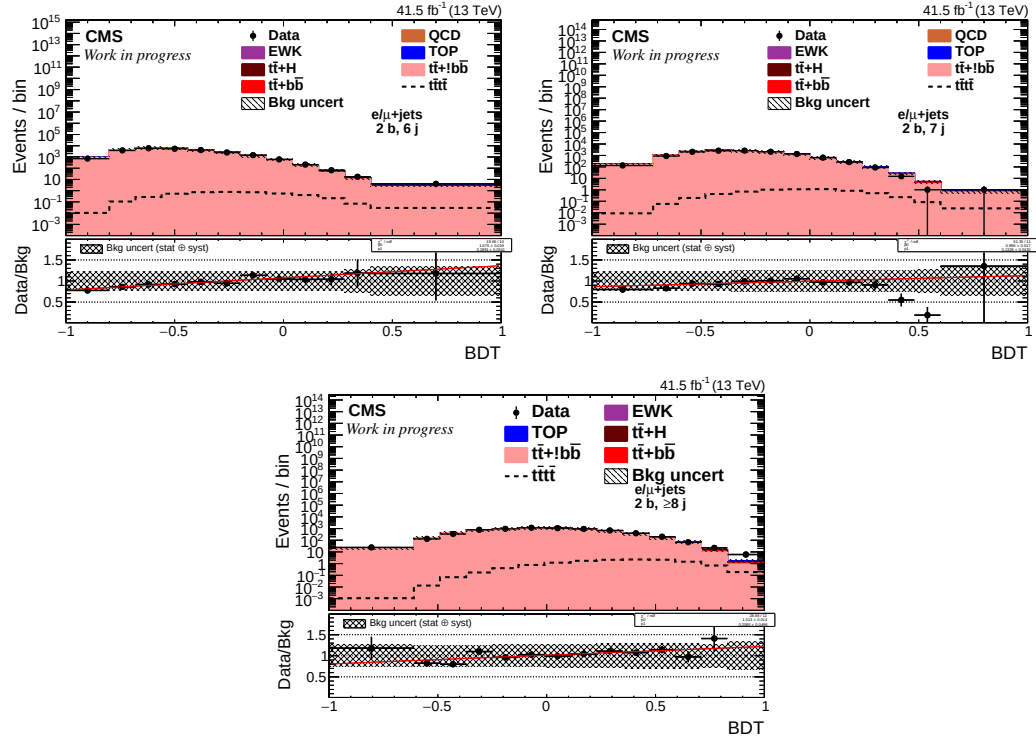


Figure 114: Distributions of BDT in data and MC with 2 b-tag and (left) 6 jet, (right) 7 jet, and (lower) ≥ 8 jets for combined lepton channels of 2017 data set. The solid red line in the lower panels show the first order polynomial fit to data to background ratio. The background uncertainties include all statistical and systematic components, where the total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin.

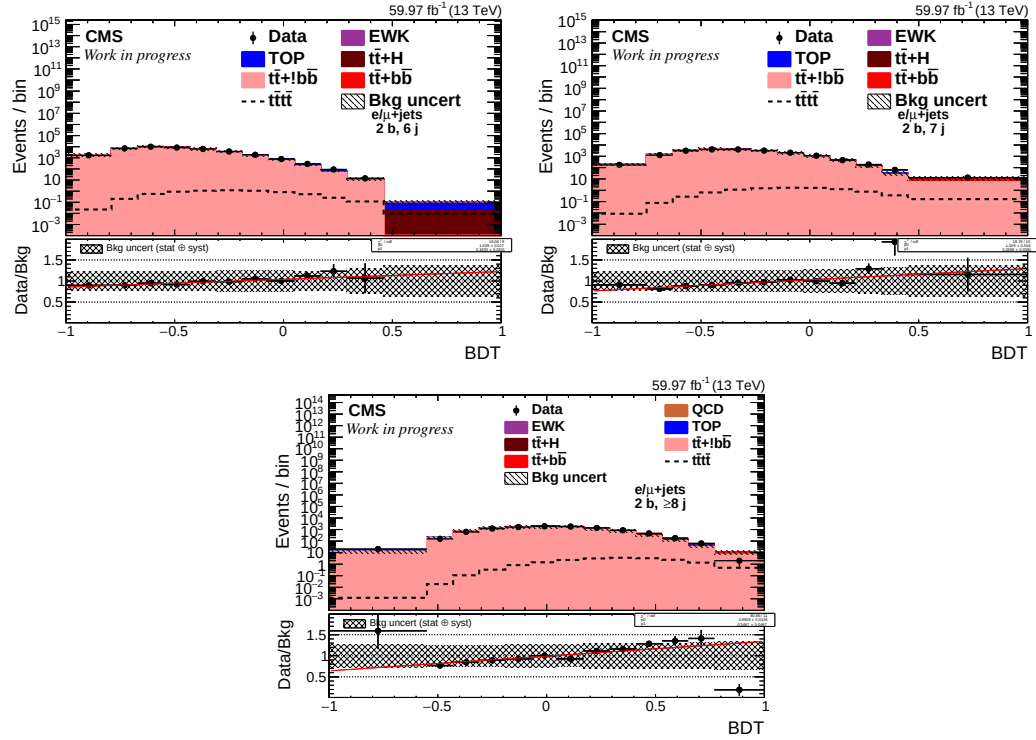


Figure 115: Distributions of BDT in data and MC with 2 b-tag and (left) 6 jet, (right) 7 jet, and (lower) ≥ 8 jets for combined lepton channels of 2018 data set. The solid red line in the lower panels show the first order polynomial fit to data to background ratio. The background uncertainties include all statistical and systematic components, where the total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin.

Table 14: AUC score of the BDT trainings in various configurations.

#Variable	#jets	Year	AUC(training)	AUC(validation)	diff(%)
40	≥ 4	2016	93.953	93.970	0.019
40	≥ 4	2017	93.744	93.757	0.014
40	≥ 4	2018	93.588	93.586	0.003
40	≥ 6	2016	90.813	90.861	0.053
40	≥ 6	2017	90.864	90.853	0.012
40	≥ 6	2018	90.740	90.681	0.065

Table 15: BDT shape correction scale factors and their statistical uncertainties.

Year	6j	7j	$\geq 8j$
2016	0.0937 ± 0.0395	-0.0089 ± 0.0538	0.1738 ± 0.0667
2017	0.2891 ± 0.0341	0.1328 ± 0.0420	0.2085 ± 0.0496
2018	0.1833 ± 0.0301	0.2658 ± 0.0381	0.3497 ± 0.0467

These scale factors will be applied to $n(\text{b-jets}) = 3$ or ≥ 4 categories which we use in the final fit. BDT shape validation after correction on these categories are shown in Figure 116 to 121.

5.6. Systematic Uncertainties

We considered the following experimental systematic uncertainties:

Integrated luminosity We use the recommended uncertainties 1.2, 2.3, and 2.5% for 2016 [85], 2017 [86], and 2018 [87] data set, respectively.

Lepton reconstruction and trigger efficiencies In Section 5.3 we discussed the uncertainties for trigger and lepton identification, isolation and reconstruction. We apply a 5% combined uncertainty.

Pileup Pileup minbias cross section has an uncertainty of 4.6% [88].

Jet energy scale We scaled the jet energy correction up and down in the MC samples so that jet and MET get the corresponding correction.

Jet energy resolution JER uncertainty is obtained by rescaling the jet momentum up and down by one standard deviation in the simulation and creating the corresponding new dis-

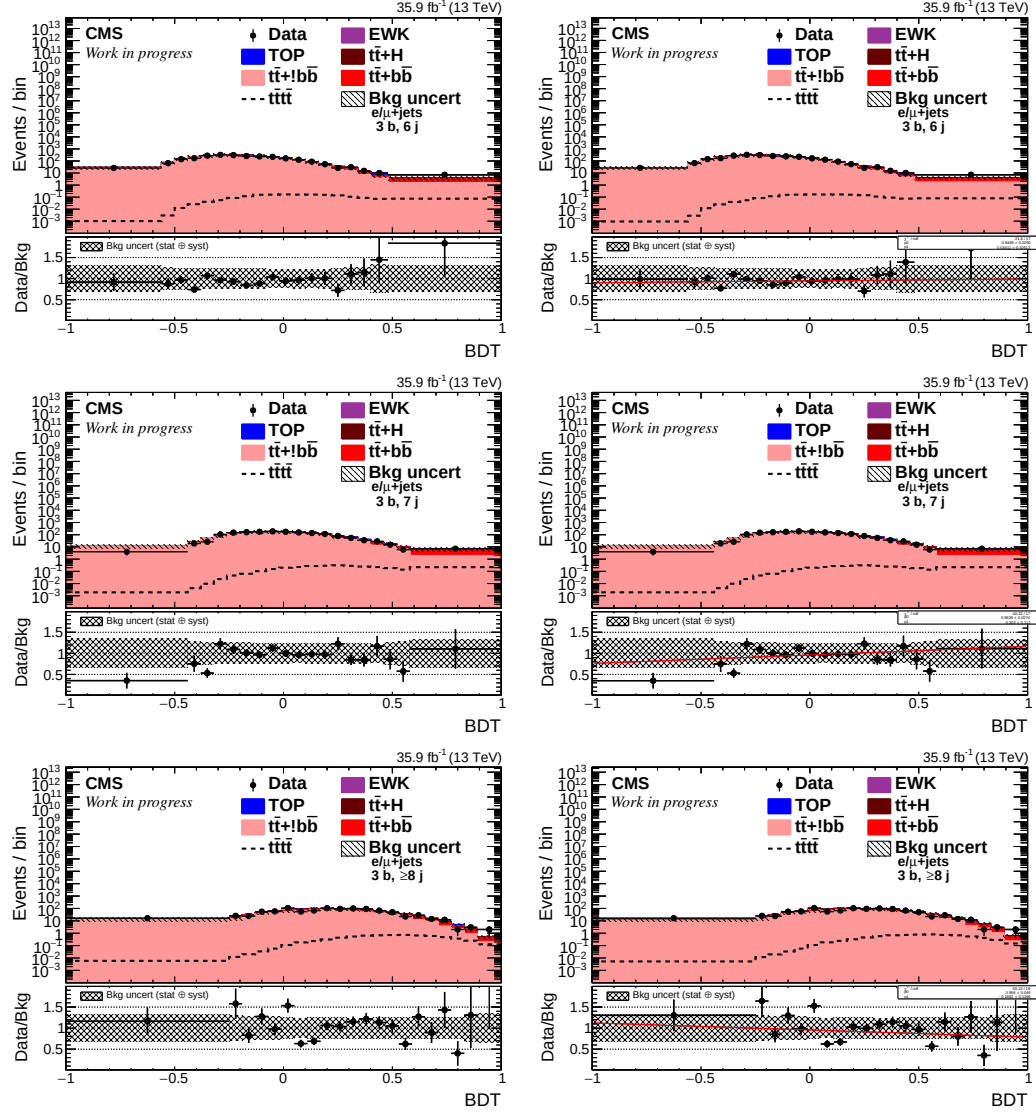


Figure 116: Distributions of BDT in data and MC (left) before and (right) after the slope correction with 3 b-tag and (upper) 6 jet, (middle) 7 jet, and (lower) ≥ 8 jets for combined lepton channels of 2016 data set. The background uncertainties include all statistical and systematic components, where the total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin.

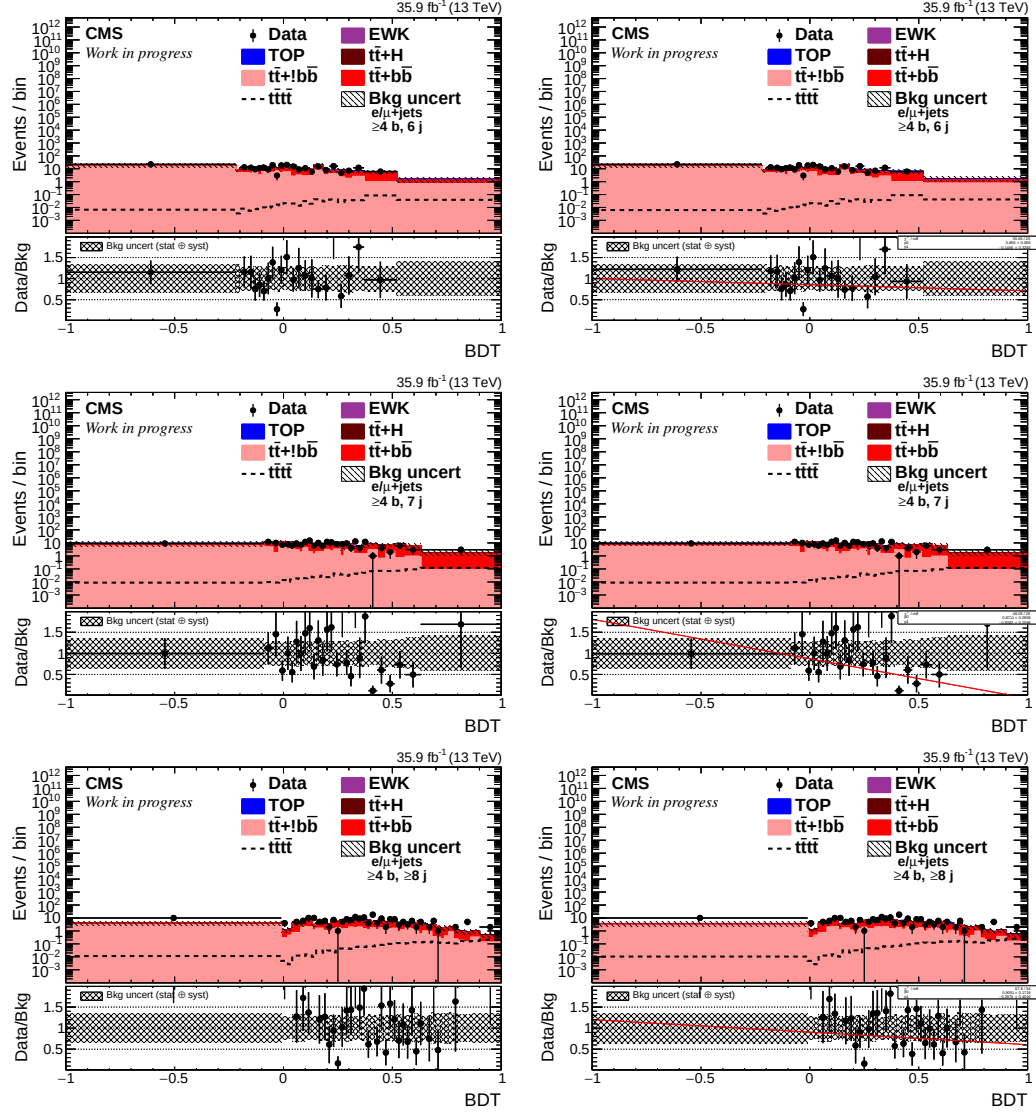


Figure 117: Distributions of BDT in data and MC (left) before and (right) after the slope correction with ≥ 4 b-tag and (upper) 6 jet, (middle) 7 jet, and (lower) ≥ 8 jets for combined lepton channels of 2016 data set. The background uncertainties include all statistical and systematic components, where the total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin.

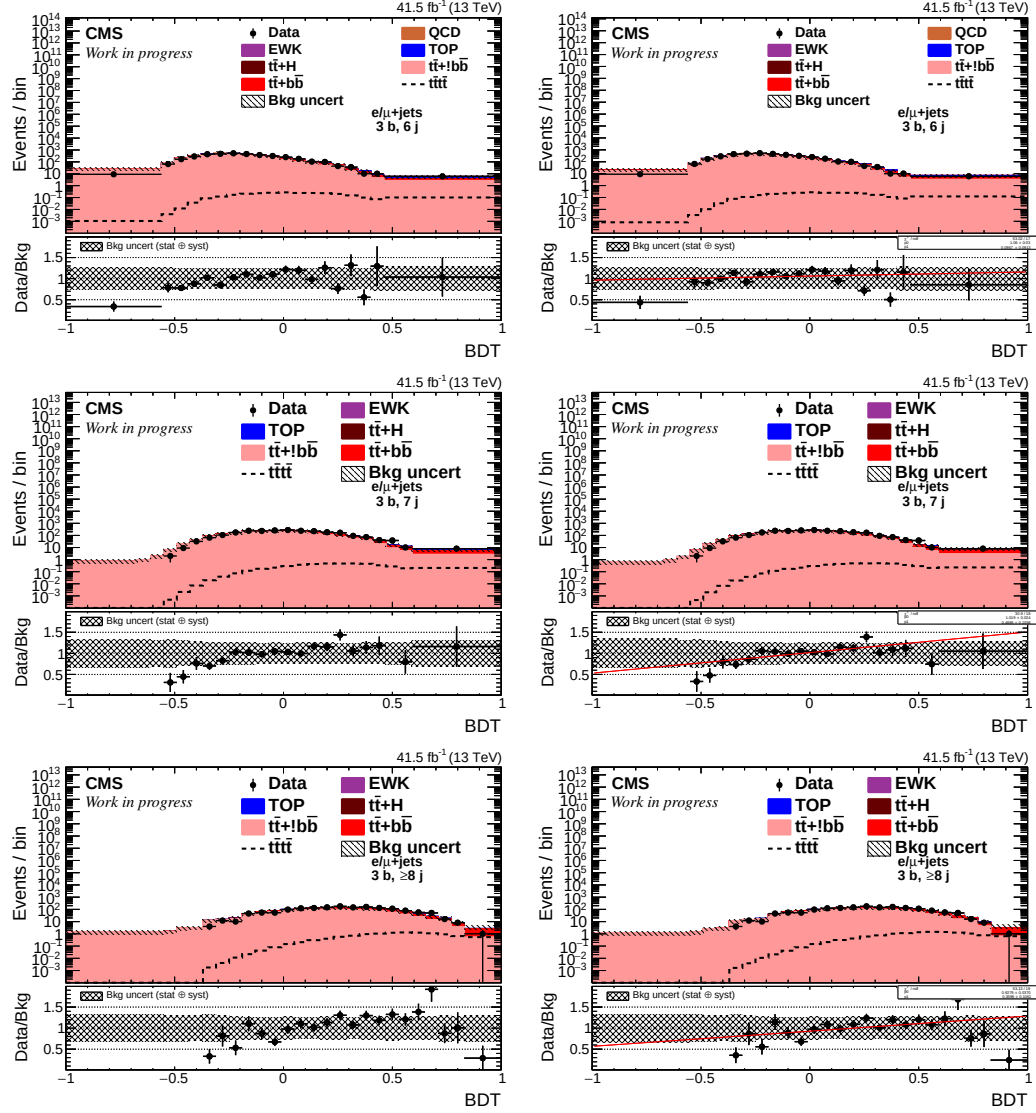


Figure 118: Distributions of BDT in data and MC (left) before and (right) after the slope correction with 3 b-tag and (upper) 6 jet, (middle) 7 jet, and (lower) ≥ 8 jets for combined lepton channels of 2017 data set. The background uncertainties include all statistical and systematic components, where the total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin.

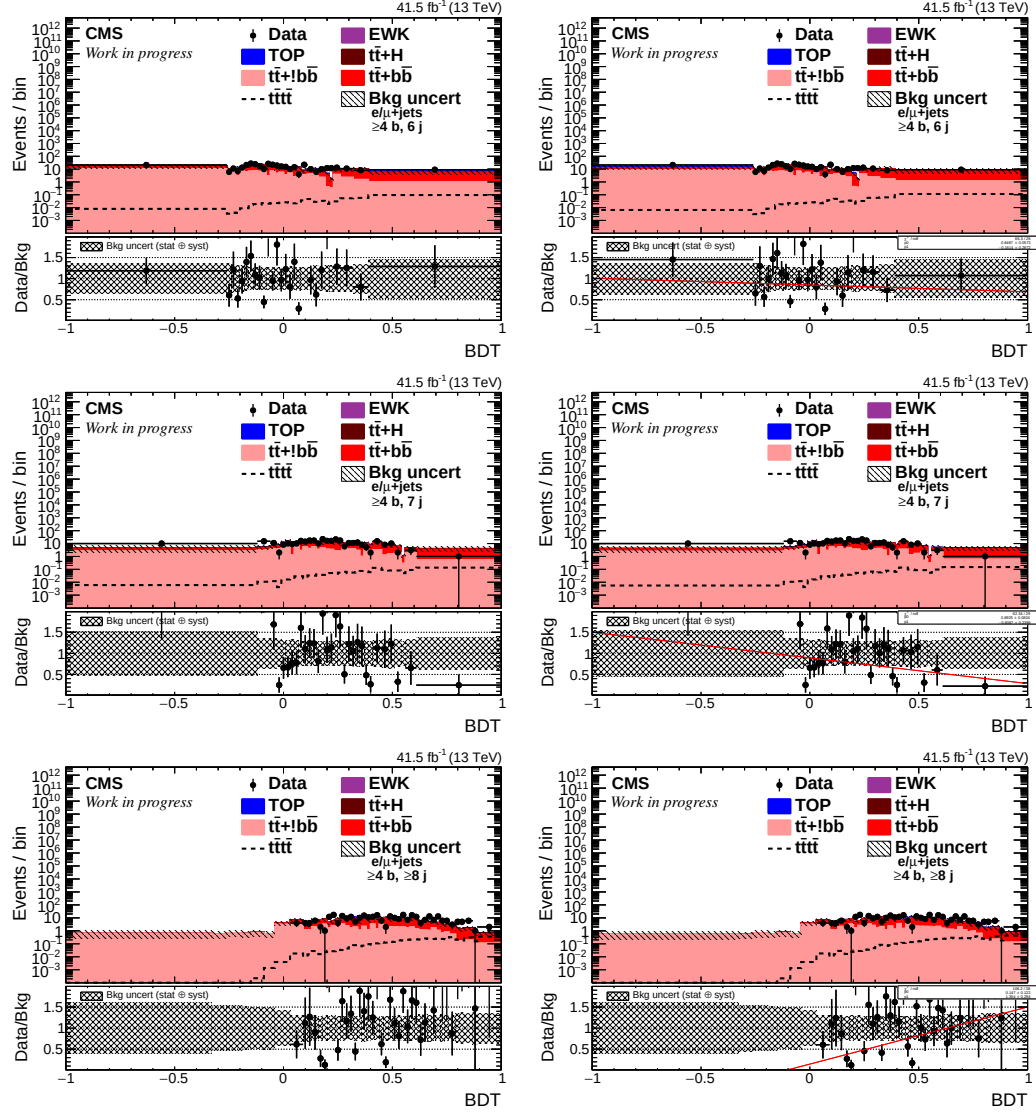


Figure 119: Distributions of BDT in data and MC (left) before and (right) after the slope correction with ≥ 4 b-tag and (upper) 6 jet, (middle) 7 jet, and (lower) ≥ 8 jets for combined lepton channels of 2017 data set. The background uncertainties include all statistical and systematic components, where the total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin.

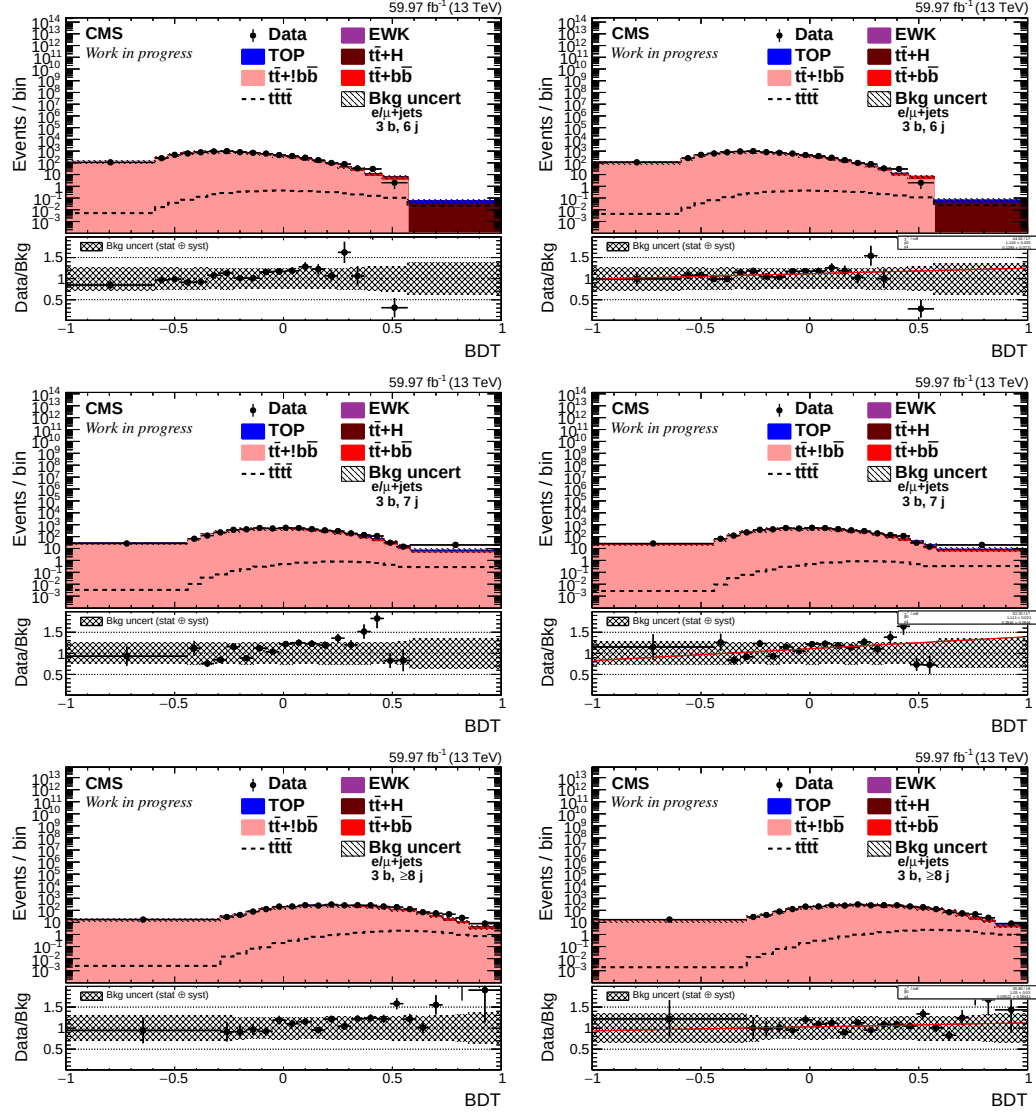


Figure 120: Distributions of BDT in data and MC (left) before and (right) after the slope correction with 3 b-tag and (upper) 6 jet, (middle) 7 jet, and (lower) ≥ 8 jets for combined lepton channels of 2018 data set. The background uncertainties include all statistical and systematic components, where the total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin.

criminant shapes.

b-tagging, mis-tagging efficiencies The b-tagging scale factor is applied in a jet-by-jet update method, so the uncertainty on this efficiency is calculated per jet.

b-tagging DeepCSV shape calibration In the MVA analysis the uncertainties in the b-tagging and light quark mistagging efficiencies are produced using the 'lf', 'hf', 'hfstats1', 'hfstats2', 'lfstats1', 'lfstats2', 'cferr1', 'cferr2' uncertainties on the weights derived for the DeepCSV shape calibration. 'lf' is the contamination from udsg+c jets in heavy flavor region (MC truth is b hadron). 'hf' is the contamination from b+c jets in light flavor region (MC thuth is udsg). 'hfstats1', 'hfstats2' are linear and quadratic statistical fluctuations for b jets. 'lfstats1', 'lfstats2' are linear and quadratic statistical fluctuations for udsg jets. 'cferr1', 'cferr2' are uncertainty for c jets.

Resolved top tagging efficiency Resolved top-tagging uncertainty has three sub-sources, statistical uncertainty on the dependence of the tagging rate on the purity of the control sample (CS purity), and scale factors deviating from unity contributing to uncertainty estimation (closure).

Heavy flavor correction The correction on the $t\bar{t} + b\bar{b}$ cross section has an uncertainty of 13%.

Theory uncertainties as follows:

Renormalization and factorization scales This uncertainty is to estimate the higher order correction in the ME calculations. By varying μ_R, μ_F with a factor of 0.5 or 2, we totally make 6 combinations (excluding opposite variations of μ_R/μ_F), and they are stored as generator level weights in the simulation [89]. The weights are applied and then the maximum variation, called envelope, in each bin is taken and is considered as one single nuisance parameter for each year.

PDFs Additional 100 PDF replicas are considered and weighted. We take the root mean square of them in each bin and take one nuisance.

Parton shower ISR/FSR parton shower effects are considered by varying the scale for 0.5 (up) or 2 (down).

Underlying events and resummation scale These effects are studied with dedicated $t\bar{t}$ simulation. Due to low statistics of these samples, the contribution to the result is not significant. We found that in pre-selection level, their effect is flat over H_T spectrum. We apply a flat rate uncertainty for the effect of resummation scale (hdamp) of +10%/-7%. Underlying events effect is too small and will not be counted in our systematics.

Background process cross section Uncertainties on cross section of $t\bar{t}$, $t\bar{t} + H$, TOP and EWK groups are rate uncertainties.

Table 16 summarizes the systematic uncertainties and how they are correlated between years. Correlation is in general by official recommendation.

Another additional uncertainty for BDT shape correction is added, numbers shown in Table 15.

5.7. Results

We use H_T and BDT to fit and find the limits on cross section of $t\bar{t}t\bar{t}$ process. We use the Higgs Combine tool [58] and take the asymptotic fit to find the 95% Confidence Level (CL) expected upper limits of the cross section. The fit determines a signal strength that presents the ratio of observed signal cross section and predicted/expected signal cross section. Nuisance parameter for systematic uncertainties take a Gaussian PDF. In the fit, MC statistical uncertainties are treated by Barlow-Beaston-lite method [90, 91].

Table 16: Summary of all systematic uncertainties in four top analysis. Corr'd = correlation between years.

Source	Uncertainty	Signal	Background	2016	2017	2018	Corr'd?
Normalization only							
Luminosity	1.2/2.3/2.5%	Yes	All	✓	✓	✓	Partial
Electron Id/Isolation/Trigger	5%	Yes	All	✓	✓	✓	No
Muon Id/Isolation/Trigger	5%	Yes	All	✓	✓	✓	No
$t\bar{t}$ + HF	13%	No	$t\bar{t} + b\bar{b}$	✓	✓	✓	Yes
Cross section $t\bar{t}$	+4.8%/-5.5%	No	$t\bar{t}$	✓	✓	✓	Yes
Cross section $t\bar{t}$ + H	20%	No	$t\bar{t}$ + H	✓	✓	✓	Yes
Cross section TOP	4%	No	TOP	✓	✓	✓	Yes
Cross section EWK	3.8%	No	EWK	✓	✓	✓	Yes
h_{damp}	+10%/-7%	No	$t\bar{t}$	✓	✓	✓	Yes
Shape and Normalization							
Prefire	$\pm\sigma$	Yes	All	✓	✓	N/A	No
Pileup	$\sigma_{minbias} \pm 4.6\%$	Yes	All	✓	✓	✓	Yes
Jet energy scale	$\pm\sigma(p_T, \eta)$	Yes	All	✓	✓	✓	No
Jet energy resolution	$\pm\sigma(\eta)$	Yes	All	✓	✓	✓	No
b/c tagging correlated	$\pm\sigma(p_T)$	Yes	All	✓	✓	✓	Yes
b/c tagging uncorrelated	$\pm\sigma(p_T)$	Yes	All	✓	✓	✓	No
udsg mistagging	$\pm\sigma$	Yes	All	✓	✓	✓	No
resolved t tagging: statistical	$\pm\sigma$	Yes	All	✓	✓	✓	No
resolved t tagging: CS purity	$\pm\sigma(p_T)$	Yes	All	✓	✓	✓	No
resolved t tagging: closure	$\pm\sigma(N_{jet})$	Yes	All	✓	✓	✓	No
PDF	$\pm\sigma$	No	All	✓	✓	✓	Yes
ISR	$\pm\sigma$	No	All	✓	✓	✓	Yes
FSR	$\pm\sigma$	No	All	✓	✓	✓	Yes
Renorm./Fact. energy scale	envelope($\times 2, \times 0.5$)	No	All	✓	✓	✓	Yes
Shape only							
PDF	$\pm\sigma$	Yes	None	✓	✓	✓	Yes
ISR	$\pm\sigma$	Yes	None	✓	✓	✓	Yes
FSR	$\pm\sigma$	Yes	None	✓	✓	✓	Yes
Renorm./Fact. energy scale	envelope($\times 2, \times 0.5$)	Yes	None	✓	✓	✓	Yes
BDT shape correction	$\pm\sigma$	No	All	✓	✓	✓	No

5.7.1. Likelihood-Based Statistical Test

This statistical test is widely used in particle physics. We often search for processes that are predicted but not seen, so we care about exclusion limits and statistical significance of a signal. The procedure for the fit is based on the modified frequentist method, referred to as CL_s [92, 93].

We construct a likelihood function

$$\mathcal{L}(data|\mu, \theta) = Poisson (data|\mu \cdot s(\theta) + b(\theta)) \cdot p(\tilde{\theta}|\theta) \quad (5.4)$$

where s (b) is the number of signal (background) events, μ is signal strength (or called r). The uncertainties are handled by nuisance parameters θ . Here “data” can be observed data or pseudo-data.

We choose a test statistic $\tilde{q}_\mu$ based on profile likelihood ratio,

$$\tilde{q}_\mu = -2\ln \frac{\mathcal{L}(data|\mu, \hat{\theta}_\mu)}{\mathcal{L}(data|\hat{\mu}, \hat{\theta})}, \quad 0 \leq \hat{\mu} \leq \mu \quad (5.5)$$

where $\hat{\theta}_\mu$ is the maximum likelihood estimators of θ , given the signal strength parameter μ and “data”. While $\hat{\mu}$, $\hat{\theta}$ are parameters correspond to global maximum likelihood. By the physical meaning of μ , we search for a process such that $\hat{\mu} > 0$, and the signal hypothesis considers only the range $\hat{\mu} \leq \mu$.

To compare data with background-only and signal plus background hypothesis, two p-values are defined

$$p_\mu = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs} | signal + background) = \int_{\tilde{q}_\mu^{obs}}^{\infty} f(\tilde{q}_\mu | \mu, \hat{\theta}_\mu^{obs}) d\tilde{q}_\mu, \quad (5.6)$$

$$1 - p_b = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs} | background - only) = \int_{\tilde{q}_\mu^{obs}}^{\infty} f(\tilde{q}_\mu | 0, \hat{\theta}_0^{obs}) d\tilde{q}_\mu, \quad (5.7)$$

$f(\tilde{q}_\mu | \mu, \hat{\theta}_\mu^{obs})$ is the pdf assuming a signal strength μ in the signal + background hypothesis and $f(\tilde{q}_\mu | 0, \hat{\theta}_0^{obs})$ is that for background only hypothesis, and we calculate $CL_s(\mu)$

$$CL_s(\mu) = \frac{p_\mu}{1 - p_b}. \quad (5.8)$$

For a 95% Confidence Level upper limit, we adjust μ until we reach $CL_s = 0.05$.

We evaluate the excess of a signal on background-only hypothesis such that the probability that the fluctuation of background is as large as the observed data. The test statistic is $\tilde{q}_0$

$$\tilde{q}_0 = -2\ln \frac{\mathcal{L}(\text{data}|0, \hat{\theta}_0)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}, \text{ and } \hat{\mu} \geq 0 . \quad (5.9)$$

We compute the p-value with respect to the observed events

$$p_0 = P(q_0 \geq q_0^{obs}) = \int_{q_0^{obs}}^{\infty} f(q_0|0, \hat{\theta}_0^{obs}) dq_0 , \quad (5.10)$$

“significance” Z is converted from p-value by a one-sided Gaussian tail

$$p = \int_Z^{\infty} \frac{1}{\sqrt{2\pi}} \exp(-x^2/2) dx = \frac{1}{2} P_{\chi_1^2}(Z^2) , \quad (5.11)$$

$P_{\chi_1^2}$ stands for survival function of χ^2 for one degree of freedom. In CMS searches, we treat a significance of 3 standard deviation (s.d.) as an “evidence” level of a signal process.

5.7.2. Results with H_T Observable

We use 60 event categories, split by

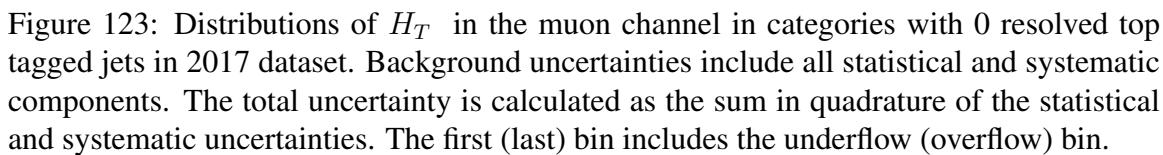
number of jets $n(\text{jets}) = 6, 7, 8, 9, \geq 10$;

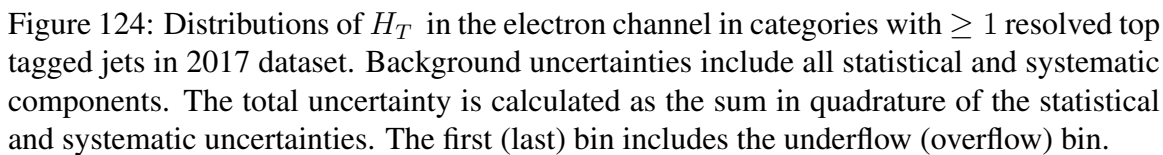
number of b-jets $n(\text{b-jets}) = 2, 3, \geq 4$;

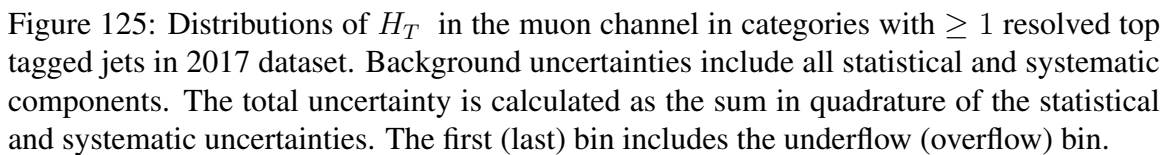
number of resolved top = 0, ≥ 1 ;

and by lepton flavor (e, μ).

We start with H_T templates that are uniformly binned to 25 GeV bin width. These templates are then rebinned starting from the last bin and merging with neighboring bin until the resulting templates have bins with statistical uncertainty less than 30% on the total background. Example of H_T templates to fit are shown in Figure 122 to 125 for the 2017 data set.







Expected and observed results are for $t\bar{t}t\bar{t}$ cross section limits and significances in Table 17.

Table 17: Expected and observed cross section limits for the HT analysis at 95% CL and significance for an integrated luminosity of 35.9 fb^{-1} in 2016, 41.5 fb^{-1} in 2017, and 59.97 fb^{-1} in 2018 as well as their combination.

Year	Obs. significance [s.d.]	Exp. significance [s.d.]	Obs. limit [fb]	Exp. limit [fb]	68% exp. [fb]	95% exp. [fb]
2016	0.000	0.379	47.25	63.37	[44.43, 91.41]	[32.68, 127.42]
2017	3.403	0.450	121.58	56.44	[40.05, 80.51]	[29.54, 110.05]
2018	2.529	0.561	91.81	39.37	[27.79, 56.48]	[20.61, 77.98]
2016+17+18	2.233	0.802	56.71	27.84	[19.38, 39.05]	[14.79, 53.49]

5.7.3. Results with BDT Discriminant

The results shown here utilizes a BDT training set with 40 variables and $n(\text{jets}) \geq 6$ selection. As mentioned in Section 5.5 we applied a shape correction for BDT distributions where $n(\text{b-jets}) = 2$ events are used to determine the correction. Therefore, only categories for $n(\text{b-jets}) = 3, \geq 4$, totally 40 categories, are used in fit to obtain the final result. The BDT distributions have variable sized bins. To obtain the variable bins, we start with BDT templates that are uniformly split in 200 bins between -1 and 1. These templates are then rebinned starting from the last bin and merging with neighboring bin until the resulting templates have bins with statistical uncertainty less than 30% on the total background. Example templates for BDT in Figure 126 to 129 for the 2017 data set.

Results for the BDT fit are in Table 18.

Table 18: Expected and observed cross section limits for the BDT analysis at 95% CL and significance for an integrated luminosity of 35.9 fb^{-1} in 2016, 41.5 fb^{-1} in 2017, and 59.97 fb^{-1} in 2018 as well as their combination. sign. = significance

Year	Obs. sign. [s.d.]	Exp. sign. [s.d.]	Obs. limit [fb]	Exp. limit [fb]	68% exp. [fb]	95% exp. [fb]
2016	0.000	0.590	25.89	45.56	[31.55, 67.17]	[23.14, 94.78]
2017	0.020	0.730	37.03	35.63	[24.67, 52.24]	[18.09, 73.93]
2018	2.790	0.910	69.12	29.91	[21.11, 42.90]	[15.65, 59.23]
2016+17+18	1.440	1.300	32.82	19.78	[14.08, 28.22]	[10.43, 38.57]

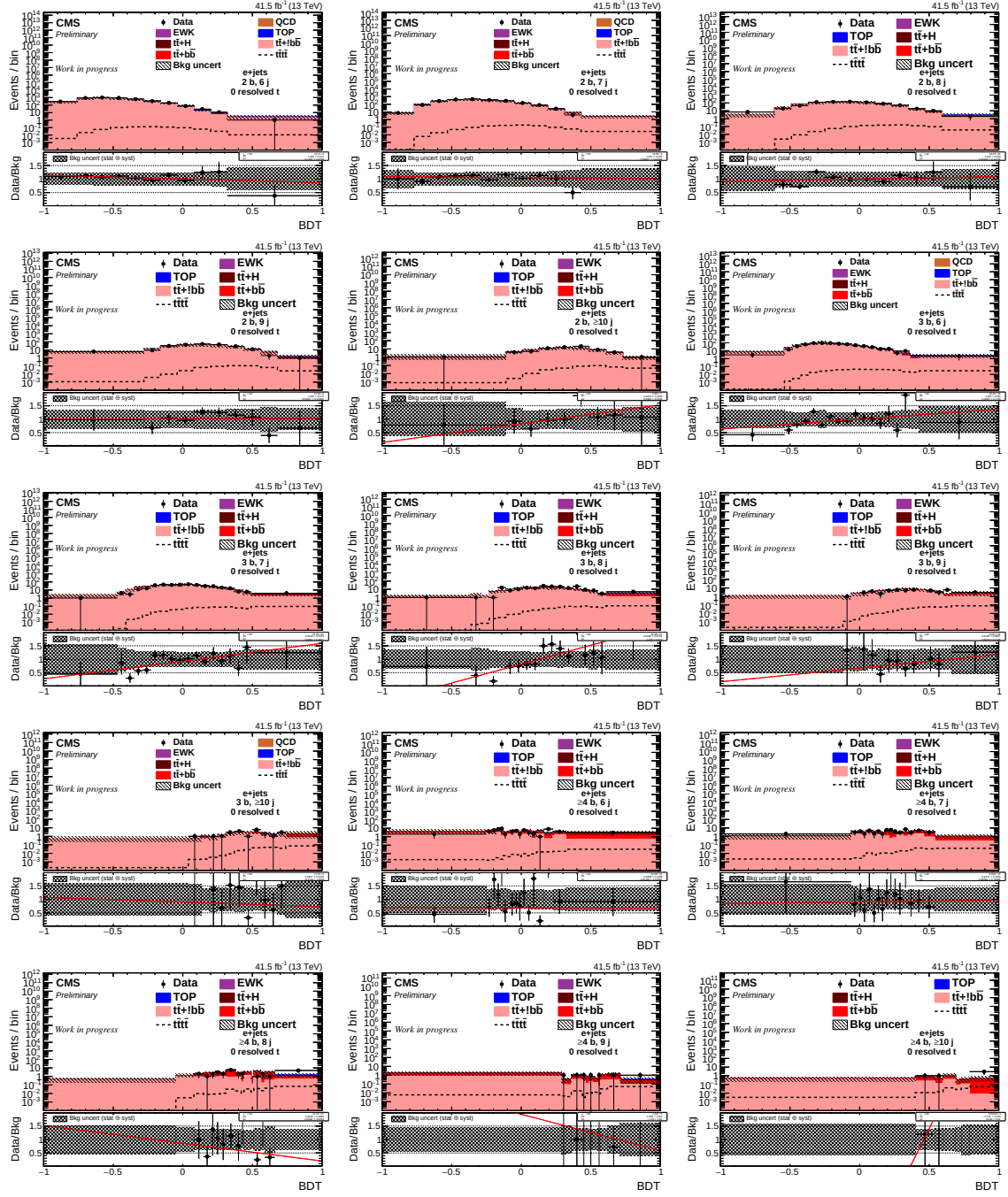


Figure 126: Distributions of BDT in the electron channel in categories with 0 resolved top tagged jets in 2017 dataset. Uncertainties include all statistical and systematic components. The total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin. Only categories for $n(\text{b-jets}) = 3, \geq 4$ are used in fit to obtain the final result.

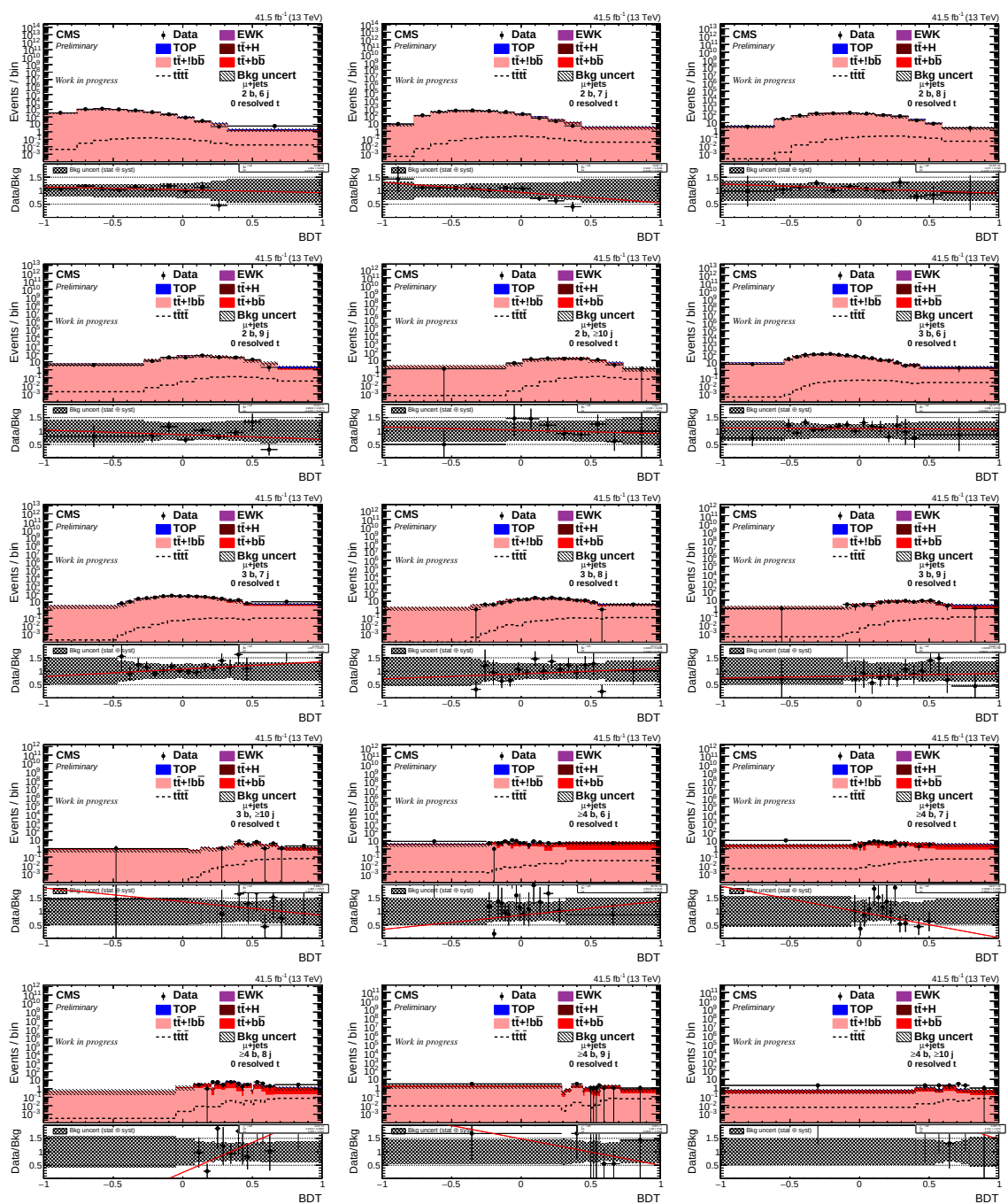


Figure 127: Distributions of BDT in the muon channel in categories with 0 resolved top tagged jets in 2017 dataset. Uncertainties include all statistical and systematic components. The total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin. Only categories for $n(\text{b-jets}) = 3, \geq 4$ are used in fit to obtain the final result.

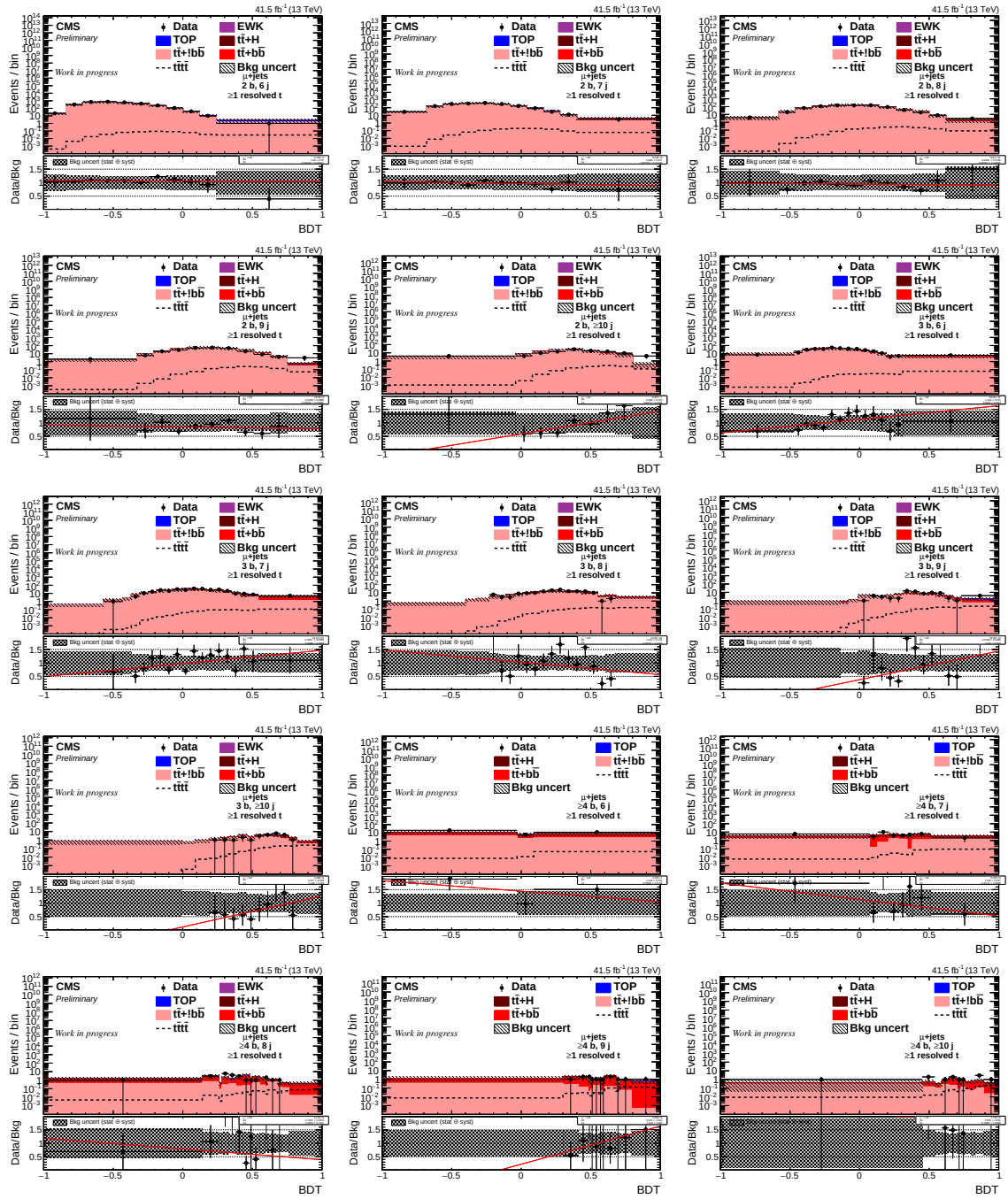


Figure 129: Distributions of BDT in the muon channel in categories with ≥ 1 resolved top tagged jets in 2017 dataset. Uncertainties include all statistical and systematic components. The total uncertainty is calculated as the sum in quadrature of the statistical and systematic uncertainties. The first (last) bin includes the underflow (overflow) bin. Only categories for $n(\text{b-jets}) = 3, \geq 4$ are used in fit to obtain the final result.

5.8. Conclusion

In summary, we performed a search for a standard model four top quark production in the single-lepton final state. We analyze the proton-proton collision data collected by the CMS experiment at center-of-mass energy of 13 TeV, corresponding to a total integrated luminosity of 137.4 fb^{-1} from 2016 to 2018. From the analysis presented in this thesis, we obtain an observed (expected) significance of 1.44 (1.30) standard deviations for four top quark production process in our data sample.

APPENDIX A

Delphes Validation

Delphes Fast Simulation is a modular simulation framework, providing a parameterized detector response. It is a project started in 2007 in order to do quick detector studies. In 2013, Delphes 3 was released with a relatively good performance and started to be widely used in the particle physics community [94]. It is known that studies in high energy particle physics contain really complex simulations, in particular to evaluate the interactions between long-lived particles and the detector matter. The full simulation commonly used in CMS is through the GEANT package [95], followed by a simulation of detector electronic response and reconstruction of physics observables. This full simulation takes a relatively large amount of computing resources. In order to avoid the usage of computing resources, given the need of phenomenological studies, Delphes is developed. It takes the common event generator output as input and does a realistic simulation of a collider detector.

Delphes simulates an inner tracker, electromagnetic and hadron calorimeters and a muon detector system. The long-lived particles propagates through a uniform axial magnetic field, and this field exists in the inner tracker volume. Charged particles may leave a track in the tracker depending on a probability that is user defined. It is assumed that the tracks have a perfect angular resolution which is valid for most particle detectors. After that, each particle hits exactly one ECAL and one HCAL cell. Delphes assumes electrons and photons

save all energy in ECAL and hadrons leave all energy on HCAL. Muons and neutrinos do not leave energy in calorimeters. At this point, a simplified particle-flow reconstruction takes place using the responses in tracking system and calorimeters. Particle-flow assumes the tracking system has a better energy resolution than calorimeters for charged particles. Pileup and jet energy corrections are considered in Delphes, too.

Delphes Fast Simulation is the simulation people use for CMS phase II upgrade studies. People have done many projections of high lumi LHC (HL-LHC) and high energy LHC (HE-LHC) with Delphes samples. We would like to provide a framework to evaluate the performance of the fast simulation compared with the official full simulations. The idea is to create basic measurements of the common physics objects, and look at the performance in full simulation (“FullSim” on figures) and Delphes. Some improvements in Delphes parameterization has been done as a result of this validation.

The validation framework workflow is shown in Figure 130. We first run Delphes on Generator level samples, then make flat trees, also called ntuples. Flat trees store event structure and inside a tree there are kinematic variables for physics objects. There is no complicated structure under the tree level. Then we developed a validation tool which can produce many common features for objects, including jet, MET, electron, muon, photon, b-tagging (and mis-tagging), tau-tagging.

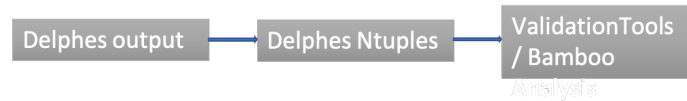


Figure 130: Delphes validation workflow.

For each object except for MET, the framework provides the following observable

- Gen level object matching efficiency, defined as

$$\frac{\text{number}(\text{gen objects that have reco matched})}{\text{number}(\text{all gen objects})} \quad (\text{A.1})$$

- p_T response, defined as $p_T(\text{reco})/p_T(\text{gen})$
- reconstruction resolution, $p_T(\text{reco})/p_T(\text{gen})$
- tagging rate, defined as $\frac{\text{tagged as } b\text{-jets among true } b\text{-jets}}{\text{all true } b\text{-jets}}$, true flavor found by matching to gen level parton flavor
- various ID quality levels considered: looseID, mediumID, tightID

For missing transverse energy (MET), we would like to look at the performance of reco level MET, the relationship between MET and number of pile-up (nPU), the relationship between MET and gen level Z p_T or gen level H_T . Here generator level Z is found by searching for generator level particles.

I will show some examples of validation results here for jet, b-tagging and MET.

MC samples used for validation in the following example are from the production campaign HLTTDRSummer20ReRECO, produced by CMSSW_11_3X in Table 19.

Table 19: MC samples for Delphes validation.

Object	Samples
MET	DYJetsToLL_M-10to50_TuneCP5_14TeV-madgraphMLM-pythia8
	DYToLL_M-50_TuneCP5_14TeV-pythia8
	ZprimeToEE_M-6000_TuneCP5_14TeV-pythia8
	ZprimeToMuMu_M-6000_TuneCP5_14TeV-pythia8
jet	QCD_Pt-15to300_TuneCP5_Flat_14TeV-pythia8
btagging	TT_TuneCP5_14TeV-powheg-pythia8
	QCD_Pt-15to300_TuneCP5_Flat_14TeV-pythia8
	GluGluToHHTo2B2Tau_node_SM_TuneCP5_14TeV-madgraph-pythia8

Figure 132 show examples of jet p_T resolution. Figure 131 shows example of jet p_T response.

Figure 133 to 135 show the performance of b-tagging efficiencies.

Figure 136 and 137 are examples of MET performance in Delphes.

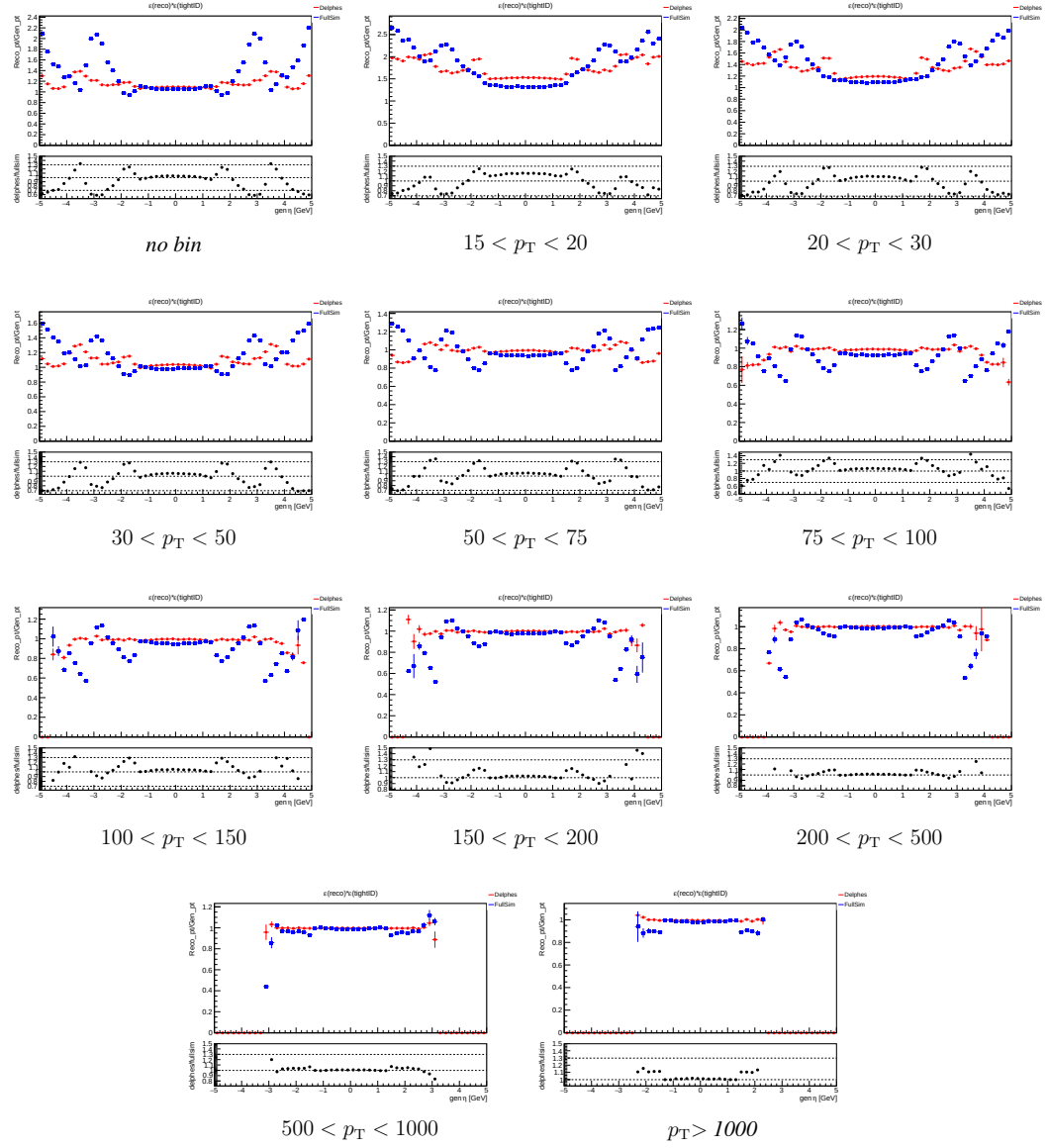


Figure 131: Delphes validation for jets, p_T response as a function of η in various p_T bins, for tightID jets.

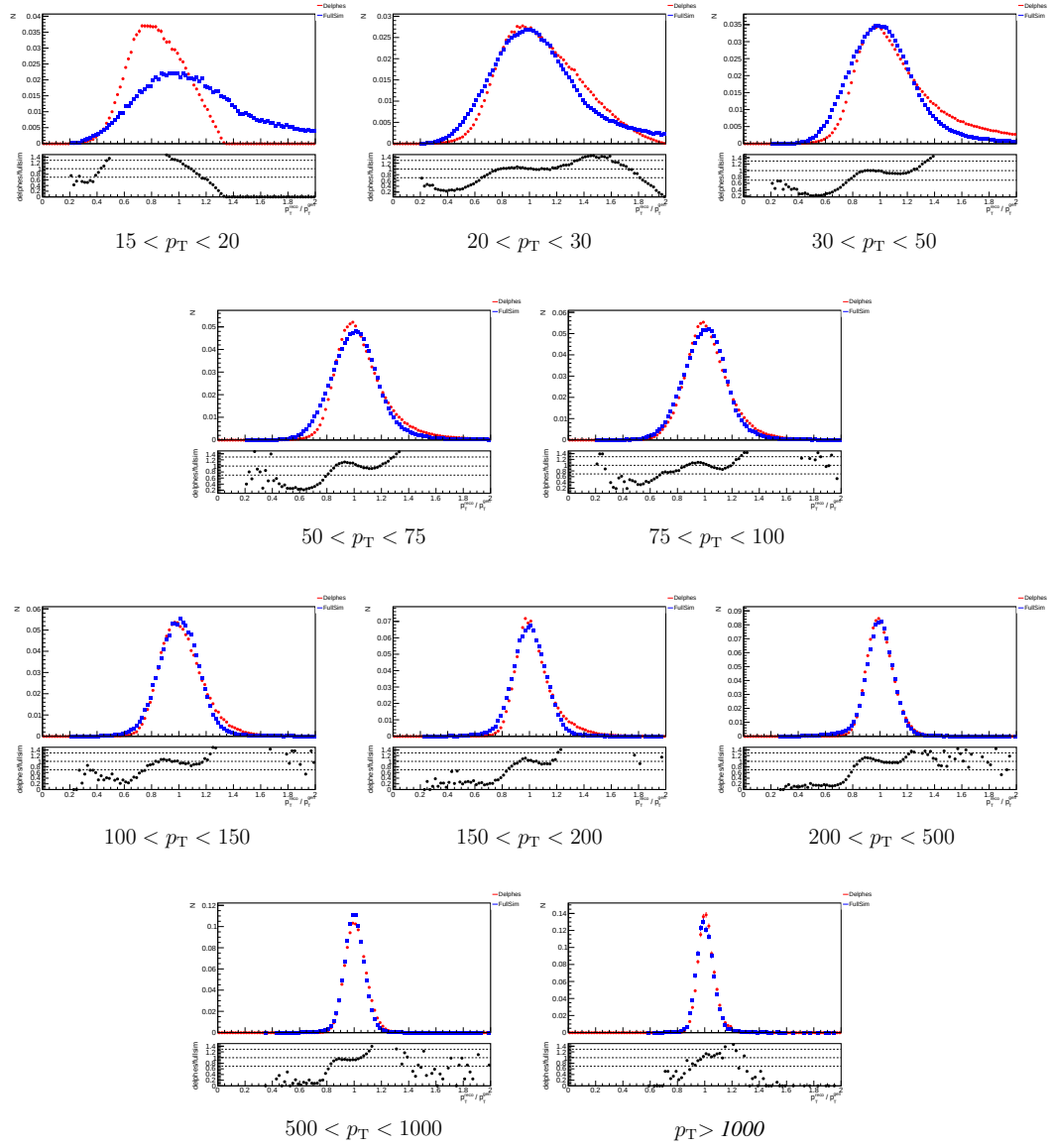


Figure 132: Delphes validation for jets, p_T resolution distribution in various p_T bins, and $0 < |\eta| < 1.5$, for tightID jets.

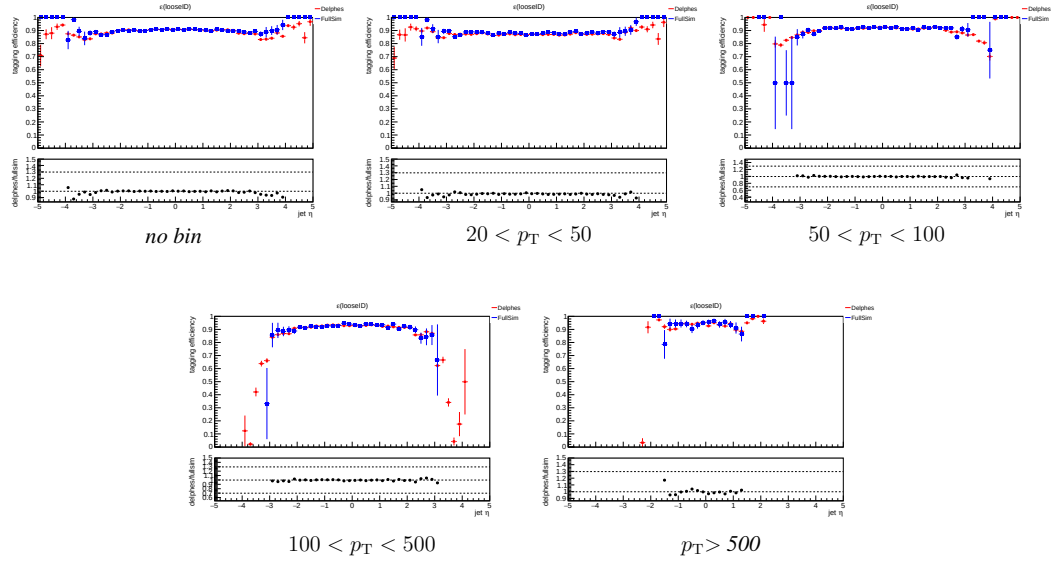


Figure 133: Delphes validation for jets, b-tagging rate as a function of η in various p_T bins, for looseID jets.

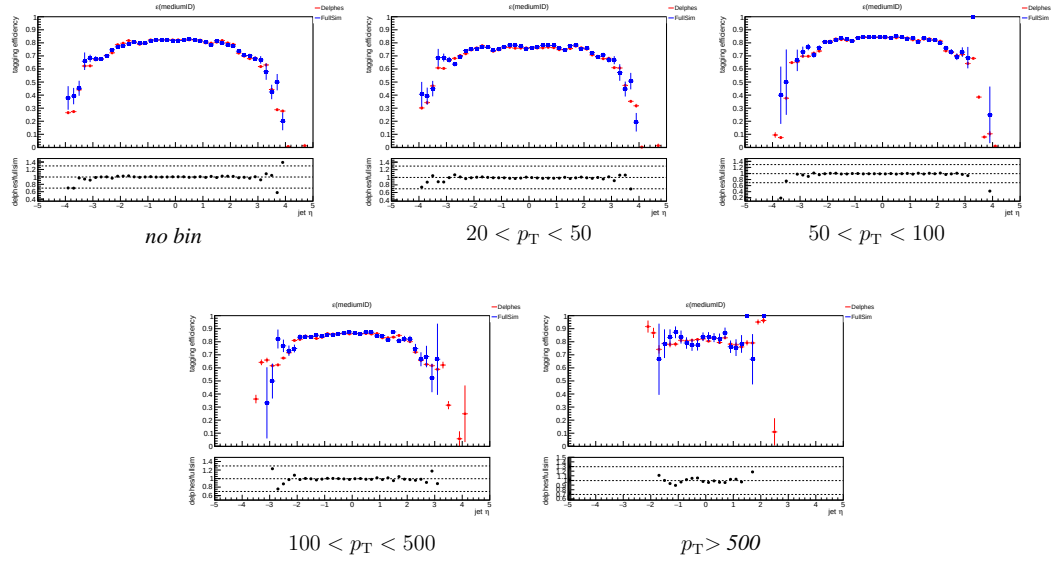


Figure 134: Delphes validation for jets, b-tagging rate as a function of η in various p_T bins, for mediumID jets.

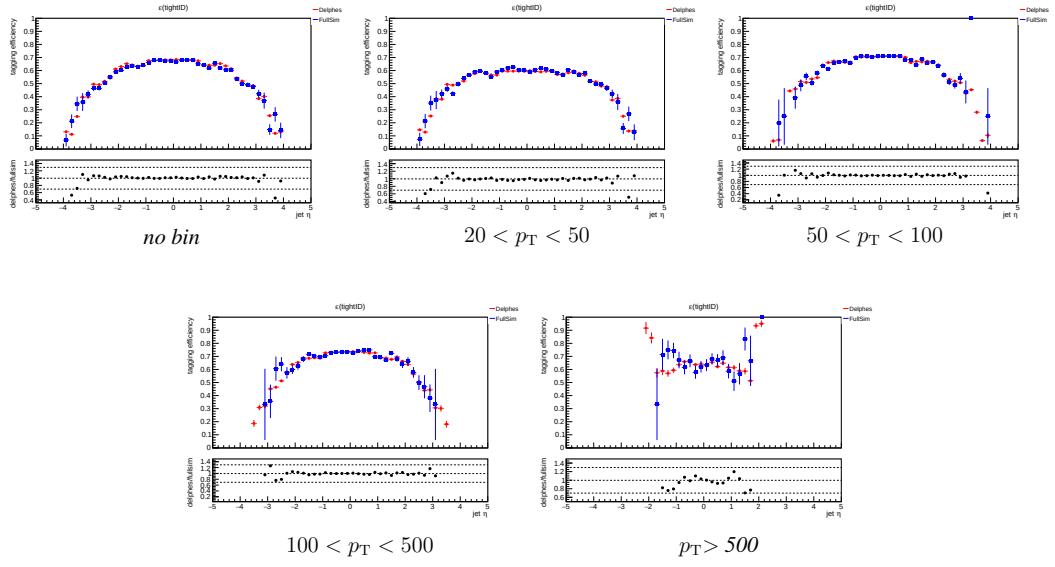


Figure 135: Delphes validation for jets, b-tagging rate as a function of η in various p_T bins, for tightID jets.

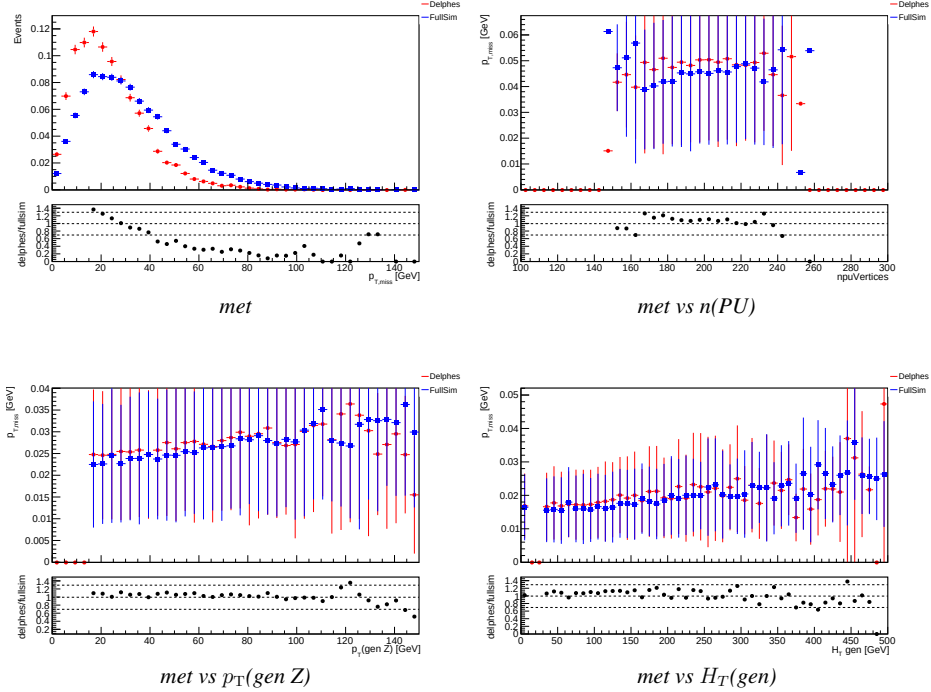


Figure 136: Delphes validation for MET.

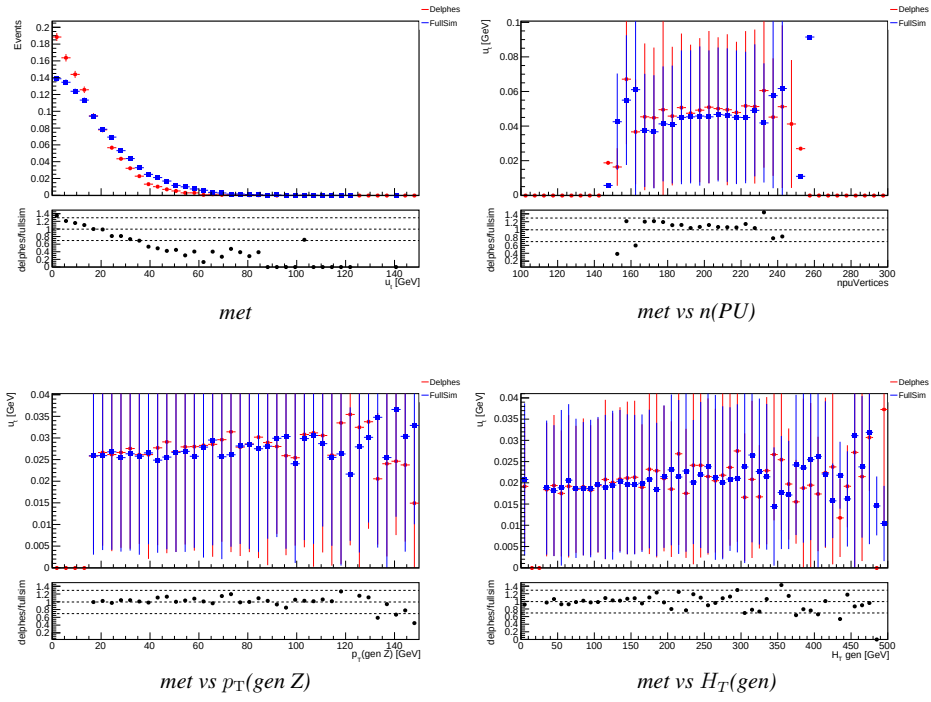


Figure 137: Delphes validation for MET, transverse projection met_t .

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