

SEARCH FOR HEAVY FCNC QUARKS AT 13 TeV pp COLLISIONS AT THE LHC

by

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ABSTRACT

SEARCH FOR HEAVY FCNC QUARKS AT 13 TeV pp COLLISIONS AT THE LHC

In this thesis, we describe a search for heavy iso-singlet quarks that is foreseen by F. Gürsey, P. Sikivie, P. Ramond's E_6 grand unification model, through the $pp \rightarrow D\bar{D}X \rightarrow HjZjX \rightarrow 4j2\ell X$ flavor-changing neutral current decay channel. We use data from proton-proton collisions at 13 TeV center-of-mass energy corresponding to 36.1 fb^{-1} integrated luminosity that have been collected during 2015-2016 with the ATLAS Detector at the Large Hadron Collider. A cut-based selection algorithm is used to choose four jets and two opposite-sign same-flavor leptons, which are used to reconstruct the Z boson. No significant excess beyond SM predictions is observed. The lower limit of $1526.2_{-14.6}^{+12.3} \text{ GeV}$ is set on the mass of E_6 quark with 95% confidence-level by CL_S method.

ÖZET

ATLAS ALGICI İLE E_6 BÜYÜK BİRLEŞİM TEORİSİ TARAFINDAN ÖNGÖRÜLEN AĞIR ISO-SINGLET QUARKLARININ $H J Z J$ BOZUNUM KANALINDA ARANMASI

Bu tez F. Gürsey, P. Sikivie, P. Ramond tarafından geliştirilmiş olan E_6 büyük birleşme kuramının öngördüğü ağır izo-singlet kuarklar $pp \rightarrow D\bar{D}X \rightarrow H_j Z j X \rightarrow 4j2\ell X$ çeşni değiştiren yüksüz akım kanalında aranmıştır. Büyük Hadron Çarpıştırıcısı'ndaki ATLAS algıcında 2015 ve 2016 yılları süresince 13 TeV kütle merkezi enerjisinde ve 36.1 fb^{-1} toplam entegre ışınığında çarpıştırılan pp verisi kullanılmıştır. Z bozonu aynı çeşnili leptonları seçmek için ardışık seçim algoritması kullanılmıştır. Z bozonu leptonik olarak yapılandırılmıştır. Aradığımız sinyale dair Standart Model'in öngördüğünden bir sapma gözlenmemiştir. CL_S yöntemi kullanılarak E_6 modelinin öngördüğü ağır kuarkların kütlesi $1526.2_{-14.6}^{+12.3} \text{ GeV}$ 'e kadar %95 güvenilirlik seviyesinde dışlanmıştır.

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LIST OF SYMBOLS

a_e	Anomalous Magnetic Moment Of Electron
A_μ	Electromagnetic Field
$b, \bar{b}$	Bottom Quark
$c, \bar{c}$	Charm Quark
d_0	Transverse Distance Between Track And The Beam Axis
D_H	The Reconstructed D Quark From A Higgs Boson
D_Z	The Reconstructed D Quark From A Z Boson
$d, \bar{d}$	Down Quark
$D, \bar{D}$	Down Type Iso-Singlet Quark
E_T	Transverse Energy
E_T^{miss}	Missing Transverse Energy
$e, \bar{e}$	Electron (Lepton)
H	Higgs Boson
j	Jet
ℓ	Lepton
L	Lagrangian
$\mathcal{L}$	Luminosity
m	Mass
m_{Higgs}^{real}	Nominal Mass Of The Higgs Boson
$m_{D_H}^{reco}$	Mass Of The Reconstructed D_H Quark Candidate
$m_{D_Z}^{reco}$	Mass Of The Reconstructed D_Z Quark Candidate
m_{Higgs}^{reco}	Mass Of The Reconstructed D_H Quark Candidate
p_T	Transverse Momentum
$p_T^{LeadingJet}$	Transverse Momentum Of The Leading Jet
$p_T^{SubleadingJet}$	Transverse Momentum Of The Subleading Jet
p	Proton
q	Quark
R	Radius Of A Particle Cone

$s, \bar{s}$	Strange Quark
$t, \bar{t}$	Top Quark
$u, \bar{u}$	Up Quark
$W^\pm$	W Boson With + Or – Electrical Charge
z_0	Longitudinal Distance Between Track And Beam Axis
Z	Z Boson
γ^μ	Dirac Matrices
η	Pseudorapidity
θ	Polar Angle
$\mu, \bar{\mu}$	Muon (Lepton)
$\nu_\mu, \bar{\nu}_\mu$	Muon Neutrino
$\nu_\tau, \bar{\nu}_\mu$	Tau Neutrino
σ_{D_H}	Reconstructed Width Of The D_H Quark
σ_{D_Z}	Reconstructed Width Of The D_Z Quark
σ_H	Reconstructed Width Of The Higgs
$\tau, \bar{\tau}$	Tau (Lepton)
ϕ	Azimuthal Angle
ψ	Fermion Field
ϕ	Mixing Between The d And The D Quarks
$\chi^2_{E_6}$	Calculated χ^2 Value For The E_6 Quark
χ^2_{Higgs}	Calculated χ^2 Value For The Higgs Boson

LIST OF ACRONYMS/ABBREVIATIONS

ATLAS	A Toroidal LHC ApparatuS
b	barn
CAST	The CERN Axion Solar Telescope
CERN	The European Organization For Nuclear Research
CKM	Cabbibo-Kobayashi-Maskawa
CMS	Compact Muon Solenoid
CSC	Cathode Strip Chamber
CTP	Central Trigger Processor
Cu	Copper
DxAOD	Derived Auxiliary Analysis Object Data
ESD	Event Summary Data
EWT	Electro-Weak Theory
GUT	Grand Unified Theory
ID	Inner Detector
IP	Interaction Point
LAr	Liquid Argon
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty
LHCf	Large Hadron Collider forward
LINAC	Linear Accelerator
L1Muon	Level 1 Muon Trigger
L1Calo	Level 1 Calorimeter Trigger
MC	Monte Carlo
MoEDAL	The Monopole & Exotics Detector At The LHC
MS	Muon Spectrometer
NLO	Next-to-Leading Order
OSSF	Opposite-Signed Same-Flavored
QED	Quantum Electrodynamics

PS	Proton Synchrotron
PSB	Proton Synchrotron Booster
RF	Radio Frequency
RPC	Resistive Plate Chamber
SCT	SemiConductor Tracker
SM	Standard Model
SPS	Super Proton Synchrotron
TGS	Thin Gap Chamber
TRT	Transition Radiation Tracker
VLQ	Vector Like Quark
W	Tungsten
xAOD	Auxiliary Analysis Object Data

1. INTRODUCTION

The Large Hadron Collider (LHC) is currently the world's highest energy particle collider with a 13 TeV center-of-mass energy. With the recent discovery of the Higgs boson [13, 14] by the ATLAS and CMS Collaborations operating on the LHC, new opportunities in the search for new physics have emerged. This thesis documents a search for heavy iso-singlet quarks foreseen in the E_6 grand unified theory (GUT) using the newly discovered Higgs boson in data collected with the ATLAS Detector. The Standard Model (SM) is the centerpiece of particle physics with its many successes [13–16]. However, it lacks explanations for some of the observed phenomena [17–19]. One of its crucial shortcomings is the presence of many free parameters, which can only be determined through experiments. The traditional way of reducing the number of free parameters is requiring that the theory is more symmetric at higher energy scales which leads to unification of fundamental forces. One such grand unified theory is based on the symmetry group E_6 , which predicts a heavy iso-singlet quark for each family of SM fermions. These new quarks can decay with the process of $D \rightarrow Vj$ where V denotes a $W^\pm$, Z or H . In this study, we analyzed $pp \rightarrow D\bar{D}X \rightarrow HjZjX \rightarrow 4j2\ell X$ flavor changing neutral current channel with the data gathered at the center-of-mass energy of $\sqrt{s} = 13$ TeV with 36.1 fb^{-1} total integrated luminosity. Monte Carlo (MC) simulations are used to model the SM background, as well as the signal signatures from heavy iso-singlet quarks at different mass values. A cut based selection algorithm is used for focusing onto a signal-rich region, and a χ^2 algorithm is utilized to reconstruct the best possible candidate for heavy D quarks. For limit setting purposes, the software TRExFitter [20] is used, which implements the CL_S method [21].

2. THE STANDARD MODEL AND BEYOND

The SM is the established centerpiece of modern particle physics. It has a known success on describing elementary particles and their interactions to great precision (Section 2.1), but it also has its shortcomings on answering various questions and observed phenomena.

2.1. The Standard Model of Particle Physics

The aim of particle physics is to gain a better understanding of the fundamental building blocks of the Universe and their interactions. A series of ground-breaking theoretical works like the unification of the electromagnetic and weak interactions into a unified interaction, called electroweak, by Glashow [22] in 1960 and the formulation of the Higgs mechanism [23–25] and its incorporation into electroweak theory by Weinberg [26], and Salam [27], led to the creation of the SM of particle physics in the mid 1970s.

One of the most impressive successes of SM is the calculation of the anomalous magnetic moment of the electron, a_e , which is compatible with the experimental measurement up to ten digits. Theoretical value [28] of $a_e(\text{theory})$ is $159652181.78(77) \times 10^{-12}$, while the experimental value [29] is $a_e(\text{experimental}) = 159652180.73(28) \times 10^{-12}$. Also, predictions made through the SM motivated successful searches for previously unknown particles. For example, $W^\pm$ [30, 31] and Z^0 [32, 33] bosons were discovered at Super Proton Synchrotron (SPS) in 1983, top quark [34, 35] at Fermilab in 1995, and the Higgs boson [13, 14] at the LHC in 2012.

2.1.1. Particle Content

All known matter is composed of a limited number of elementary particles called quarks and leptons. Interaction between these particles are mediated through force carriers. All quarks and leptons are fermions, i.e., they have half-integer spin. All force carriers are bosons, i.e., they carry integer spin. Fermions follow Fermi-Dirac statistics and they obey the Pauli exclusion principle which forbids them to be on the exact same quantum state in the same quantum system simultaneously. On the other hand, bosons follow Bose-Einstein statistics and they do not have such restrictions. Furthermore, they tend to occupy the same ground state at temperature very close to absolute zero.

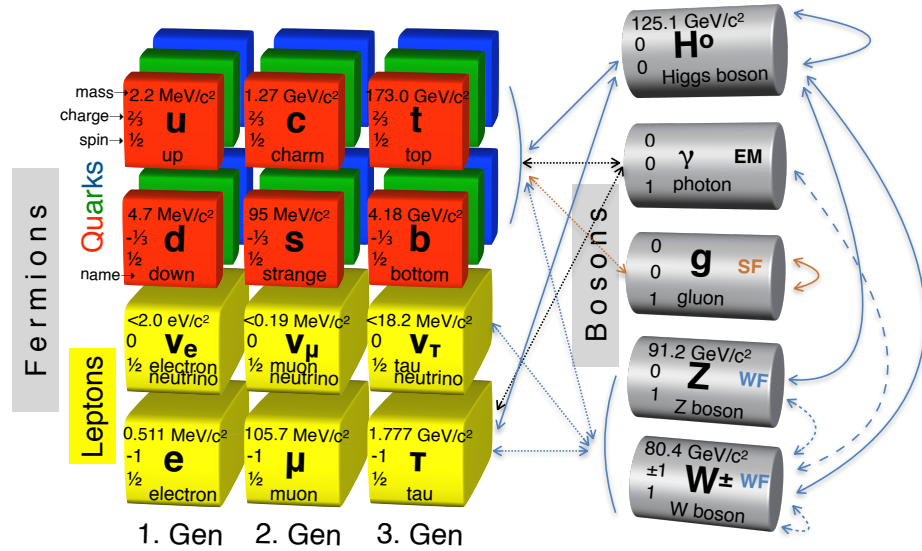


Figure 2.1: The elementary particles that are present in the SM of particle physics. [1]

All existing fundamental fermions are divided into three generations. Each generation consists of positively charged quark ($+\frac{2}{3}e$), negatively charged quark ($-\frac{1}{3}e$), a charged lepton, and its corresponding lepton neutrino. The differences in generations are only the mass of particles. In a generation, there are two doublets: quarks form one doublet and leptons form the other doublet. Quarks can be of one of six flavors,

with the quark doublets being $\begin{pmatrix} u \\ d \end{pmatrix}$, $\begin{pmatrix} s \\ c \end{pmatrix}$, and $\begin{pmatrix} t \\ b \end{pmatrix}$. The lepton doublets are $\begin{pmatrix} e \\ \nu_e \end{pmatrix}$, $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$, and $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$.

Quarks also carry color charge in addition to electric charge. There are three types of color charge: blue, green, red. Quarks are bound to color-neutral hadronic states by strong interaction: they can be found in the form of either baryons (qqq where all of them has different color charge), or mesons ($q\bar{q}$, a quark and anti-quark pair with same but opposite colors) or possible exotic states (such as pentaquarks). The strong interaction is mediated with massless gluons, g , which only interact with color-charge carrying particles; hence, quarks and themselves. The weak force is mediated with W^+ , W^- , Z^0 massive gauge bosons. They couple to every fermionic particle in the SM. The Z boson cannot be responsible for flavor changing process; hence, it only decays to a fermion anti-fermion pair. Electromagnetic interactions are transmitted with massless gauge boson, γ , and γ couples to all particles with electric charge. The last boson and a huge success of the SM is the electrically neutral, colorless, spin-0 scalar particle: the Higgs boson. It couples to all elementary particles with mass. An overview of all particles can be found in Figure 2.1.

2.1.2. Electroweak Theory

Electroweak theory (EWT) is unification of quantum electrodynamics (QED) and the weak interaction theory at the energy scale $\mathcal{O}(100)$ GeV, which are fundamentally different at low energy levels. The symmetry group of the gauge theory is $SU(2)_L \otimes U(1)_Y$ where L denotes the fact that the $SU(2)$ interaction is only for left-handed fermions and right-handed anti-fermions, and Y represents the hypercharge. The gauge bosons of EWT, W^+ , W^- , Z^0 , and γ interact with each other through the following couplings: $WW\gamma$, $WW\gamma\gamma$, $WWZ\gamma$, WWZ , $WWZZ$, $WWWW$ and charge conservation is implied.

The Feynman diagrams for the fundamental interactions governed by EWT are shown in Figure 2.2.

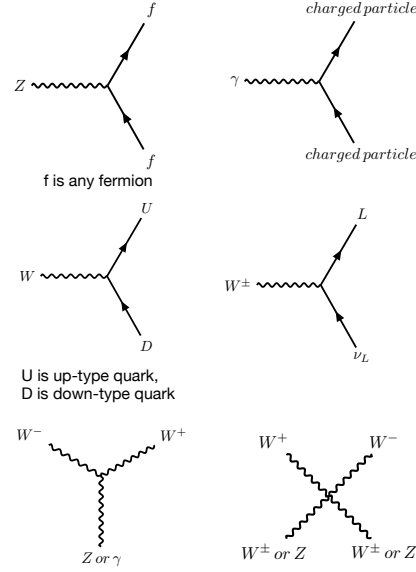


Figure 2.2: The Feynman diagrams of fundamental EWT interactions.

The interaction term of W boson with quarks is

$$L_{Wq} = \frac{ig_2}{\sqrt{2}} (V_{mn} \bar{u}_{m,L} \gamma^\mu d_{n,L} W_\mu^+ + (V^\dagger)_{mn} \bar{d}_{m,L} \gamma^\mu u_{n,L} W_\mu^-) \quad (2.1)$$

where V_{mn} represents the Cabbibo-Kobayashi-Maskawa (CKM) matrix. CKM matrix gives information on the possibility of flavor-changing weak decays between quarks. It is very close to being a diagonal unitary matrix, but not exactly; thus, it is also called the quark mixing matrix; since, it quantifies the strength of inter-generational quark interactions. CKM matrix is given as follows:

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}. \quad (2.2)$$

The interaction term of W bosons with leptons is

$$L_{Wl} = \frac{ig_2}{\sqrt{2}}(\bar{\nu}_{m,L}\gamma^\mu\ell_{m,L}W_\mu^+ + \bar{\ell}_{m,L}\gamma^\mu\nu_{m,L}W_\mu^-). \quad (2.3)$$

Finally, the interaction between fermions and electroweak neutral gauge bosons, Z^0 and γ , is described with

$$L_{(Z/\gamma)\bar{\psi}} = ig_{EM}\bar{\psi}_m\gamma^\mu Q\psi_mA_\mu + ig_Z\bar{\psi}_m\gamma^\mu\left(\frac{1+\gamma^5}{2}T_3 - Q\sin^2\theta_W\right)\psi_mZ_\mu. \quad (2.4)$$

It is important to note that, unlike charge carrying W bosons, Z bosons cannot change flavor or type of the fermions. So, flavor changing neutral currents are forbidden at the tree level within the SM.

2.1.3. Quantum Chromodynamics

Quantum chromodynamics (QCD) describes the strong interaction between quarks and gluons. Similar to QED, quarks carry a color charge that makes them couple to gluons, i.e., massless gauge bosons of QCD. Unlike QED, gluons also carry color and anti-color charge which make them couple to themselves. This causes much richer spectrum for possible QCD vertices, and few of them are shown in Figures 2.3 2.4 2.5. Color charges are represented with red, green and blue and their opposites, and the total charge must be preserved at each vertex as in the case of electrical charge. Gluons can be found in eight physical states while a naive expectation from counting color-anticolor pairs would predict nine physical states. However, the singlet state for gluon, $(r\bar{r} + b\bar{b} + g\bar{g})/\sqrt{3}$, is forbidden in QCD; since the color-singlet stable, “colorless”, particles, i.e., hadrons, would be able to interact over a long distance if gluons could also be in a color-singlet state. On the other hand, the range of strong interaction is

limited roughly to the size of the proton; hence, gluons cannot be found in the color-singlet state. This color-octet structure is described by $SU_C(3)$ where C stands for color.

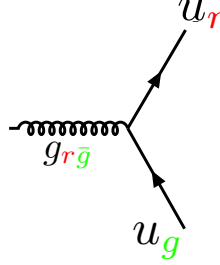


Figure 2.3: Quark-gluon interaction.

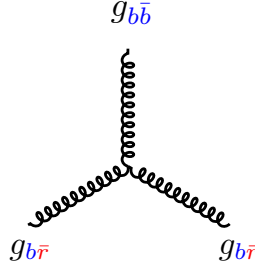


Figure 2.4: Gluon-gluon interaction.

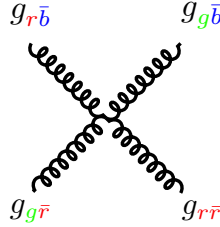


Figure 2.5: Glueball.

The dynamics between quarks and gluons are governed with following Lagrangian

$$L_{QCD} = \psi_i (i(\gamma^\mu D_\mu)_{ij} - m\delta_{ij}) \psi_j - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} \quad (2.5)$$

where $\psi_i(x)$ is the quark field, D_μ is gauge covariant derivative, γ^μ is Dirac matrices and $G_{\mu\nu}^a$ represents the gauge invariant gluon field strength tensor. $G_{\mu\nu}^a$ is equal to $G_{\mu\nu}^a = \partial_\mu \mathcal{A}_\nu^a - \partial_\nu \mathcal{A}_\mu^a + gf^{abc} \mathcal{A}_\mu^b \mathcal{A}_\nu^c$.

Quarks carry non-integer electrical charge, and no one has ever observed a free fractional charge, yet. This is known as the color confinement problem and it states that quarks cannot be observed alone, but they can rather be found in the form of mesons, $q\bar{q}$, or baryons, qqq . When we try to separate two quarks the coupling constant between them increases so much so that with the energy provided to increase the distance is enough to create new pair of quark and anti-quark which bounds to the initial quarks to form stable states. The idea is illustrated in Figure 2.6. At high energies, or at small distances, quarks and gluons can move freely. And at this scale, QCD processes can be calculated with perturbation theory. This is called as asymptotic freedom.

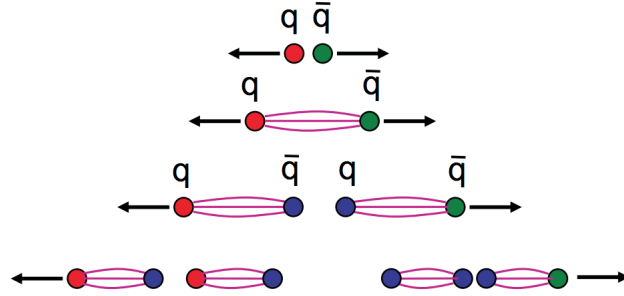


Figure 2.6: Formation of new quark anti-quark pair due to interaction between separating quarks.

2.1.4. Higgs Mechanism

The SM Lagrangian without the Higgs mechanism cannot predict any mass value for the gauge bosons, while $W^\pm$ and Z has mass of 80.39 GeV and 91.19 GeV, respectively. This is a big theoretical problem and in order to solve this problem, a scalar field that permeates all spacetime is added to the model which has non-zero value at its ground state; and therefore causes spontaneous symmetry breaking in electroweak symmetry. The simplest possible scalar field to address this problem is

$$\phi = \begin{bmatrix} \phi^+ \\ \phi^0 \end{bmatrix} \quad (2.6)$$

with ϕ^+ and ϕ^0 is complex scalar fields. The potential of this complex scalar field is

$$V(\phi^\dagger\phi) = \lambda(\phi^\dagger\phi)^2 - \mu^2\phi^\dagger\phi + \frac{\mu^4}{4\lambda^2} \quad (2.7)$$

where λ and μ^2 are real and positive. If these parameters are such that the ground state is not at zero but at a higher value, i.e., the minima of the potential is for $\phi^\dagger\phi = \frac{\mu^2}{2\lambda} \equiv \frac{\nu^2}{2}$, we get a non-zero vacuum expectation value. In such a scenario the potential looks like a Mexican hat as depicted in Figure 2.7.

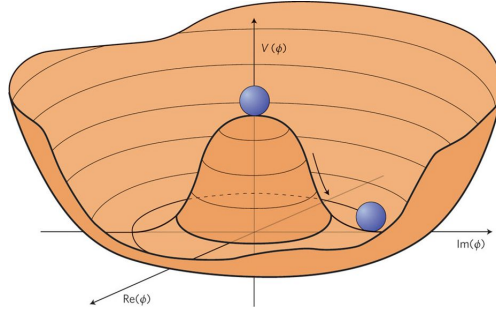


Figure 2.7: Mexican hat potential of Higgs field.

This is how the excitation of that field with non-zero vacuum expectation value, i.e, the Higgs boson, gain mass. Then, the other fundamental particles interact with the Higgs field to obtain their masses. After some calculations which can be followed here [36], the masses of particles are defined as

$$M_W = \frac{g_2}{2}\nu \quad (2.8)$$

$$M_Z = \frac{\sqrt{g_1^2 + g_2^2}}{2}\nu \quad (2.9)$$

$$M_H = \sqrt{2\lambda}\nu. \quad (2.10)$$

Thanks to experimental values of mass of the W and Z bosons, we find ν to be 246 GeV.

2.2. The E_6 Model

Unification of underlying mechanisms of seemingly different phenomena has been encountered throughout history from unification of what makes apples fall down and what makes planets revolve around each other to unification of electromagnetic and weak theory. The SM of particle physics has its astonishing triumphs, but it is rather patchy theory with its 19 free parameters (not including the neutrino sector) that can only be fine-tuned with experiments. It is natural to expect all of these fundamental forces to unite at some high energy scale. One such theory is the E_6 model. E_6 GUT proposed by F. Gürsey and collaborators [37, 38] 40 years ago is still favored by Super String inspired Super Gravity Models [39] and requires the presence of new heavy particles at the TeV scale. For example, one heavy new iso-singlet quark for each SM quark family is predicted. Possible production means of $D\bar{D}$ quarks are presented in Figure 2.8.

These heavy quarks are expected to interact with the $W^\pm$, Z and Higgs bosons according to Lagrangian from the article [40]. Such a heavy iso-singlet quark is expected to decay into quarks of its family via the mechanism $D \rightarrow Vj$ where V denotes a W^{pm} , Z or H citeSG,Mehdiyev. Branching ratios of the iso-singlet quark decaying into different final states are shown in Figure 2.9 as a function of its mass. Let us mention that the branching ratios depend on the D quark mass only, whereas the decay widths are proportional to $\sin^2 \phi$ where ϕ is the mixing angle between the left component of D and d quarks. The limits on ϕ can be obtained from the precision measurements of the 3×3 CKM matrix elements assuming that its 3×4 extension has the sum of the squares of the elements of a row equal to one. Although the upper limit 0.045 [41] is used throughout this work, the results are essentially insensitive to $\sin \phi$ as the pair production considered here proceeds mostly via gluon fusion.

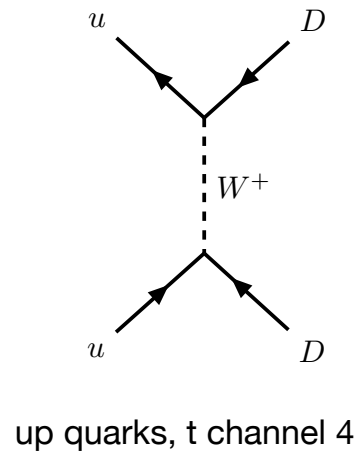
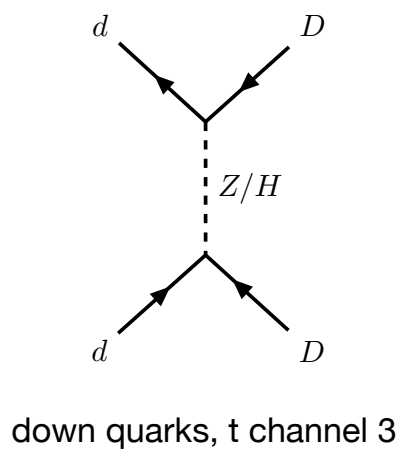
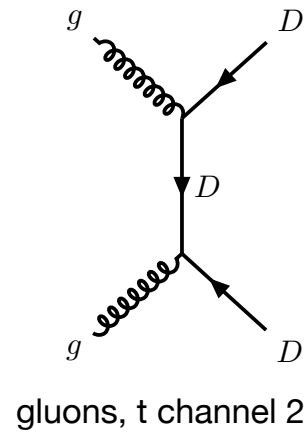
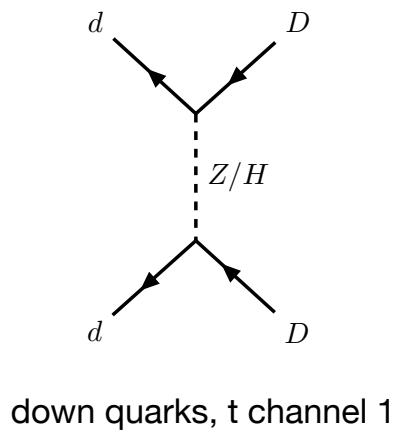
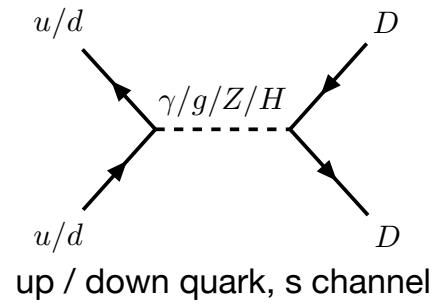
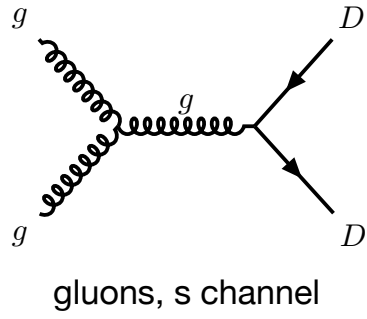


Figure 2.8: Possible pair production channels for heavy D quark.

2.3. The Search For Iso-Singlet Quark

In this study, a search for pair-produced vector-like (iso-singlet) down type heavy quarks is performed in the final state $pp \rightarrow D\bar{D}X \rightarrow H j Z j X \rightarrow 4j 2\ell X$. There is no requirement in the model for the lightest of the iso-singlet quarks to be the one associated with the first generation, so here D denotes whichever of the new quarks is the lightest amongst the three. Data collected by the ATLAS detector in 2015 and 2016, when LHC was colliding protons at $\sqrt{s} = 13$ TeV, are used, with total integrated luminosity of 36.1 fb^{-1} .

In Figure 2.10, representative Feynman diagram of pair-produced iso-singlet quarks that decay into H and Z bosons is shown. In this study we focus on the final state with 4 jets and a charged lepton pair. Since two of these jets are direct decay products of the iso-singlet quarks, they are expected to have high transverse momenta. We call these *prompt* jets. The other two jets are likely to be b -tagged, as the SM Higgs boson has $\sim 60\%$ decay rate to a $b\bar{b}$ pair.

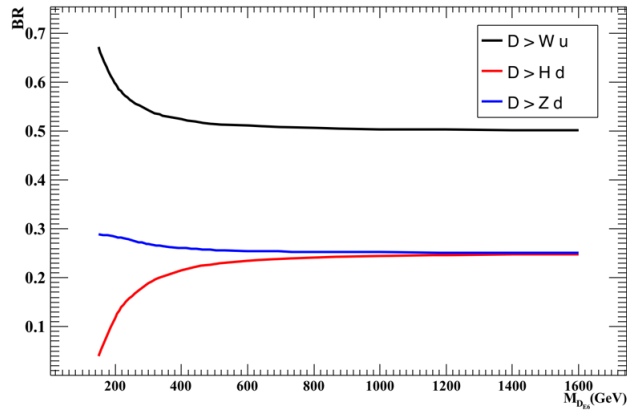


Figure 2.9: Branching ratios vs the mass of the iso-singlet quark.

Pair production cross-section of iso-singlet quarks is shown in Figure 2.11. At a mass of 1000 GeV pair production cross section of iso-singlet quarks is 39.9 fb at the NLO level and the iso-singlet quark pair has a 12.5% probability of decaying into a $H j Z j$ among all the possible decay channels. The Z boson, in turn has a rate of 3.36% to decay in to an electron or muon pair, each. Therefore the probability of an

iso-singlet quark pair decaying into our chosen final state is 0.84% (0.50% if we require Higgs daughters to be b quarks). Hence at 36.1 fb^{-1} , for a 1000 GeV iso-singlet quark, ATLAS would be expected to have recorded about ≈ 11 (≈ 7 for b jet final state) signal events.

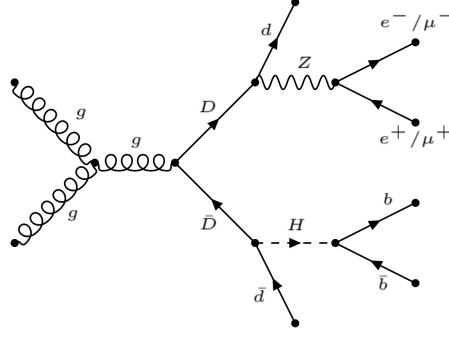


Figure 2.10: Iso-Singlet quark pair decaying in the H - Z channel, with the Z boson later decaying into a pair of charged leptons, and the H boson decaying into a pair of b -jets.

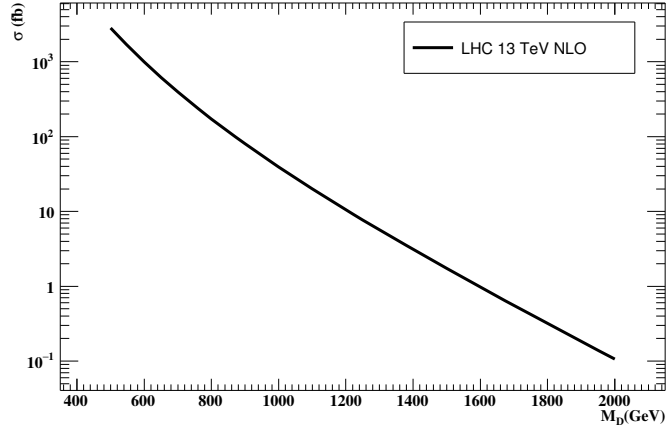


Figure 2.11: Pair production cross-section of iso-singlet quarks at the LHC.

The total width of the D quark as a function of its mass (obtained from the generator COMPHEP 4.5.2) is shown in Figure 2.12 for $\sin\phi = 0.045$, where ϕ is the mixing angle between left component of D and d quarks. It is seen that $\Gamma_D = 1.33 \text{ GeV}$ and 4.50 GeV for $m_D = 1000 \text{ GeV}$ and 1500 GeV , respectively, so in the analysis detector effects are dominant in the reconstructed mass resolutions.

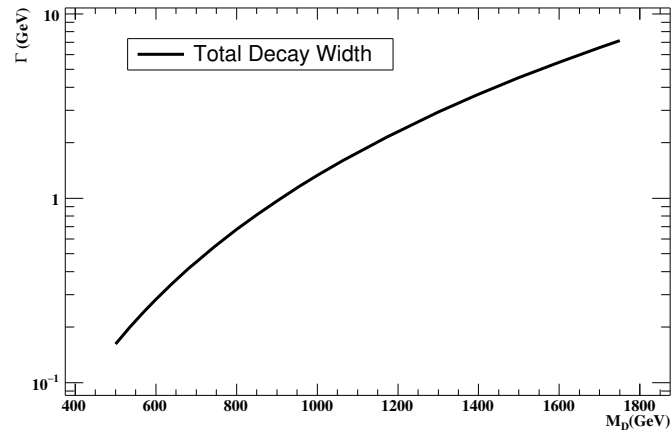


Figure 2.12: The generator-level width of the E_6 iso-singlet quarks, obtained with COMPHEP.

3. THE ATLAS EXPERIMENT AT LARGE HADRON COLLIDER

CERN, the European Organization for Nuclear Research, is the world's largest particle physics laboratory located at Franco-Swiss border near Geneva, Switzerland with its over 2600 scientific, technical, and administrative staff and with its vast community of users around 12200 [42] scientists from institutes all over of the world. It hosts various accelerators, decelerators (LHC, LINAC 2, The Antiproton Decelerator, etc.) and detectors (ATLAS, CMS, CAST, etc.). The Large Hadron Collider (LHC) and the ATLAS Experiment are the main experimental setups used in this thesis and explained in detail in the following sections.

3.1. The Large Hadron Collider

The Large Hadron Collider [43–45] with its 26659 m circumference is the largest particle collider built so far, and is the single biggest machine on the earth. It is located at the tunnel approximately 100 m under ground which was previously occupied with Large Electron Positron (LEP) collider [46] and operated by CERN. It is originally designed to collide at the center of mass energy $\sqrt{s}=14$ TeV,¹ but due to superconductivity of magnets highly sensitive to energy provided [47], it is unable to reach such energy. The LHC is designed for proton-proton, proton-ion, and ion-ion collisions for various research. The particles are accelerated in bunches, and the separation between the bunches are about 24.95 ns, or 7.5 m [48].

At the LHC, there are seven experiments using the proton or ion beams. Four of them are the big detectors located at the interaction point of the LHC beams: A Large Ion Collider Experiment (ALICE), ATLAS, CMS, Large Hadron Collider beauty (LHCB). ATLAS and CMS are the biggest of them, and they are designed to

¹ $\sqrt{s}$ represents the Mandelstem variable s , which is a measure of incoming and outgoing particles' four momentum.

Table 3.1: LHC center of mass collision energy since the beginning of the operation.

year	$\sqrt{s}$
2009	≤ 7 TeV
2010-2011	7 TeV
2012 ≥ 2	8 TeV
2015-2018	13 TeV

Table 3.2: Summary of current status of LHC [10].

Quantity	Number
Circumference	26659 m
Dipole operating temperature	1.9 K
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities (per beam)	8

study the largest range of physics phenomenon possible. ALICE and LHCb focuses on rather specialized topics: ALICE records proton-lead collisions which creates quark-gluon plasma in order to study early stages of the Big Bang, and LHCb tries to find the reason for matter antimatter asymmetry. Then, there are two detectors to investigate the forward particles which just brush past each other instead of meeting head on when the beams collide: LHCf (Large Hadron Collider forward) and TOTEM (Total Elastic and diffractive cross section measurement). The seventh, and the latest experiment MoEDAL (Monopole and Exotics Detector at the LHC) is searching for magnetic monopoles [49].

3.1.1. Luminosity and Pileup

Besides the energy of the beam, another important parameter of a collider for its discovery power is instantaneous luminosity as it provides a link between interaction

rate and cross section for certain physical process.

$$\frac{\Delta N}{\Delta t} = \mathcal{L} \times \sigma. \quad (3.1)$$

Luminosity is defined as how many particles pass through per unit area per unit time. In high-energy physics, we express luminosity in terms of barns where a barn is 10^{-28} m. Here, the cross section means the possibility of observing certain scattering process rather than slice of an physical object.

For head-on collisions where we can represent the distribution of bunches of protons in terms of Gaussian distribution in all profiles, luminosity can be defined as

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} \quad (3.2)$$

where N_1 and N_2 represents intensity of two colliding bunches, f is the collision frequency, N_b is number of bunches in a beam, σ_x and σ_y is measure of spread of the beam with the assumption of equal beams, i.e.: $\sigma_{1x} = \sigma_{2x}$, $\sigma_{1y} = \sigma_{2y}$ and $\sigma_{1s} = \sigma_{2s}$. Here, x and y represents the Cartesian coordinate system, and s is the length of the bunch.

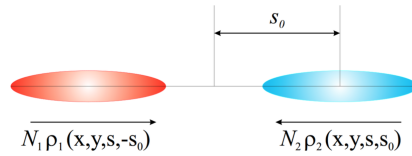


Figure 3.1: The representation of head-on collision of two particle bunches at s_0 [2].

Initially, LHC is designed to deliver $\mathcal{L}=1.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [49], but at 2016 it has surpassed that value and reached up to $\mathcal{L}=1.38 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Peak values for instantaneous luminosity at 2015 and 2016 pp data is plotted in the Figures 3.2 3.3.

In this thesis, we have used full 2015 and 2016 pp collision data. The total integrated luminosity delivered by LHC for 2015 is $L_{2015} = \int \mathcal{L} dt = 4.2 \text{ fb}^{-1}$, and

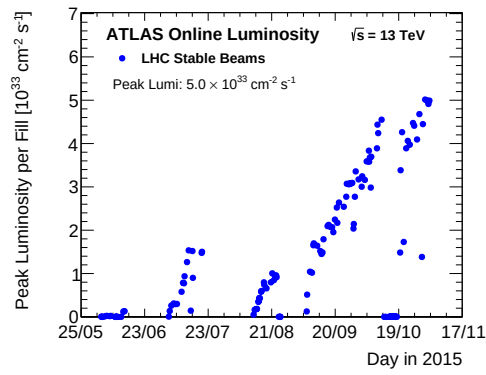


Figure 3.2: Instantaneous luminosity for 2015 [3].

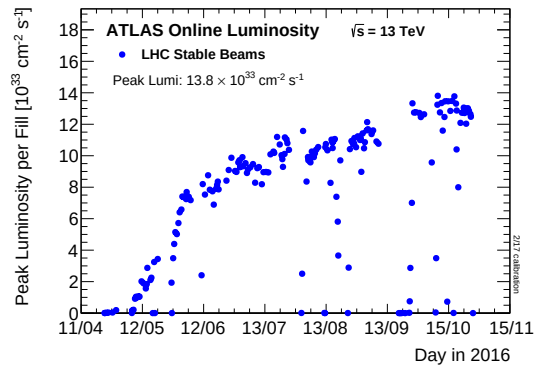


Figure 3.3: Instantaneous luminosity for 2016 [3].

3.2 fb^{-1} of this value is good for physics analysis. For 2016, LHC $L_{2016} = \int \mathcal{L} dt = 38.5 \text{ fb}^{-1}$, and 32.9 fb^{-1} of this value is used for physics analysis. Overall, the integrated luminosity for half run 2 recorded by ATLAS experiment and used in physics analysis is $\int \mathcal{L} dt = 36.1 \text{ fb}^{-1}$ as it can be seen in Figure 3.4. Colliding particles at such high

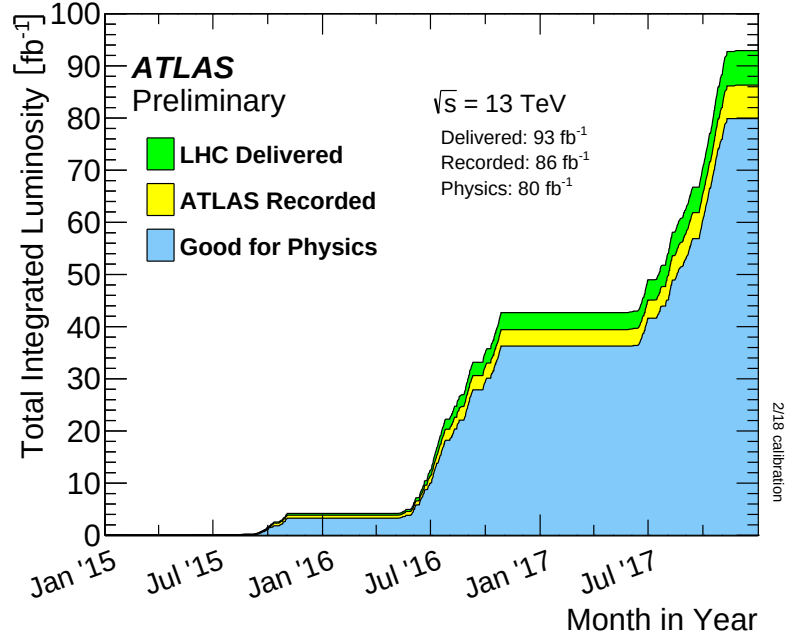


Figure 3.4: The representation of head-on collision of two particle bunches at s_0 [3]

luminosity come at the expense of a concept called: pile-up. There are two types of main source of pile-up; one of them is in-time pile-up and the other one is out-of-time pile-up. The in-time pile-up is due to additional pp collisions in a single bunch crossing while the so-called out-of-time pile-up is due to signals from collisions coming out of other bunch crossings. This occurs when the detector and/or electronics integration time is significantly larger than the time between crossings. As it can be seen from Figure 3.5, for 2015 the average number of interactions per crossing is $\langle \mu \rangle_{2015} = 13.7$, and for 2016 $\langle \mu \rangle_{2016} = 24.9$. The larger the number of simultaneous interactions, the more challenging the event topology for later analysis, as many interesting physical processes get drowned in additional detector activity caused by pile-up.

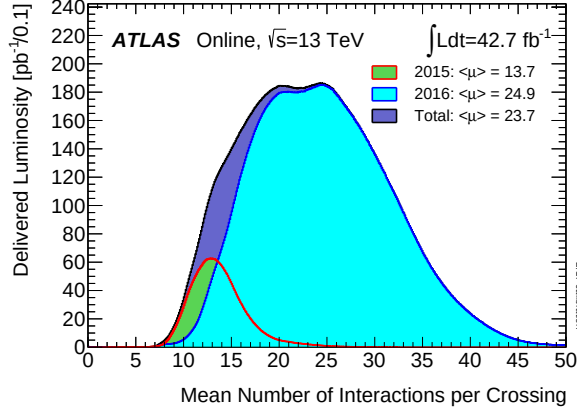


Figure 3.5: Mean number of interactions per beam crossing: i.e. pile-up. [3]

3.1.2. Acceleration Chain and Filling Scheme

It all starts from a bottle full of hydrogen. In order to strip of electrons from the hydrogen gas, high electric field is applied which results in freed protons. The protons first get accelerated in the linear accelerator called LINAC 2 to 50 MeV before they move in to series of cyclic particle accelerators. Secondly, they are accelerated to 1.4 GeV with the Proton Synchrotron Booster (PSB). Afterwards, they are injected into the Proton Synchrotron (PS) [50], brought up to 26 GeV and further accelerated to 450 GeV by the Super Proton Synchrotron (SPS). Eventually, the proton bunches get injected into the LHC, in which they are brought to unprecedented 6.5 TeV in about 20 minutes [51]. Unlike particle-antiparticle colliders which requires single ring for both beams, LHC collides two beams of same sign. Therefore, there are two rings with counter-rotating highly collimated beams which came into contact at four interaction points where four detector experiments are located: ATLAS, CMS, ALICE, LHCb. 8 radio-frequency (RF) cavities per beam is used to accelerate the particles. In order to obtain the circular shape of the collider, 1232 superconducting magnetic dipoles are used at 1.9 K. They are cooled to such low temperature with help of 150 tons of liquid helium. They create magnetic field at the strength of 8.33 T. In order to increase the quality of the beam by focusing 392 quadrupole magnets and additional higher order multipole magnets are used. After all this acceleration cycles, two proton bunches at transverse spread of $15\ \mu\text{m}$ and at the length of 7 cm come into contact at ATLAS.

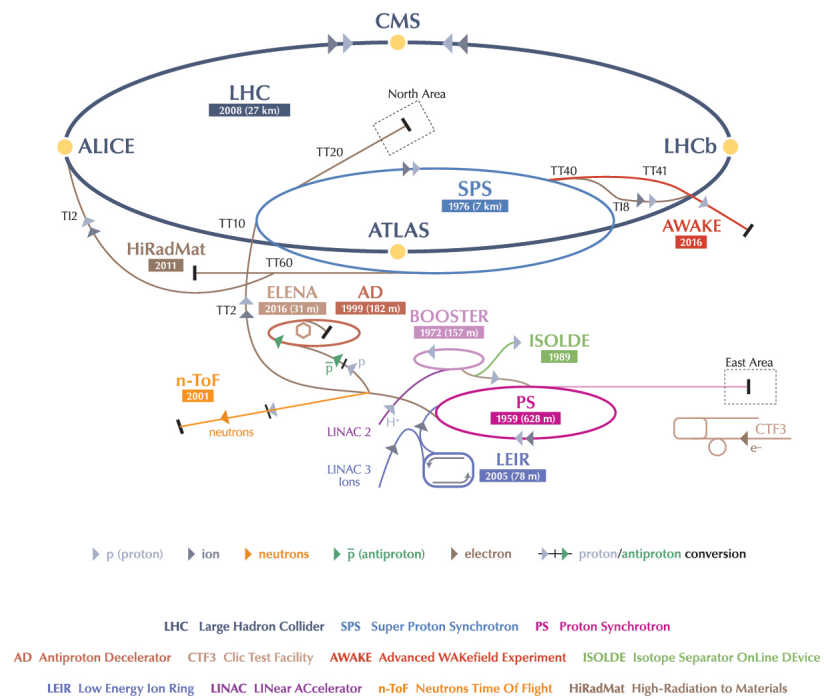


Figure 3.6: The CERN Accelerator Complex [4].

Table 3.3: Comparison of design values and the period where data used in this thesis of LHC [11, 12].

Quantity	Design Value	2015	2016
Proton energy (GeV)	7000	6500	6500
Peak luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	1.0×10^{34}	0.5×10^{34}	1.38×10^{34}
Protons per bunch	1.15×10^{11}	1.2×10^{11}	1.1×10^{11}
Maximal number of bunches	2808	2244	2220
Bunch spacing (ns)	24.95	24.95	24.95
Simultaneous collisions	23	13.7	24.9

3.2. The ATLAS Detector

ATLAS detector [52,53] is one of the two multi-purpose detectors at LHC designed for approving the Standard Model predictions, and looking for new physics beyond the Standard Model. At such high center-of-mass energy and luminosity, it is a great tool to look for new particles that may emerge at TeV scale, to study high energy spectrum of the Standard Model like top quark and flavor physics, or to make high-precision measurements on QCD and electroweak interactions. It is the largest of all experiments at LHC with its 25 m diameter and 44 m long cylindrical design at the weight of 7000 tons. It is situated at one of the primary IPs. Computer-generated representation can be found at Figure 3.7.

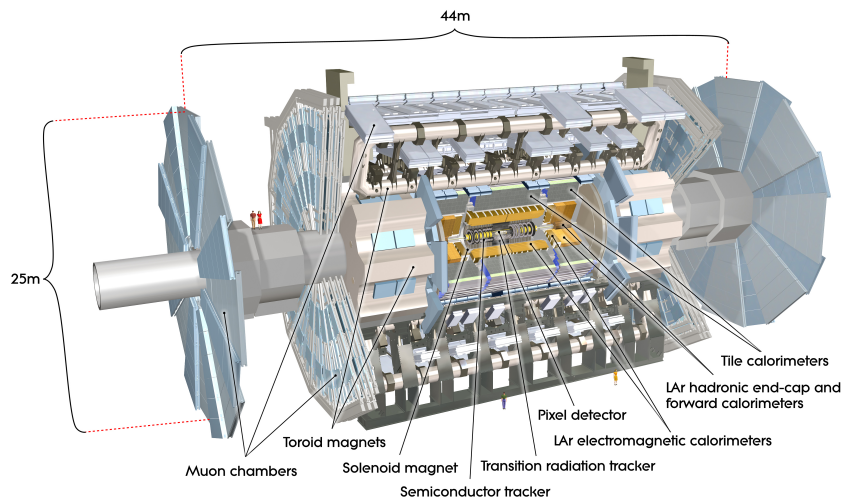


Figure 3.7: The ATLAS Experiment. [5]

3.2.1. The Detector Design

ATLAS mainly composed of three layers of concentric subsystem. Moving out from the IP, particles will first move through the Inner Detector (ID) which consists of multiple tracking detectors for charged particles, then they will go through calorimeters where most particles get absorbed and their energy is evaluated. And finally, if anything left from collision, they will go through the Muon Spectrometer (MS) which is designed for measuring the trajectory of muons using muon chambers. The cen-

tral part of the detector parallel to beam line is called barrel, and the forward region perpendicular to the beam line is called end-cap region. The ID is designed for measuring charge and track of charged particles, and this is done by covering it with a thin solenoid superconducting magnet for bending the charged particles while they are moving through ID. The solenoid magnet system provides nearly homogeneous 2.0 T magnetic field through the center, but towards the windings it changes to 2.6 T. ATLAS takes its name from the second and larger magnetic system of it as it can be seen in Figure 3.8. The second system consists of 8 air-core barrel toroid magnets kept at 4.7 K which provides magnetic field up to 3.9 T for muon spectrometer, and 8 air-core end-cap toroid magnets providing magnetic field around 4.1 T [54, 55]. The two-fold magnetic system designed in order to achieve higher resolution for momentum of muons [56].

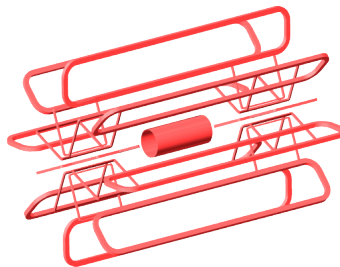


Figure 3.8: Magnetic system of ATLAS consists of a solenoid superconducting magnet at the center and 8 toroid superconducting magnets in each barrel and end-cap regions [6].

The concentric subdetector system is not only designed to different properties of particles, but it also helps identification of particles. For example, a photon and an electron may leave similar tracks on electromagnetic calorimeter, but photon will not interact with ID and it won't be affected from magnetic field as it is chargeless. Or a muon, it will bend in ID and will leave track there, but in calorimeters rather designed for measuring energy of less massive particles, and a muon will fly through calorimeters but it will interact with muon spectrometer. So it is possible to differentiate a muon from an electron. In the case of quarks, they will bend leave a track in ID, pass the electromagnetic calorimeter, but will interact with hadronic calorimeter. Due to color confinement problem, it is not possible to observe a single quark, they will hadronise and rather look as collimated spray of hadronic particles which we call as jets. Last

but not least, neutrinos won't be affected from any layer of subdetectors, but thanks to energy and momentum conservation we will be able to identify them in the form of missing energy. Different particles moving through ATLAS can be seen in the Figure 3.9.

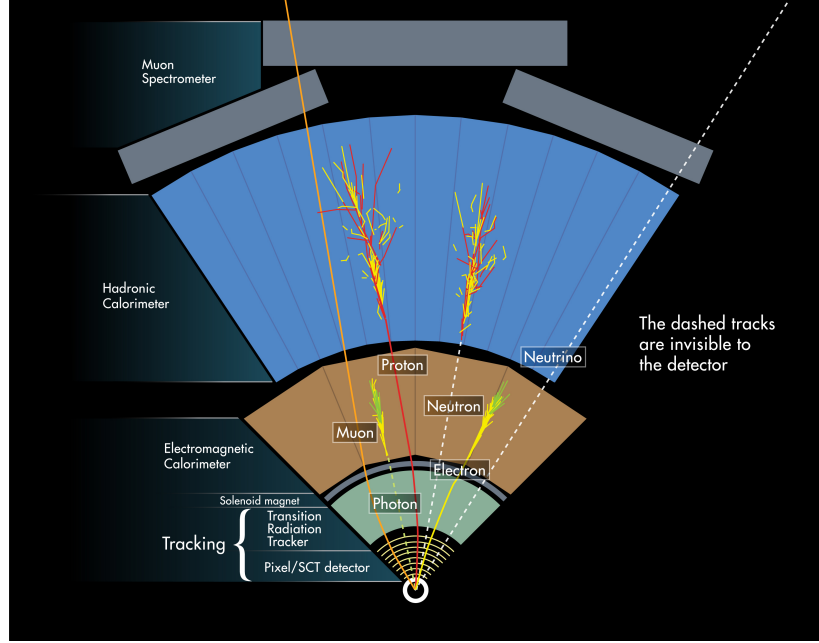


Figure 3.9: Magnetic system of ATLAS consists of a solenoid superconducting magnet at the center and 8 toroid superconducting magnets in each barrel and end-cap regions [7].

3.2.2. The Coordinate System

A common right-handed Cartesian coordinate system (x - y - z) which origin defined at IP is used throughout ATLAS. The z -axis is along the direction of beam line, and the positive part of the axis called as A-side and the negative part is called as C-side. The perpendicular plane to the z -axis is called as transverse plane and spanned by x and y axes. Particle momenta and energy measured on this plane called as transverse momenta p_T and E_T , respectively. The y -axis points upwards toward the surface of the earth, and the x -axis points towards the center of LHC. The representation is depicted at 3.10. Often in data analysis, the spherical coordinate system (r - ϕ - θ) is also used with r is the distance from the beam line, and the azimuthal angle ϕ measured from positive x -axis around the beam. The polar angle, θ , is defined

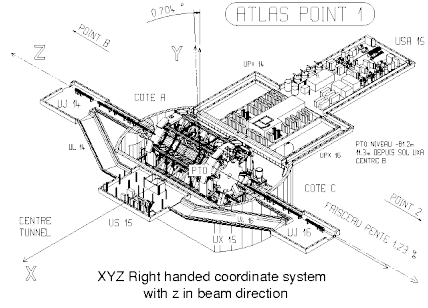


Figure 3.10: The right-handed Cartesian coordinate system of ATLAS [8].

from positive z-axis. But, the polar angle is not invariant under a Lorentz boost in z-axis. Instead of θ , we generally use pseudorapidity, η , which is defined with equation 3.3.

$$\eta = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right). \quad (3.3)$$

Unlike θ , the differences in pseudorapidity is invariant under boosts in z-axis [57]. The relationship of θ and η can be further seen in Figure 3.11. Also, another commonly

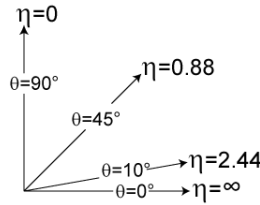


Figure 3.11: The relationship of pseudorapidity η with polar angle θ .

used parameter defined in η - ϕ space for angular separation is ΔR , and it is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

3.2.3. The Inner Detector

The ID [58, 59] consists of three high-resolution detectors: Pixel Detector, Semi-Conductor Tracker (SCT) and Transition Radiation Tracker (TRT) submerged into magnetic field at the strength of 2.0 T which allows for track reconstruction and particle identification. It is sensitive to objects with transverse momentum higher than 0.4 GeV, and covers the range of $|\eta| < 2.5$. Charged particles will ionize the active cells and

create a charge that can be read out. This allows for discretely connecting the dots, and creating the track of the particles. The magnetic field will bend the trajectory; the direction of the bend will determine the sign of the charge, the magnitude of the curvature will determine the momentum of the particle. The detailed representation can be found at Figure 3.12.

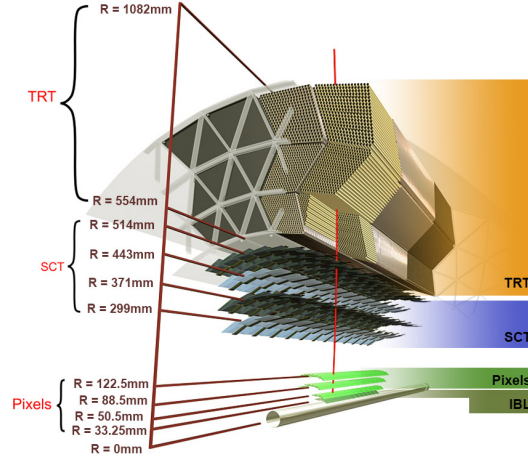


Figure 3.12: Layers of inner detector.

3.2.3.1. Pixel Detector. Pixel detector consists of three layers of silicon detectors at radial distances 50.5, 88.5 and 122.5 mm away from the IP and enclosed with three disks at end-caps in order to increase the acceptance of η . The resolution of pixel detector is $10 \mu m$ in ϕ direction, $115 \mu m$ in z-direction with the help of 1744 silicon strips where each has 46080 pixels in it. It is upgraded on May, 2014 with additional layer called insertable B-layer [60] at 33 mm which improves the tracking performance.

3.2.3.2. Semi-Conductor Tracker. SCT [61,62] is another silicon-based detector consists of double layers of microstrips at 30.0 and 52.2 cm. There are 9 disks at each end-caps. For a single track, we expect around 8 precision measurements. The spatial resolution in the transverse plane is $16 \mu m$, and $580 \mu m$ in the beam direction. Overall, it allows for 6.4 million readout channel.

3.2.3.3. Transition Radiation Tracker. It [63] consists of 370000 straws covered with polypropylene foils and filled with gas and a gold-plated tungsten wire is centered at each straw acting as anode. The gas consists of 70% Xe , 27% CO_2 , and 3% O_2 . Transversing particle causes radiation that depends on the velocity of the particle, which allows us to differentiate between electrons and hadrons. The readout is possible at the ends of the straws; therefore, it is not possible to take any information in z-direction. But, it allows for spatial resolution of $170 \mu m$. Finally, on average, 36 hits are expected for each track.

3.2.4. Calorimeters

After ID, particles reach to electromagnetic and hadronic calorimeter [64–66] where energy of the most particles is measured. They are specifically designed to measure energy of particles which can interact through electromagnetic and strong force. Both of them are sampling calorimeter of the non-compensating type. The main idea is that first there is an absorber layer which causes showering, and the second layer is active layer which converts the energy to a measurable quantity. Then, with the help of calibration from known sources, incoming energy is deduced. All calorimeters in ATLAS shown in Figure 3.13.

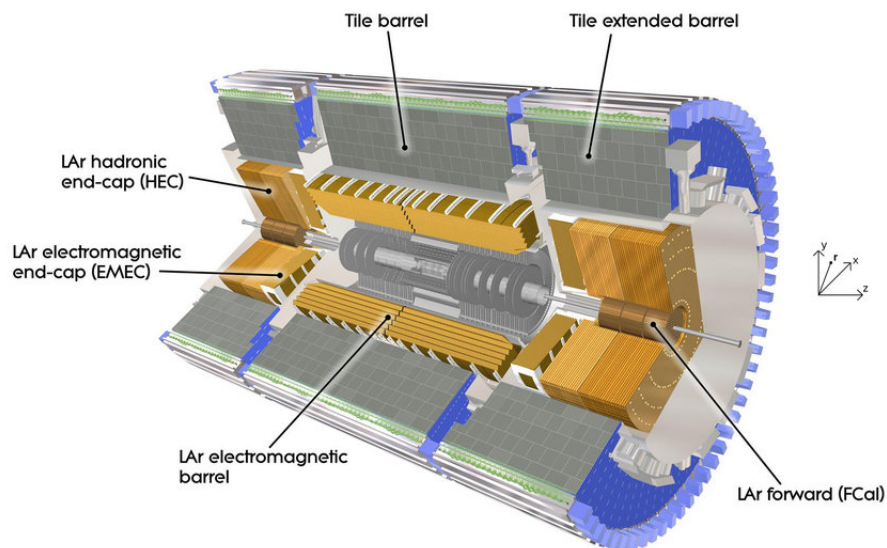


Figure 3.13: Calorimeters of the ATLAS Detector.

3.2.4.1. Electromagnetic Calorimeter. It is designed for measuring energy of particles which interacts through electromagnetic force. The absorber layer is made of lead, and the active layer is liquid argon. Lead with its heavy nucleus causes bremsstrahlung phenomena for incoming energetic electron. The electron will decelerate, and produce a photon. Photon will be still highly energetic, and it will decay through pair-production process. There will be more electrons to interact with lead nucleus, and there will be more photons to decay into electron-positron pair. This two process will feed each other, and there will be showering of particles. Incoming photon will start with pair production, and resulting electrons will continue with bremsstrahlung. After lead layer, liquid argon (LAr) is ionized, and ionized particles are collected with electrodes. The created signal is proportional to energy of incoming particle. The resolution in η and ϕ plane reaches to the granularity of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ in barrel region, $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the end-cap region. It covers $\eta < 1.475$ in the barrel region, $1.375 < |\eta| < 3.2$ in the end-caps.

3.2.4.2. Hadronic Calorimeter. The working point of hadronic calorimeters is similar to electromagnetic calorimeter but hadronic particles are more penetrative and energetic than electromagnetic showers. The major part of the hadronic calorimeter is tile calorimeter and it consists of 14 mm iron plates to create showers and 3 mm active scintillating-tile to measure the energy deposit. The scintillating tile is attached to series of photomultiplier tubes in order to increase the electrical signal. Tile calorimeter covers the barrel range of $\eta < 1$ and extended barrel range of $0.8 < |\eta| < 1.7$. It achieves granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. It also includes LAr calorimeter described in Electromagnetic calorimeter in the end-cap region covering $1.5 < \eta < 3.2$ with granularity $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$.

3.2.4.3. Forward Calorimeter. It consists of layers of hadronic and electromagnetic calorimeters with active matter LAr and prevents particles other than muons to punch through muon spectrometer. It covers the very forward region of $3.1 < |\eta| < 4.4$. Electromagnetic calorimeter is composed of Cu/LAr, and the hadronic one composed

of W/LAr.

3.2.5. Muon Spectrometers

The aim of muon spectrometer [67] is two-fold: tracking of muons at high-precision, and delivery of fast trigger signals stemming from muons. It accurately measures muons with range of $3 < p_T < 1000 \text{ GeV}$ in transverse momentum, and $|\eta| < 2.7$ in pseudorapidity. For high-precision tracking Monitored Drift Tubes (MDTs) are used in the $|\eta| < 2.0$ region, and Cathode Strip Chambers (CSCs) are used in forward region where $2.0 < |\eta| < 2.7$. For triggering, Resistive Plate Chambers (RPCs) are used in barrel region where $|\eta| < 1.05$, and Thin Gap Chambers installed in end-caps with $1.05 < |\eta| < 2.4$. RPCs are made of two parallel charged plates filled out with gas. It has spatial resolution of 1 cm, and time resolution of 1 ns which allows for fast triggering system.

3.2.6. Trigger System

In the ATLAS detector, pp collision rate is 40 MHz. Considering the fact that an event is about 0.8 MB, it is almost technologically impossible to record all the data generated by LHC. Instead of recording every single data, we try to choose the interesting ones. For this purpose, ATLAS has dedicated two-level trigger system [68]. Level 1 [69] is a hardware trigger which has Central Trigger Processor (CTP) as its decisive mechanism. CTP is fed with triggers from calorimeters (L1Calo), muon spectrometer (L1Muon), and L1Topo which is a trigger based on topological properties of analysis objects such as angular separation. After Level 1 system, the event rate is reduced to $\approx 100 \text{ KHz}$ and the information is temporarily stored and handed over High Level Trigger system which consists of Level 2 trigger, and Event Filter. Level 2 [70] trigger system is a software based system with fast selection algorithm. In order to eliminate events, the selection algorithm uses a threshold in general in the p_T of the object. The output rate of Level 2 is about 5 KHz. The last phase of trigger system is Event Filter which follows offline object reconstruction parameters. The resulting rate

of events is ≈ 1 KHz.

3.2.7. Event Data Model

After the recorded number of events per second is limited to manageable value, we also need to make them analysis ready. All information recorded in raw data form has size of ≈ 0.8 MB. At first, the size per event is increased and recorded in the form of Event Summary Data (ESD) which has enough information for particle identification, track re-fitting, or jet calibration, etc. Then, Analysis Object Data (xAOD)'s are formed by storing reconstructed objects and sufficient information for common analysis. In the Run 2 [71], a new step is introduced for reduction of data: Derived Analysis Object Data (DxAOD) [72]. Only necessary information of analyzable physical object collections for specific analysis is recorded. This allows for reduced disk space, and faster processing time. The idea is shown in Figure 3.14.

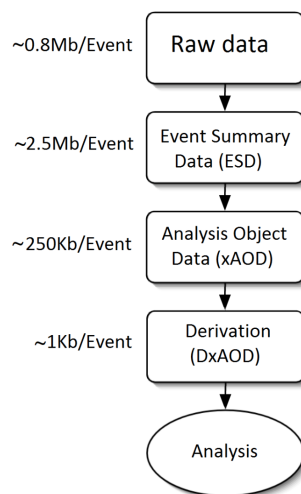


Figure 3.14: Event data model of ATLAS is summarized [9].

3.2.8. Object Reconstruction

In this analysis, electrons, muons and jets are used in order to reconstruct the heavy quarks. The jets used to reconstruct the Higgs boson can be *b*-tagged according to working point of the analysis. *b*-tagged means a jet originating from hadronization of

b-quark. All physics objects have been recorded following the ATLAS overlap removal procedure. We closely follow the object identification criteria of the similar analysis, given the similarity between the final states and to minimize the computational load in producing the background ntuples. Hence the following four subsections are mostly taken from reference [73].

3.2.8.1. Electrons. Electrons are reconstructed [74,75] from clusters in the electromagnetic calorimeter with inner-detector tracks matched to them, and they are required to fulfill the tight likelihood identification criteria. They are calibrated [76] and required to have a transverse energy of at least 28 GeV and to be in the fiducial region $|\eta| < 2.47$, excluding the barrel-endcap transition regions ($1.37 < |\eta| < 1.52$). In order to suppress the background from non-prompt electrons and from hadrons being misidentified as electrons, electron candidates must be isolated using the FixedCutTightTrackOnly criteria, which requires $ptvarcone20/p_T$ of the electron to be below 0.6, and $topoetcone20/p_T$ below 0.06. The isolation criterion is applied that requires the scalar sum of the p_T of the tracks which point to the primary vertex within a cone around the electron (but excluding its track) be less than 6% of its E_T . Meaning that: $\Delta R = \min(10 \text{ GeV}/E_T, 0.2)$ is used as isolation criteria. Furthermore, electron candidates must be likely to originate from the primary vertex in the event by requiring the d_0 significance to be smaller than 5, i.e., $d_0/\sigma(d_0) < 5.0$ and $|z_0 \cdot \sin\theta| < 0.5 \text{ mm}$, where z_0 is the distance in the z-axis between primary vertex and the closest point of the track.

3.2.8.2. Muons. Muons are reconstructed [77] from combined tracks in the muon spectrometer and the inner detector, and they are required to fulfill medium identification criteria. Muons are calibrated and are required to have a transverse momentum of at least 28 GeV and to be in the fiducial region $|\eta| < 2.5$. So as to suppress background from non-prompt muons, muon candidates must be isolated using the FixedCutTightTrackOnly criteria, which requires $ptvarcone30/p_T$ of the muon to be below 0.6. As it was the case for electrons, the isolation working point the scalar sum of the p_T of

the tracks around the muon which point to the primary vertex, excluding the muon track, must be smaller than 6% of its p_T . Meaning that: $\Delta R = \min(10 \text{ GeV}/p_T, 0.3)$. Furthermore, muon candidates must be likely to originate from the primary vertex in the event by requiring the d_0 significance to be smaller than 3 and $|z_0 \cdot \sin\theta| < 0.5 \text{ mm}$.

3.2.8.3. Jets. Jets are reconstructed using the *anti* - k_t algorithm [78] with a radius parameter of 0.4 from topological clusters in the calorimeter [79, 80]. They are calibrated to the jet energy scale (JES) [81, 82] (EMTopo jets) and are required to fulfill $p_T > 25 \text{ GeV}$ and $|\eta| < 4.5$, i.e. jets in the forward calorimeters are also considered. Jets with $|\eta| < 2.4$ and $p_T < 60 \text{ GeV}$ are required to fulfill a value of the jet-vertex tagger [83] of at least 0.59. b -tagging is performed using the MV2c10 algorithm [84] with a fixed cut of > 0.645925 , which corresponds to a tagging efficiency in simulated $t\bar{t}$ events of 77%, a c -jet rejection of ~ 6 and a light-jet rejection of ~ 130 .

3.2.8.4. Overlap Removal. The overlap removal between the reconstructed physics objects is done sequentially in order to avoid double-counting of tracks or energy deposits, and in order to improve particle identification. The latest recommended working point of the AssociationUtils package [49, 50] is followed. First any calo-tagged muon which shares a track in the ID with an electron is removed. After that, any electron sharing an ID track with one of the remaining muons is removed. Any jet within a $\Delta R < 0.2$ of an electron is removed. Then electrons within $\Delta R < 0.4$ of the remaining non-pile-up jets are removed. The overlap removal between muons and jets is modified with respect to the recommended working point. Any jet within a $\Delta R = 0.04 + 10 \text{ GeV}/p_T(\mu)$ of a muon is removed. Any muon within the same ΔR of any remaining jet with at least 3 tracks is removed. This overlap removal procedure improves the sensitivity on final states with high energy particles.

4. THE SEARCH FOR E_6 ISO-SINGLET QUARKS

The focus of this section is to describe the selection and reconstruction algorithm of $D\bar{D}$ events in the $HjZj$ channel. For this analysis, we have used dbxA2 framework which is the second version of dbxA2 developed by Gökhan Ünel et al., 2010. A guide for dbxA2 can be found in [85]. In dbxA2 algorithm, we use a software named CutLang [86] in order to ease the programming part of the analysis.

4.1. Event Selection

The event selection algorithm uses the objects that are reconstructed according to the criteria in Section 3.2.8. The event selection criteria themselves can be classified under two broad groups. The first type is meant to remove the low quality data from the analysis. The second type is designed to remove the background events in order to boost the signal significance.

The complete list of data and dominant/non-dominant Monte-Carlo backgrounds used in this analysis given in Section A.1. In these Ntuples, for all channels a common preselection is applied, which slims the number of events analysed. Events are required to have fired the single lepton triggers defined in Table 4.1, and events with less than two leptons with $pT > 28$ GeV are rejected. Single-lepton triggers used for both, 2015 and 2016 data. The different triggers in each category are combined with an OR logical operation. For MC generated events they are randomly taken to belong to the 2015 or 2016 pile-up profile and relative to the luminosity for each data taking year. Depending on which year they have been assigned, the proper triggers are required. Events are then required to have at least two leptons of the same flavor and with opposite-sign electric charge, i.e., OS-SF (opposite sign, same flavor). Events are hence categorised into the ee and $\mu\mu$ channels, which are defined by the pair of OS-SF leptons which reconstructs the best Z-boson candidate in the event, i.e. $m_{\ell\ell}$ closest to m_Z . Events where the best Z-boson candidate has $m_{\ell\ell} > 400$ GeV are rejected. This best Z-boson candidate is

from now on just denoted as the Z boson candidate. In order to be consistent with the requirements of the EXOT4-derivation slim, the at least 2 jets are required.

Table 4.1: Lepton triggers used in the analysis.

	Single-electron triggers
2015 data	HLT_e24_lhmedium_L1EM20VH, HLT_e60_lhmedium, HLT_e120_lhloose
2016 data	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0, HLT_e140_lhloose_nod0
	Single-muon triggers
2015 data	HLT_mu20_loose_L1MU15 HLT_mu50
2016 data	HLT_mu26_ivarmedium HLT_mu50

After Ntuple production pre-selection, our analysis cut flow begins. First, our preselection cuts which is applied to all regions within our own object selection are applied. Our preselection cuts are listed below:

- (i) At least 1 electron or 1 muon
- (ii) At least 2 electron or 2 muon
- (iii) Exactly 2 good leptons of opposite sign and same flavor
 - $p_T(e) > 30.0 \text{ GeV}$, $|\eta(e)| < 2.47$;
 - $p_T(\mu) > 30.0 \text{ GeV}$, $|\eta(\mu)| < 2.5$;
 - $p_T(j) > 25.0 \text{ GeV}$, $|\eta(j)| < 2.5$;
- (iv) At least 2 good jets

After our preselection, the cuts change according to our regions. We have one signal region, and two control regions. The signal region is where we expect to observe signal from the quarks we have been searching for, so the cuts are designed to eliminate the background as much as possible, an enrich the signal. On the other hand, control

region is actually opposite of signal region and designed the cuts in order to enrich the dominant backgrounds. In our process, we have two dominant background: Z +jets and $t\bar{t}$ with $\approx 91\%$ and $\approx 5\%$ contribution, respectively. The reasoning behind the control region is that the Monte-Carlo simulation must be able to predict data within the reasonable limits of statistical and systematic uncertainties; so that, we must be able to tell with high confidence-level if we observe a signal or not. Furthermore, signal region and control regions must be perpendicular to each other: there can be no event which is found in both regions.

In the signal region, we tighten the good jet multiplicity cut to at-least-4, and a Z boson mass window cut ($|m_{\ell\ell} - m_Z| < 10 \text{ GeV}$) is applied. Finally a χ^2 algorithm is used to reconstruct the Higgs boson and the iso-singlet quarks. The details of this algorithm are described in Section 4.2.1. In order to improve the speed of the χ^2 algorithm and to get an idea about the impact of the p_T requirements we will later apply on the prompt jet candidates are, we require that the event contains at least two jets that could satisfy the prompt jet p_T constraints. These are listed as $p_T^{LeadingJet}$ and $p_T^{SubleadingJet}$ rows in Tables 4.5 and 4.6. Finally we require that at least one of the two Higgs boson daughter candidates identified by the χ^2 algorithm to be b -tagged. Naturally, the b -tagging related scale factor is applied to the Monte Carlo samples at this point. The cut flow summary for the signal region can be seen in Table 4.2.

For $t\bar{t}$ and Z +jets Control Regions, different cut flows are applied after our pre-selection cuts, as summarized in Tables 4.3 and 4.4. The details can be found in Sections 4.3.5.1 and 4.3.5.2.

On Tables 4.5, and 4.6, the expected event yields from the signal and SM backgrounds are listed after various selection requirements are gradually applied.

Table 4.2: Cut flow for the signal region.

#	Cut	Explanation
0	ALL	Initial count with weights
1	$n_{\text{LEP}} \geq 1$	At least 1 electron or 1 muon
2	$n_{\text{LEP}} = 2$	Exactly 2 leptons
3	$q_{\text{LL}} = 0$	Opposite sign and same flavor
4	LEPsf	Include lepton scale factor
5	$n_{\text{JET}} \geq 2$	At least 2 jets
6	$n_{\text{JET}} \geq 4$	At least 4 jets
7	$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	Z Mass window cut
8	$p_T^{\text{LeadingJet}} > 100 \text{ GeV}$	Leading Jet p_T
9	$p_T^{\text{SubleadingJet}} > 65 \text{ GeV}$	Subleading Jet p_T
10	$\chi^2 < 15$	Reject event if no combination with total $\chi^2 < 15$ can be found
11	≥ 1 b -tagged jet Higgs	At least one of the Higgs candidate's daughters should be b -tagged

Table 4.3: Cut flow for the $t\bar{t}$ control region.

#	Cut	Explanation
0	PreSelection	$n_{\text{LEP}} \geq 1$ & $n_{\text{LEP}} \geq 2$ $q_{\text{LL}} = 0$ & LEPsf & $m_{\text{LL}} \leq 400$ are defined as preselection cuts ²
1	$n_{\text{LEP}} = 2$	Exactly 2 leptons
2	$n_{\text{JET}} \geq 2$	At least 2 Jets
3	$n_{\text{BJET}} \geq 2$	At least 2 b-tagged Jets
4	m_{ll} veto	$ m_{ll} - m_Z > 10 \text{ GeV}$ and $ m_{ll} > 50 \text{ GeV}$
5	$p_T^Z < 600 \text{ GeV}$	pT of the Z-boson candidate $< 600 \text{ GeV}$
6	$E_t^{\text{miss}} < 200 \text{ GeV}$	Missing transverse energy $< 200 \text{ GeV}$
7	ΔR_{Zj_L} veto	Exclude $2.0 < R(Z, \text{Leadingjet}) < 2.8$
8	$n_{\text{JET}} \geq 4$	At least 4 Jets
9	$\chi^2 < 15$	require at least one of the Higgs daughter jets to be b -tagged reject event if no combination with total $\chi^2 < 15$ can be found

Table 4.4: Cut flow for the Z +jets control region.

#	Cut	Explanation
0	PreSelection	$n_{\text{LEP}} \geq 1$ & $n_{\text{LEP}} \geq 2$ $q_{\text{LL}} = 0$ & LEPsf & $m_{\text{LL}} \leq 400$ are defined as preselection cuts ³
1	$n_{\text{LEP}} = 2$	Exactly 2 leptons
1	$n_{\text{LEP}}=2$	Exactly 2 leptons
2	$n_{\text{JET}} \geq 2$	At least 2 Jets
3	$n_{\text{BJET}} \geq 1$	At least 1 b-tagged Jets
4	$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	Z Mass window cut
5	$\text{SumHTJET} < 1050 \text{ GeV}$	the scalar sum of the pT of jets
6	$n_{\text{JET}} \geq 4$	At least 4 Jets
7	$\chi^2 < 15$	Reject event if no combination with total $\chi^2 < 15$ can be found
8	b -tagged jet veto	veto b -tagged jets in Higgs daughters

Table 4.5: Expected signal and background yields for the electron channel in the signal region.

	Signal (1 TeV)	Z +jets	$t\bar{t}$
ALL	176.9 ± 1.2	$(1367 \pm 2) \times 10^4$	$(106.0 \pm 0.2) \times 10^3$
nLEP ≥ 1	176.9 ± 1.2	$(1360 \pm 2) \times 10^4$	$(105.9 \pm 0.2) \times 10^3$
nLEP ≥ 2	175.2 ± 1.2	$(1253 \pm 2) \times 10^4$	$(97.36 \pm 0.19) \times 10^3$
nLEP = 2	175.2 ± 1.2	$(1253 \pm 2) \times 10^4$	$(97.36 \pm 0.19) \times 10^3$
qLL = 0	175.2 ± 1.2	$(1253 \pm 2) \times 10^4$	$(97.36 \pm 0.19) \times 10^3$
LEPsf	167.4 ± 1.1	$(1087 \pm 1) \times 10^4$	$(87.46 \pm 0.17) \times 10^3$
nJET ≥ 2	167.3 ± 1.1	$(756.3 \pm 2.7) \times 10^3$	$(72.3 \pm 0.2) \times 10^3$
nJET ≥ 4	146.6 ± 1.1	$(60.8 \pm 0.3) \times 10^3$	$(17.3 \pm 0.1) \times 10^3$
$ m_{ll} - m_Z < 10 \text{ GeV}$	144.8 ± 1.1	$(53.3 \pm 0.3) \times 10^3$	2213 ± 27
$p_T^{\text{LeadingJet}} > 100 \text{ GeV}$	144.8 ± 1.1	$(28.7 \pm 0.1) \times 10^3$	1373 ± 21
$p_T^{\text{SubleadingJet}} > 65 \text{ GeV}$	144.8 ± 1.1	$(21.7 \pm 0.1) \times 10^3$	1115 ± 19
$\chi^2 < 15$	124.4 ± 1.0	$(15.2 \pm 0.1) \times 10^3$	870.3 ± 17.0
1 b -tagged jet	77.7 ± 0.8	1305 ± 11	471.6 ± 12.7
	$t\bar{t} + V$	single top	dibosons
ALL	587.0 ± 2.6	9551 ± 41	$(56.4 \pm 0.6) \times 10^3$
nLEP ≥ 1	586.6 ± 2.6	9537 ± 41	$(56.2 \pm 0.6) \times 10^3$
nLEP ≥ 2	554.4 ± 2.6	8796 ± 39	$(50.8 \pm 0.4) \times 10^3$
nLEP = 2	554.4 ± 2.6	8796 ± 39	$(50.8 \pm 0.4) \times 10^3$
qLL = 0	554.4 ± 2.6	8796 ± 39	$(50.8 \pm 0.4) \times 10^3$
LEPsf	502.7 ± 2.3	7908 ± 36	$(4.4 \pm 0.3) \times 10^3$
nJET ≥ 2	492.2 ± 2.3	3867 ± 25	8408 ± 246
nJET ≥ 4	372.1 ± 2.0	534 ± 9	1262 ± 29
$ m_{ll} - m_Z < 10 \text{ GeV}$	254.3 ± 1.3	109 ± 3	673 ± 24
$p_T^{\text{LeadingJet}} > 100 \text{ GeV}$	195 ± 1.2	67.01 ± 2.2	481.5 ± 21.3
$p_T^{\text{SubleadingJet}} > 65 \text{ GeV}$	175.2 ± 1.1	53.21 ± 1.9	375.4 ± 19.2
$\chi^2 < 15$	157.3 ± 1.1	39.28 ± 1.7	266 ± 12
1 b -tagged jet	74.3 ± 0.7	18.8 ± 1.4	19.0 ± 2.7

Table 4.5: Expected signal and background yields for the electron channel in the signal region (cont.).

	Total SM bkg	Signal + SM bkg	Data
ALL	$(1384 \pm 2) \times 10^4$	$(1384 \pm 2) \times 10^4$	$1.246 \times 10^7 \pm 3530$
nLEP ≥ 1	$(1377 \pm 2) \times 10^4$	$(1377 \pm 2) \times 10^4$	$1.24 \times 10^7 \pm 3522$
nLEP ≥ 2	$(1269 \pm 2) \times 10^4$	$(1269 \pm 2) \times 10^4$	$1.144 \times 10^7 \pm 3382$
nLEP = 2	$(1269 \pm 2) \times 10^4$	$(1269 \pm 2) \times 10^4$	$1.144 \times 10^7 \pm 3382$
qLL = 0	$(1269 \pm 2) \times 10^4$	$(1269 \pm 2) \times 10^4$	$1.144 \times 10^7 \pm 3382$
LEPsf	$(1101 \pm 1) \times 10^4$	$(1101 \pm 1) \times 10^4$	$1.144 \times 10^7 \pm 3382$
nJET ≥ 2	$(841 \pm 3) \times 10^3$	$(8416 \pm 4) \times 10^2$	$(8.899 \pm 0.01) \times 10^5$
nJET ≥ 4	$(802 \pm 3) \times 10^2$	$(803.7 \pm 3.4) \times 10^2$	$(8.015 \pm 0.28) \times 10^4$
$ m_{ll} - m_Z < 10 \text{ GeV}$	$(565 \pm 3) \times 10^2$	$(566.8 \pm 3.1) \times 10^2$	$(54.48 \pm 0.23) \times 10^3$
$p_T^{\text{LeadingJet}} > 100 \text{ GeV}$	$(308 \pm 1) \times 10^2$	$(3093 \pm 11) \times 10^1$	blinded
$p_T^{\text{SubleadingJet}} > 65 \text{ GeV}$	$(234 \pm 1) \times 10^2$	$(2358 \pm 8.7) \times 10^1$	blinded
$\chi^2 < 15$	$(165 \pm 1) \times 10^2$	$(1663 \pm 6.6) \times 10^1$	blinded
1 <i>b</i> -tagged jet	2371 ± 27	$(244.9 \pm 2.7) \times 10^1$	blinded

Table 4.6: Expected signal and background yields for the muon channel in the signal region.

	Signal (1 TeV)	Z +jets	$t\bar{t}$
ALL	176.9 ± 1.1	$(2032 \pm 2.0) \times 10^4$	$(1338 \pm 2.0) \times 10^2$
nLEP ≥ 1	176.9 ± 1.1	$(2022 \pm 2.0) \times 10^4$	$(1336 \pm 2.0) \times 10^2$
nLEP ≥ 2	174.9 ± 1.1	$(1868 \pm 1.9) \times 10^4$	$(1227 \pm 2.0) \times 10^2$
nLEP = 2	174.9 ± 1.1	$(1868 \pm 1.9) \times 10^4$	$(1227 \pm 2.0) \times 10^2$
qLL = 0	174.9 ± 1.1	$(1868 \pm 1.9) \times 10^4$	$(1227 \pm 2.0) \times 10^2$
LEPsf	163.3 ± 1.1	$(1743 \pm 1.7) \times 10^4$	$(1144 \pm 2.0) \times 10^2$
nJET ≥ 2	163.3 ± 1.1	$(1198 \pm 3.7) \times 10^3$	95440 ± 2
nJET ≥ 4	147.1 ± 1.0	$(9777 \pm 52) \times 10^1$	24000 ± 91
$ m_{ll} - m_Z < 10 \text{ GeV}$	134.6 ± 1.0	$(8424 \pm 49) \times 10^1$	3170 ± 34
$p_T^{\text{LeadingJet}} > 100 \text{ GeV}$	134.6 ± 1.0	$(4372 \pm 15) \times 10^1$	1902 ± 26
$p_T^{\text{SubleadingJet}} > 65 \text{ GeV}$	134.5 ± 1.0	$(3307 \pm 13) \times 10^1$	1529 ± 24
$\chi^2 < 15$	116.5 ± 0.9	$(2222 \pm 11) \times 10^1$	1163 ± 21
1 b -tagged jet	72.1 ± 0.7	2629 ± 114	608 ± 15
	$t\bar{t} + V$	single top	dibosons
ALL	893.7 ± 3.2	$(1213 \pm 4.6) \times 10^1$	$(3943 \pm 15) \times 10^1$
nLEP ≥ 1	893 ± 3.2	$(1210 \pm 4.6) \times 10^1$	$(3928 \pm 15) \times 10^1$
nLEP ≥ 2	840.7 ± 3.086	$(1113 \pm 4.4) \times 10^1$	$(3537 \pm 14) \times 10^1$
nLEP = 2	840.7 ± 3.1	$(1113 \pm 4.4) \times 10^1$	$(3537 \pm 14) \times 10^1$
qLL = 0	840.7 ± 3.1	$(1113 \pm 4.4) \times 10^1$	$(3537 \pm 14) \times 10^1$
LEPsf	781.1 ± 2.9	$(1037 \pm 4.1) \times 10^1$	$(3300 \pm 13) \times 10^1$
nJET ≥ 2	759.4 ± 2.8	5210 ± 29	6222 ± 46
nJET ≥ 4	548.2 ± 2.4	772.1 ± 10.9	1006 ± 18
$ m_{ll} - m_Z < 10 \text{ GeV}$	320.8 ± 1.5	162.7 ± 4.0	510.2 ± 14.1
$p_T^{\text{LeadingJet}} > 100 \text{ GeV}$	242.2 ± 1.3	102.9 ± 3.1	334.4 ± 9.9
$p_T^{\text{SubleadingJet}} > 65 \text{ GeV}$	217.4 ± 1.3	81.03 ± 2.8	253.4 ± 8.6
$\chi^2 < 15$	193.1 ± 1.2	57.7 ± 2.2	178.1 ± 7.4
1 b -tagged jet	91.6 ± 0.8	26.5 ± 1.6	13.9 ± 1.8

Table 4.6: Expected signal and background yields for the muon channel in the signal region (cont.).

	Total SM bkg	Signal + SM bkg	Data
ALL	$(2050 \pm 2.0) \times 10^4$	$(2050 \pm 1.9) \times 10^4$	$(1991 \pm 0.4) \times 10^4$
nLEP ≥ 1	$(2040 \pm 2.0) \times 10^4$	$(2040 \pm 1.9) \times 10^4$	$(1981 \pm 0.4) \times 10^4$
nLEP ≥ 2	$(1885 \pm 2.0) \times 10^4$	$(1885 \pm 1.8) \times 10^4$	$(1832 \pm 0.4) \times 10^4$
nLEP = 2	$(1885 \pm 2.0) \times 10^4$	$(1885 \pm 1.8) \times 10^4$	$(1832 \pm 0.4) \times 10^4$
qLL = 0	$(1885 \pm 2.0) \times 10^4$	$(1885 \pm 1.8) \times 10^4$	$(1832 \pm 0.4) \times 10^4$
LEPsf	$(1759 \pm 1.7) \times 10^4$	$(1759 \pm 1.7) \times 10^4$	$(1832 \pm 0.4) \times 10^4$
nJET ≥ 2	$(1306 \pm 3.7) \times 10^3$	$(130.6 \pm 0.4) \times 10^4$	$(1399 \pm 1.2) \times 10^3$
nJET ≥ 4	$(124.2 \pm 0.5) \times 10^3$	$(124.1 \pm 0.5) \times 10^3$	$(126.4 \pm 0.4) \times 10^3$
$ m_{ll} - m_Z < 10 \text{ GeV}$	$(88.5 \pm 0.5) \times 10^3$	$(884.1 \pm 4.9) \times 10^2$	$(880.9 \pm 0.3) \times 10^3$
$p_T^{LeadingJet} \geq 100 \text{ GeV}$	$(46.4 \pm 0.32) \times 10^3$	$(464.4 \pm 1.6) \times 10^2$	blinded
$p_T^{SubleadingJet} \geq 65 \text{ GeV}$	$(35.3 \pm 0.1) \times 10^3$	$(351.5 \pm 1.3) \times 10^2$	blinded
$\chi^2 < 15$	$(23.9 \pm 0.1) \times 10^3$	$(238.1 \pm 1.1) \times 10^2$	blinded
1 <i>b</i> -tagged jet	2617 ± 57	3370 ± 115	blinded

4.2. Reconstruction

The event reconstruction of the E_6 analysis involves two steps. The reconstruction of the Z boson is straightforward: we simply combine the two oppositely-charged leptons that remain after the cuts. The real challenge is the reconstruction of the Higgs boson and the D quark pair, which requires proper assignment of the prompt and Higgs-daughter jets. This is performed by minimizing a total event χ^2 which is computed for all possible jet combinations. Further details of the χ^2 computation are provided below, in Subsection 4.2.1. The current E_6 analysis is capable of computing three separate χ^2 s concurrently, for alternative ways of handling the flavor tagging of the jets that are used to reconstruct the Higgs boson. The first case is to disregard any b -tagging information, while the second (third) cases might require at least of one (both) of the Higgs-daughter-candidate jets to be b -tagged. The Figure 4.1 shows the signal efficiencies for the three working points (untagged, 1 b -tagged and 2 b -tagged) for both channels.

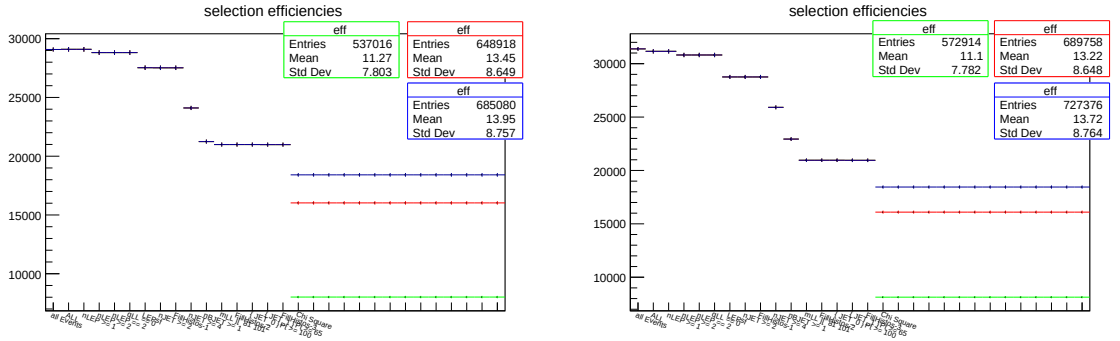


Figure 4.1: Signal efficiencies for three working points (left for the ee channel and right for the $\mu\mu$ channel). The colors represent three working point of the analysis: blue one is for the untagged case, red is for 1 b -tagged case and green one is for 2 b -tagged case.

Each of these three alternatives represent a separate analysis working point. While the case with no b -tagging has the highest signal efficiency, it suffers from high backgrounds. Furthermore, a significant feed through can be expected from various other E_6 decay channels that contains a Z boson, ie. from $ZjZj$ or $ZjWj$. When b -tagging for at least one of the Higgs daughter candidates, this feedthrough is greatly

reduced. The Z bosons $b\bar{b}$ decay branching fraction is about 15% and W 's hadronic decays containing b jets are rare due to small V_{ub} and V_{cb} elements of the CKM matrix.

Furthermore, the background is lower. Finally when both jets that reconstructs the Higgs boson are required to be b -tagged, the background is greatly suppressed, but at a major cost on the signal efficiency.

Therefore, the present analysis works with the untagged jets up until the last selection criteria, and as the last step of the selection algorithm, at least 1 b -tagged jet is required as a Higgs boson daughter jet.

4.2.1. The χ^2 Algorithm

The inputs to the χ^2 algorithm are any set of four jets in the event, as well as the reconstructed Z boson. For every possible combination of these objects that satisfy certain criteria, a χ^2 value is computed according to the combination's resemblance to the E_6 signal. The particular combination with the lowest χ^2 is chosen to reconstruct the E_6 signal. Below is a summary of this algorithm:

- Pick any combination of four jets out of the event.
- Any two jets out of four are assigned as Higgs boson daughter candidates. The sum of their 4-momenta is then used to compute a candidate Higgs mass, denoted as m_H^{reco} .
- Remaining two jets are taken as prompt jet candidates. Each prompt jet candidate is then coupled to a reconstructed boson, either the Z or the Higgs.

In short, we end up with $2 \times \binom{N_{jet}}{4}$ possible combinations, where N_{jet} is the jet multiplicity. We reject some of those using the following requirements:

- Reject the event if $\chi_H^2 \equiv \frac{(m_H^{reco} - m_H^{nominal})^2}{\sigma_H^2}$ already greater than 15.

- The P_T of both prompt jet candidates should be higher than a given value (65 GeV).
- The P_T of at least one of the prompt jet candidates should be higher than a more stringent value (100 GeV).
- The ΔR between each prompt jet and its associated boson should be larger than 1.

For each combination that remains, a total χ^2 is computed according to Equation 4.1. This includes two pieces: The reconstructed (m_H^{reco}) and nominal ($m_H^{nominal} = 125 \text{ GeV}$) Higgs masses should be close to each other; and the mass difference between the reconstructed D quarks should be minimal. In the equation, σ_H stands for the reconstructed width (resolution+natural width) of the Higgs boson mass, while σ_{D_Z} (σ_{D_H}) is the reconstructed width of the D_Z (D_H) quark.

$$\begin{aligned}
\chi^2 &= \chi_H^2 + \chi_{E_6}^2 + p_T \text{ of prompt jet requirements} \\
&\equiv \frac{(m_H^{reco} - m_H^{nominal})^2}{\sigma_H^2} + \frac{(m_{D_Z}^{reco} - m_{D_H}^{reco})^2}{\sigma_{D_Z}^2 + \sigma_{D_H}^2} \\
&\quad + \Theta(p_T^{both \text{ of prompt jets}} > 65 \text{ GeV}) + \Theta(p_T^{at least one of prompt jets} > 100 \text{ GeV}). \quad (4.1)
\end{aligned}$$

The combination that minimizes the total χ^2 is selected as the final jet assignments of a given event. That lowest χ^2 value is named the event χ^2 . Events with event χ^2 higher than a set value (15) are rejected.

It is worth noting that the performance of the χ^2 algorithm in identifying the best combination can be improved by requiring at least one of the two Higgs daughter candidates to be b -tagged. However, to ensure the complete orthogonality between our signal and Z +jets regions, we have decided to defer applying b -tagging requirements to a later stage of the analysis. In $t\bar{t}$ control region, we require Higgs daughter jet candidates to be at least one b -tagged while starting to χ^2 minimization. Since we do not have any orthogonality issue in $t\bar{t}$ control region with respect to the other regions.

4.2.2. Determination of Event Selection/Reconstruction Parameters

In this subsection we describe how the various parameters of the analysis are determined. The background for this search channel is expected to be quite low thanks to the presence of the Z boson reconstructed from tight leptons. So our default philosophy while setting the analysis parameters is to have high efficiency for the signal while keeping jet combinatorics under control. Keeping the analysis parameters not too tight also helps with making sure that data are accurately represented by the Monte Carlo simulation: In past analyses of similar channels, disagreements between data and simulation tended to get worse as the phase space was getting more constrained: the more cuts one applied, the less accurate the MC simulation generally got. Finally we have also required to get the truth-matched signal efficiency high so as to increase our probability of assigning correct jets during reconstruction.

The main parameters to set are the size of the Z mass window, the minimum P_T and ΔR for being considered prompt jet candidates, E_6 χ^2 errors (σ_{D_Z} , σ_{D_H}), the Higgs χ^2 error σ_H and the maximum allowed event χ^2 . One should note that, while the sigma values used in χ^2 definition simply represent the resolution for the reconstruction of various invariant masses, the determination of their values is performed through a bootstrapping technique which is described in Section 4.2.2. The complete list of the parameters can be found in Table 4.7.

The listed variables have been set targeting an iso-singlet E_6 quark of a mass of 1 TeV. This value is reasonably above the previously established quark mass limits, and the analysis is sensitive to a good region of possible quark masses. We have refrained from fine tuning the analysis for multiple different mass points, as the low background nature of the channel and our loose cuts generically provide reasonable coverage and the changing of the cut values seemed to provide very limited gains in our tests.

4.2.2.1. Z Boson Mass Window Range. The Z boson mass window variable holds a crucial importance on removing some of the major sources of the background from the

Table 4.7: The values of the parameters used in the analysis.

Parameter	$Z \rightarrow e^+e^-$ Channel	$Z \rightarrow \mu^+\mu^-$ Channel
Z window width	± 10 GeV	± 10 GeV
σ_H	18 GeV	17 GeV
Minimum P_T for prompt jets	65 GeV	65 GeV
Minimum P_T for first prompt jet	100 GeV	100 GeV
σ_{D_Z}	35 GeV	42 GeV
σ_{D_H}	62 GeV	54 GeV
Maximum allowed event χ^2	15	15

analysis. The current Z window is set according to the reconstructed width of the Z boson in the 1000 GeV E_6 signal sample. The Figure 4.2 left and right plots show the Z mass histograms of 1000 GeV E_6 quark signal for both triggers. The Z shapes in both triggers are completely observed to be Gaussian with a small width. The width of the electron sample is about 1.4 GeV and the width of the muon sample is about 3.8 GeV. In this analysis it is decided to set the Z window as ± 10 GeV. This decision ensures that the majority of the Z signals to reconstructed while still being able to reject a significant amount from the background. (The Z +jets background makes up the 95% of the overall background.

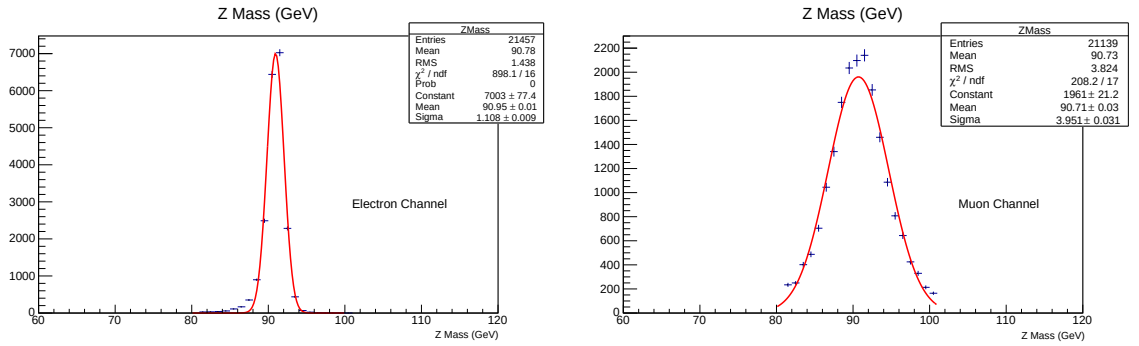


Figure 4.2: Reconstructed Z mass histogram from the 1000 GeV signal Monte Carlo sample in the electron (left) and muon (right) channels.

4.2.2.2. σ_H Parameter. This parameter is set by considering the width of the reconstructed Higgs mass histogram of the 1000 GeV E_6 signal MC sample. The determination method does not involve the truth information but a recursive algorithm that fits a Gaussian function to the mass of the reconstructed Higgs boson candidates. At each step of the recursion, the σ_H obtained from previous step is re-determined from the width of the Gaussian fit and it is fed back to calculate its value for the next step. The algorithm ends when consecutive σ_H calculations start to converge. The convergence is defined by a deviation of less than 0.5%, and quickly attained after only few (4-5) iterations. Figure 4.3 shows such a the Gaussian fit to the reconstructed Higgs mass in the electron and muon channels. The Gaussian fit appears qualitatively decent for the Higgs signal, although the effect of the χ^2 algorithm making the distribution sharper (narrower) than the Gaussian fit function cannot be disregarded.

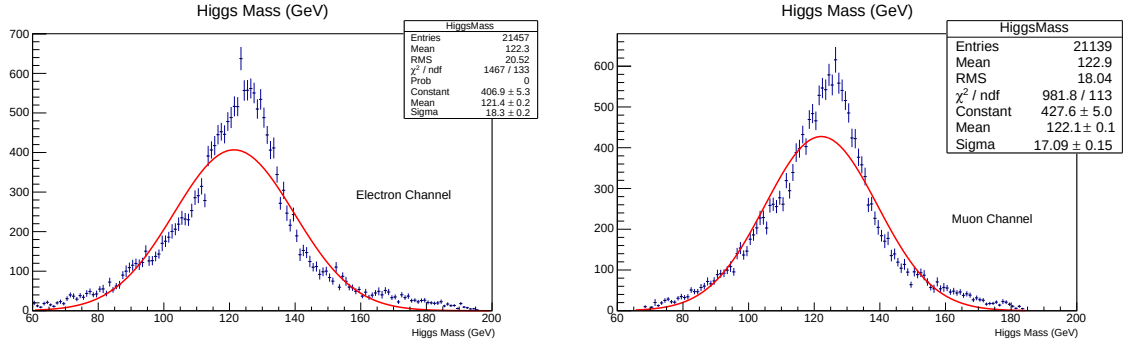


Figure 4.3: Reconstructed H mass histogram from the 1000 GeV signal Monte Carlo sample in the electron (left) and muon (right) channels.

According to these results, the electron channel's width is determined to be ~ 18 GeV and the muon channel's width is found to be ~ 17 GeV.

4.2.2.3. Prompt Jet Minimum P_T . The E_6 heavy quark can also be distinguished from the known SM particles by the help of the fact that when it decays, the daughters are expected to have high P_T . For this reason, we expect that the P_T of the prompt jet candidates to be higher than 65 GeV [87, 88]. Moreover, requiring at least one of the prompt jets to have an even higher P_T improves background rejection and the correct jet assignment in the reconstruction of the iso-singlet quarks, particularly in the absence of b -tagging. However, Monte Carlo modelling of jet momentum is not

entirely reliable, so we performed a quick optimization study to see if the statistical gain obtained by setting high thresholds would benefit the expected search limits in any significant manner. In the untagged case, we have extracted the expected 95% CL limit for different values of the threshold for the 1000 GeV signal, and observed that increasing the threshold from 100 GeV (where the cut is 100% efficient, see Figure 4.4) up to 400 GeV gradually improves the final results, but above 400 GeV, the expected limit gets to a rough plateau. On the other hand, we have also observed that, compared to untagged case with 400 GeV threshold, the expected limit is still slightly better for 100 GeV threshold when at least one of the Higgs daughter candidates is required to be b -tagged. So we prefer to stick to a 100 GeV threshold and b -tagging, in line with our as-loose-as-reasonably-possible philosophy described earlier. The details of this study can be found in Appendix A.7.

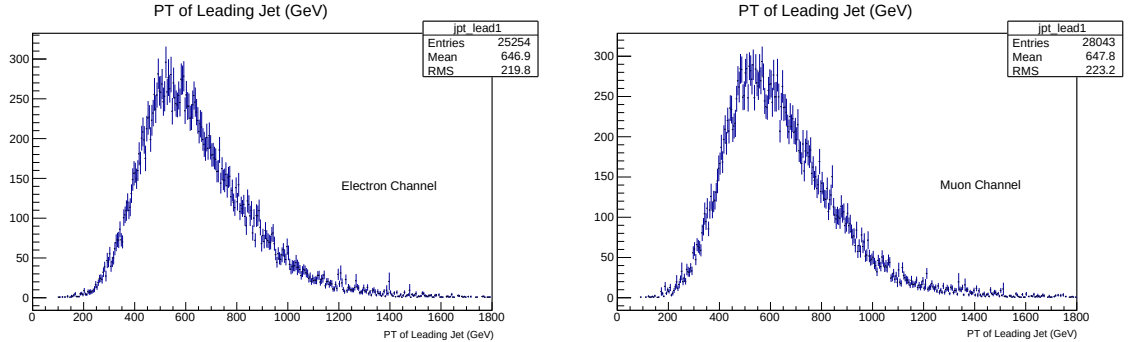


Figure 4.4: Transverse momentum of the leading jet for the 1000 GeV signal Monte Carlo sample in the electron (left) and muon (right) channels.

4.2.2.4. σ_{D_Z} and σ_{D_H} Parameters. Similar to the σ_H parameter, the σ_{D_Z} and σ_{D_H} parameters are obtained by Gaussian fit in the 1000 GeV E_6 signal MC samples. This width range nearly stays constant with small variations as the E_6 signal's mass is swept. Figure 4.5 shows the width of the E_6 iso-singlet quark reconstructed from a Z boson. According to these figures, in the electron channel the width is 35 GeV and in the muon channel the width is 42 GeV. Figure 4.6 plots the width of the E_6 iso-singlet quark reconstructed from a Higgs boson. In the electron channel the width is 62 GeV and in the muon channel the width is 54 GeV. As it is visible, the Gaussian fits on these graphs are not perfect but they are decent enough to provide benchmark values.

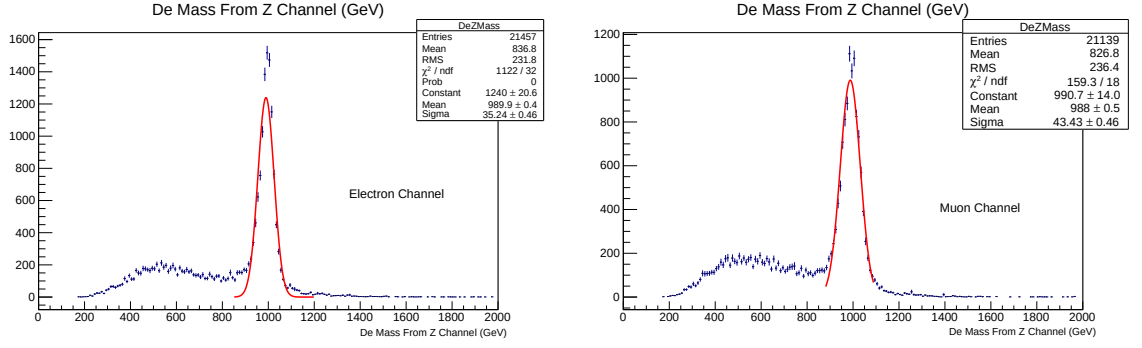


Figure 4.5: Mass of a 1000 GeV E_6 iso-singlet quark reconstructed from a Z boson and a prompt jet, obtained in the electron (left) and muon (right) channels.

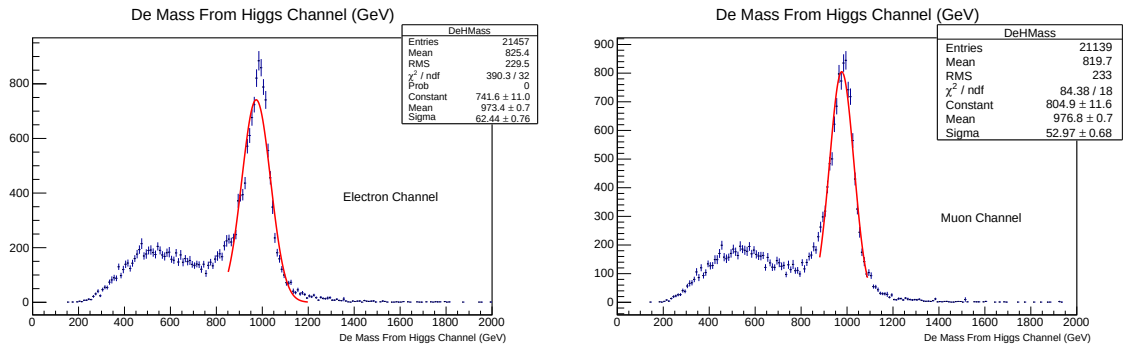


Figure 4.6: Mass of a 1000 GeV E_6 iso-singlet quark reconstructed from a H boson and a prompt jet, obtained in the electron (left) and muon (right) channels.

4.2.2.5. Maximum Allowed χ^2 Value. If the total χ^2 value is very high, one concludes that either the Higgs reconstruction has failed or the reconstructed E_6 quarks have a large mass difference between them, indicating a random combination of objects mimicking the signal. For this reason, we set a maximum allowed event χ^2 value. This threshold is again set according to the χ^2 distribution of the E_6 signal at 1000 GeV (Figure 4.7), though we have chosen a relatively loose value (15), so the efficiency of the requirement is high for any signal quark mass. We also include Figure 4.8 and 4.9 only to demonstrate that data/MC is well-modelled.

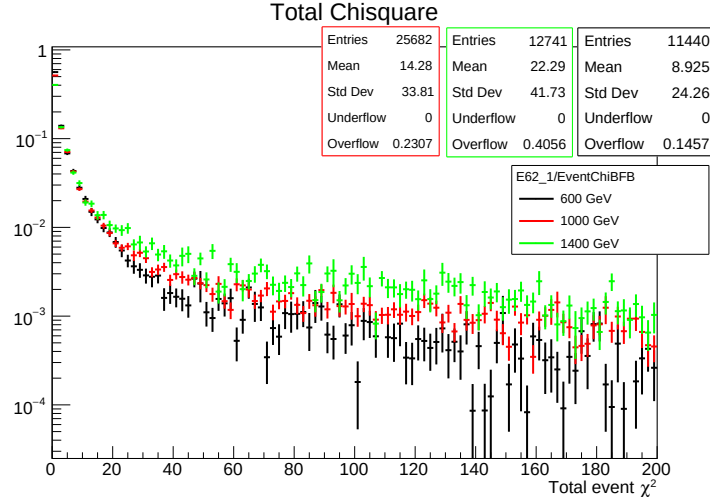


Figure 4.7: Total event χ^2 for the 600, 1000 and 1400 GeV signal Monte Carlo samples with one b -tag required.

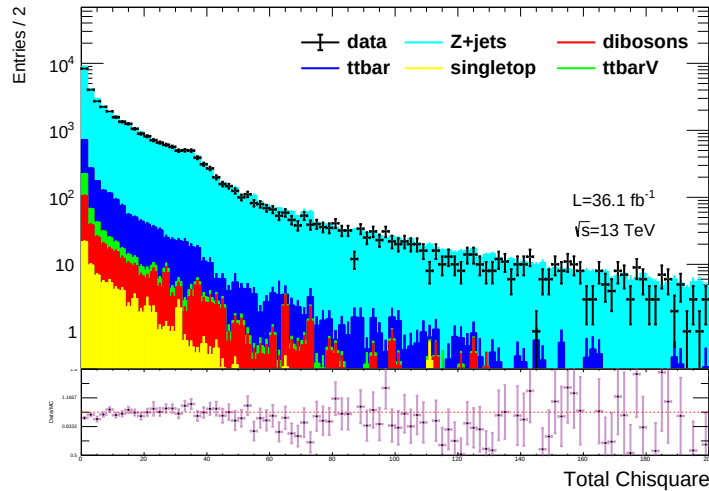


Figure 4.8: Total event χ^2 for the data and Monte Carlo background in the $\mu\mu$ channel in the signal region.

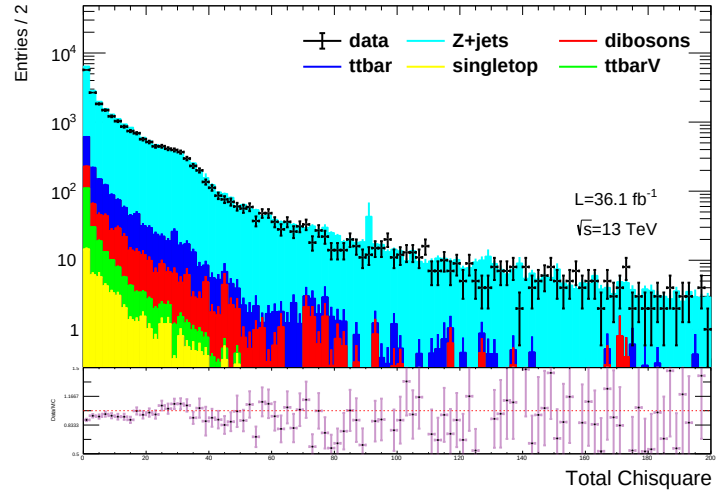


Figure 4.9: Total event χ^2 for the data and Monte Carlo background in the ee channel in the signal region.

4.3. Data, Signal and Background

This section summarizes all the data and MC samples used in the analysis, and describes the control regions for checking the validity of the Monte Carlo simulation for the two dominant background sources.

4.3.1. Data

For this analysis, data collected at $\sqrt{s} = 13 \text{ TeV}$ during 2015 and 2016, corresponding to an integrated luminosity of 36.1 fb^{-1} , are used. We start with the ntuples generated for the VLQ OSML analysis [73], located at `/eos/atlas/atlascerngroupdisk/physics-exotics/hqt/OSML/*`. A complete list of the runs is presented in Appendix Section A.1.

4.3.2. E_6 Signal Samples

The signal for this analysis is a pair of heavy iso-singlet quarks (each denoted as D , though one of them is actually $\bar{D}$). We assume that the E_6 iso-singlet quarks that are used are the lightest iso-singlet quarks proposed in the model. The signal events are generated with COMPHEP v4.5.1 [89] in the process $pp \rightarrow DD \rightarrow VjVj$ ($V = Z, H, W$). The events that are produced by COMPHEP are then fed to PYTHIA 8 for parton showering, fragmentation and hadronization [90]. The signal sample is generated with equal branching ratio for all D decay channels. For this reason, an event weight that corrects the E_6 -predicted branching ratios are applied to the signal. The signal MC events have been generated with varying mass, with 200 GeV increments spanning the range of 600-1600 GeV (with the exception of 800 GeV). Finally the current signal samples have a single lepton cut applied to them at the generator level. The list of all the samples can be found in Appendix A.1.

4.3.3. Simulated Background Samples

The search for iso-singlet quarks in the $ZjHj$ channel requires a clean lepton pair signal that can be reconstructed back to a Z boson. Since the ATLAS detector has high Z reconstruction efficiency and a good Z mass resolution, most of the non- Z background can easily be removed. For this reason, the dominant background is from the Z +jets processes which amount to 95% of the overall background. The second biggest contribution comes from the $t\bar{t}$ and di-boson backgrounds which together contribute 9% of the total. The rest of the background is composed of single-top, and W +jets backgrounds, whose contributions are minimal.

4.3.3.1. Z +Jets Background. For the description of the Z boson production plus associated jets, the samples produced by SHERPA 2.2.1 [91] using the NNPDF30NNLO PDF set are used. In order to ensure enough statistics are available in the high P_T range, the samples are produced in slices of the Z boson P_T and with different mutually exclusive filters for the heavy flavour composition.

4.3.3.2. $t\bar{t}$ and Single Top Background. The SM $t\bar{t}$ background process is modelled by samples generated with POWHEG BOX with the CT10 PDF set and interfaced with PYTHIA 6.428 with the CTEQ6L PDF set and the Perugia2012 tune. In this sample non all-hadronic final states only are considered, since the main contribution for the multileptonic topologies of the analysis comes from the leptonic decays of $t\bar{t}$.

The singletop background process have been generated by POWHEG + PYTHIA 8, with the Perugia2012 tune and the CT10 PDF set.

4.3.3.3. Di-Boson Background. The contribution from diboson processes (i.e. ZZ , WZ and WW) is evaluated using samples generated by SHERPA 2.1 using the CT10 PDF set. These samples seem to better describe topologies with high jet multiplicity. The hadronization is performed by PYTHIA 8 using the AZNLO tune.

4.3.3.4. W +Jets Background. The processes corresponding to the production of a W boson plus extra jets in the final states are generated with POWHEG + PYTHIA using the CTEQ6L1 PDF set and the AZNLO tune.

4.3.4. QCD Background Estimation

In this analysis the QCD background's contribution is expected to be negligible as the analysis makes use of a tight lepton selection and reconstructs a Z boson. This was tested experimentally in the Run 1 analyses [87, 92], by using the MM matrix method developed by the D0 Collaboration implemented in the FakesMacros tool. In the final state we are interested in, the QCD background estimate was found to not even reach 0.2% of the overall background. Actually, the event weights calculated by the FakesMacros tool were generally observed to be negative, we had concluded that the QCD background was entirely negligible in Run 1.

4.3.5. Control Region Studies (Z +Jets and $t\bar{t}$)

In order to study the reliability of the Monte Carlo modelling of the backgrounds, two regions which are enriched in the two dominant backgrounds were defined. So as to allow cross-checking of the yields with the other ATLAS exotics analyses, we have chosen the most of the early selection criteria to mimic those of Reference [73], and apply additional requirements later to follow our own signal requirements.

4.3.5.1. $t\bar{t}$ Control Region. Events in this control region are required to contain at least 2 b -tagged jets and a dilepton invariant mass away from resonances, ie. outside the Z window ($m_{\ell\ell} - m_Z > 10$ GeV) and with $m(\ell\ell) > 50$ GeV which also makes sure the orthogonality of signal region and $t\bar{t}$ control region. Avoiding the lower dilepton masses improves the $t\bar{t}$ purity of the CR. We also reject events with $P_T(Z) > 600$ GeV to make sure no signal (either from our own final state or other E_6 channels accidentally contaminates the CR. ΔR_{Zj} veto stands for rejecting events for which the reconstructed Z and the leading jet, $2.0 \leq \Delta R_{Z,LeadingJet} \leq 2.8$. Also, at least one b -tagged jet in

Higgs-daughter jet candidates is required.

This CR is $\sim 94\%$ pure in the $t\bar{t}$ process, and hence is a clear cross-check of the quality of the $t\bar{t}$ Monte Carlo simulation. Figures 4.13-4.18 show that all the relevant kinematic variables compare very well between data and simulation. Tables 4.8, 4.8, 4.9, and 4.9 compare the yields⁴, again with very good agreement for both the ee and $\mu\mu$ channels of the analysis.

⁴In the yields table, the number of events left after χ^2 cut given according to non b -tagged working point, while we actually studied with 1 b -tagged working point.

Table 4.8: Signal and background yields in the $t\bar{t}$ control region; electron channel. $m_{\ell\ell}$ veto stands for the requirement: $|m_{ee} - m_Z| > 10 \text{ GeV}$ and $m_{ee} > 50 \text{ GeV}$. ΔR_{Zj} veto stands for rejecting events for which the reconstructed Z and the leading jet, $2.0 \leq \Delta R_{Z, \text{LeadingJet}} \leq 2.8$.

	Signal(1 TeV)	Z +jets	$t\bar{t}$
PreSelection	176.9 ± 1.2	$(1087 \pm 1.4) \times 10^4$	$(87.46 \pm 0.17) \times 10^3$
nLEP = 2	$(1885 \pm 2.0) \times 10^4$	$(1087 \pm 1.4) \times 10^4$	$(87.46 \pm 0.17) \times 10^3$
nJET ≥ 2	167.3 ± 1.1	$(756.4 \pm 2.7) \times 10^3$	$(72.3 \pm 0.2) \times 10^3$
nBJET ≥ 2	65.9 ± 0.7	$(10.1 \pm 0.1) \times 10^3$	$(33.1 \pm 0.1) \times 10^3$
$m_{\ell\ell}$ veto	0.74 ± 0.07	954 ± 35	$(25.76 \pm 0.01) \times 10^3$
$p_T^Z < 600 \text{ GeV}$	0.61 ± 0.07	952 ± 36	$(25.76 \pm 0.01) \times 10^3$
$E_T^{\text{miss}} < 200 \text{ GeV}$	0.59 ± 0.07	952 ± 36	$(253.1 \pm 0.1) \times 10^2$
ΔR_{Zj} veto	0.34 ± 0.05	676 ± 32	$(166.9 \pm 0.8) \times 10^2$
nJET ≥ 4	0.32 ± 0.05	176.4 ± 8.4	4735 ± 41
$\chi^2 < 15$	0.31 ± 0.05	62.2 ± 2.3	1979 ± 27
	$t\bar{t} + V$	singletop	dibosons
PreSelection	502.7 ± 2.3	7908 ± 36	$(44.4 \pm 0.3) \times 10^3$
nLEP = 2	502.7 ± 2.3	7908 ± 36	$(44.4 \pm 0.3) \times 10^3$
nJET ≥ 2	492.2 ± 2.3	3867 ± 25	8408 ± 246
nBJET ≥ 2	217.1 ± 1.6	852 ± 12	59.3 ± 6.6
$m_{\ell\ell}$ veto	68.0 ± 1.2	635 ± 11	20.4 ± 3.2
$p_T^Z < 600 \text{ GeV}$	67.9 ± 1.2	635 ± 11	20.4 ± 3.1
$E_T^{\text{miss}} < 200 \text{ GeV}$	62.8 ± 1.1	616 ± 10	19.6 ± 3.1
ΔR_{Zj} veto	42.0 ± 0.9	419.8 ± 8.6	14.0 ± 3.1
nJET ≥ 4	33.4 ± 0.8	87.3 ± 3.8	8.9 ± 2.4
$\chi^2 < 15$	20.1 ± 0.7	35.2 ± 2.5	4.6 ± 1.6

Table 4.8: Signal and background yields in the $t\bar{t}$ control region; electron channel. $m_{\ell\ell}$ veto stands for the requirement: $|m_{ee} - m_Z| > 10 \text{ GeV}$ and $m_{ee} > 50 \text{ GeV}$. ΔR_{Zj} veto stands for rejecting events for which the reconstructed Z and the leading jet, $2.0 \leq \Delta R_{Z, \text{Leading Jet}} \leq 2.8$ (cont.).

	Total SM bkg	Signal + SM bkg	Data	data/mc
PreSelection	$(1101 \pm 1.4) \times 10^4$	$(1101 \pm 1.4) \times 10^4$	$(1144 \pm 0.3) \times 10^4$	1.04
nLEP = 2	$(1101 \pm 1.4) \times 10^4$	$(1101 \pm 1.4) \times 10^4$	$(1144 \pm 0.3) \times 10^4$	1.04
nJET ≥ 2	$(84.2 \pm 1.1) \times 10^4$	$(84.2 \pm 0.3) \times 10^4$	$(889.9 \pm 0.9) \times 10^3$	1.06
nBJET ≥ 2	$(4.428 \pm 4.411) \times 10^4$	$(4.435 \pm 0.2) \times 10^4$	47410 ± 218	1.07
$m_{\ell\ell}$ veto	$(2744 \pm 10.3) \times 10^1$	$(2744 \pm 10.3) \times 10^1$	27580 ± 166	1.01
$p_T^Z < 600 \text{ GeV}$	$(2744 \pm 10.3) \times 10^1$	$(2744 \pm 10.3) \times 10^1$	27580 ± 166	1.01
$E_T^{\text{miss}} < 200 \text{ GeV}$	$(2697 \pm 10.2) \times 10^1$	$(2697 \pm 10.2) \times 10^1$	27160 ± 165	1.01
ΔR_{Zj} veto	$(1784 \pm 8.3) \times 10^1$	$(1784 \pm 8.3) \times 10^1$	17980 ± 134	1.01
nJET ≥ 4	5041 ± 42	5041 ± 42	5221 ± 72	1.04
$\chi^2 < 15$	2101 ± 28	2101 ± 28	2150 ± 46	1.02

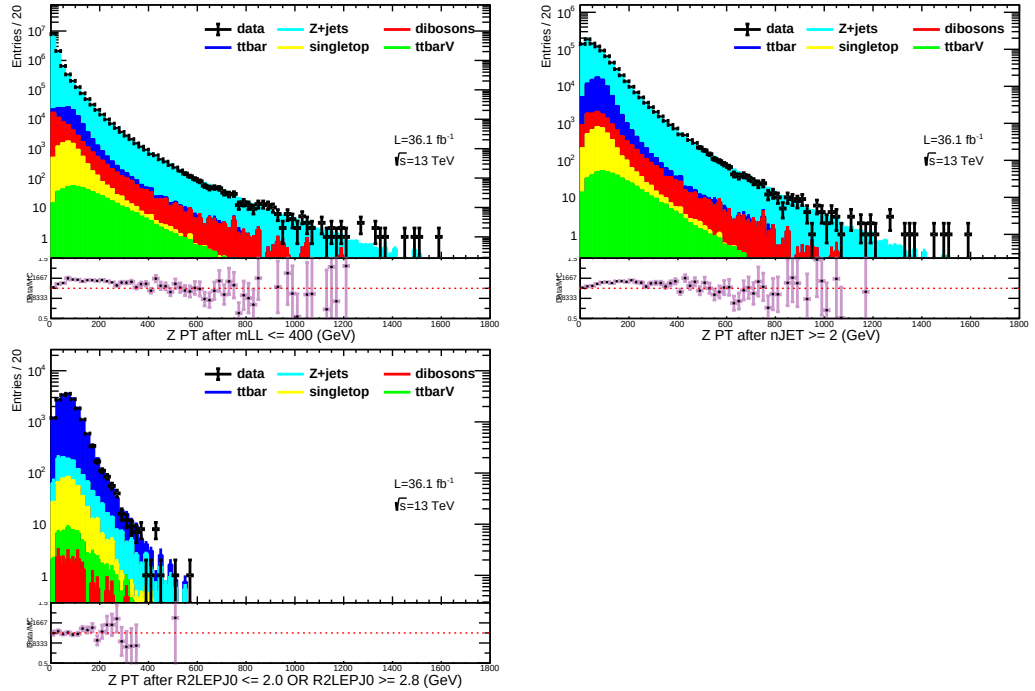


Figure 4.10: Z boson P_T distribution in the ee channel in the $t\bar{t}$ control region at various levels of the analysis algorithm. (*Top-left*) after preselections, (*top-right*) after cut #2 and (*bottom-left*) after cut #7 (see Table 4.3) .

Table 4.9: Signal and background yields in the $t\bar{t}$ control region; muon channel. $m_{\ell\ell}$ veto stands for the requirement: $|m_{\mu\mu} - m_Z| > 10 \text{ GeV}$ and $m_{\mu\mu} > 50 \text{ GeV}$. ΔR_{Zj} veto stands for rejecting events for which the reconstructed Z and the leading jet,

$$2.0 \leq \Delta R_{Z, \text{LeadingJet}} \leq 2.8.$$

	Signal (1 TeV)	Z +jets	$t\bar{t}$
PreSelection	163.3 ± 1.1	$(1743 \pm 2) \times 10^4$	$(114.4 \pm 0.2) \times 10^3$
nLEP == 2	163.3 ± 1.1	$(1743 \pm 2) \times 10^4$	$(114.4 \pm 0.2) \times 10^3$
nJET ≥ 2	163.3 ± 1.1	$(1198 \pm 4) \times 10^3$	$(95.44 \pm 0.18) \times 10^3$
nBJET ≥ 2	66.18 ± 0.70	$(14.57 \pm 0.19) \times 10^3$	$(44.0 \pm 0.1) \times 10^3$
$m_{\ell\ell}$ veto	5.24 ± 0.20	1515 ± 48	$(34.16 \pm 0.11) \times 10^3$
$p_T^Z < 600 \text{ GeV}$	3.13 ± 0.15	1513 ± 47	$(34.16 \pm 0.11) \times 10^3$
$E_T^{\text{miss}} < 200 \text{ GeV}$	2.92 ± 0.14	1511 ± 47	$(33.54 \pm 0.11) \times 10^3$
ΔR_{Zj} veto	1.71 ± 0.11	1120 ± 43	$(22.24 \pm 0.09) \times 10^3$
nJET ≥ 4	1.61 ± 0.11	302 ± 12	6628 ± 49
$\chi^2 < 15$	1.54 ± 0.10	95 ± 5	2667 ± 31
	$t\bar{t} + V$	singletop	dibosons
PreSelection	781.1 ± 2.875	10370 ± 41	33000 ± 134
nLEP == 2	781.1 ± 2.875	10370 ± 41	33000 ± 134
nJET ≥ 2	759.4 ± 2.841	5210 ± 29	6222 ± 46
nBJET ≥ 2	139.6 ± 1.515	1160 ± 14	40 ± 23
$m_{\ell\ell}$ veto	139.6 ± 1.515	862 ± 12	17.5 ± 2.4
$p_T^Z < 600 \text{ GeV}$	139.3 ± 1.5	862 ± 12	17.5 ± 2.4
$E_T^{\text{miss}} < 200 \text{ GeV}$	129.0 ± 1.5	564.4 ± 9.8	15.8 ± 2.3
ΔR_{Zj} veto	86.4 ± 1.2	132.3 ± 4.4	11.5 ± 2.0
nJET ≥ 4	63.89 ± 1.08	132.3 ± 4.4	8.3 ± 1.6
$\chi^2 < 15$	38.2 ± 0.9	46.2 ± 2.6	3.2 ± 1.0

Table 4.9: Signal and background yields in the $t\bar{t}$ control region; muon channel. $m_{\ell\ell}$ veto stands for the requirement: $|m_{\mu\mu} - m_Z| > 10 \text{ GeV}$ and $m_{\mu\mu} > 50 \text{ GeV}$. ΔR_{Zj} veto stands for rejecting events for which the reconstructed Z and the leading jet, $2.0 \leq \Delta R_{Z, \text{Leading Jet}} \leq 2.8$ (cont.).

	Total SM bkg	Signal + SM bkg	Data	data/mc
PreSelection	$(1759 \pm 1.8) \times 10^4$	$(1759 \pm 1.8) \times 10^4$	$(1832 \pm 0.43) \times 10^4$	1.04
nLEP=2	$(1759 \pm 1.8) \times 10^4$	$(1759 \pm 1.8) \times 10^4$	$(1832 \pm 0.43) \times 10^4$	1.04
nJET ≥ 2	$(1306 \pm 35.3) \times 10^3$	$(1306 \pm 3.71) \times 10^3$	$(1399 \pm 1.2) \times 10^3$	1.07
nBJET ≥ 2	$(6.011 \pm 1.7) \times 10^4$	$(60.18 \pm 0.23) \times 10^3$	64920 ± 255	1.08
$m_{\ell\ell}$ veto	36690 ± 121	36700 ± 121	36840 ± 192	1.00
$p_T^Z < 600 \text{ GeV}$	36690 ± 121	36690 ± 121	36830 ± 192	1.00
$E_T^{\text{miss}} < 200 \text{ GeV}$	36030 ± 120.1	3604 ± 120	36220 ± 190	1.01
ΔR_{Zj} veto	24020 ± 99.74	24020 ± 100	24180 ± 156	1.01
nJET ≥ 4	7135 ± 51	22750 ± 90	7365 ± 86	1.03
$\chi^2 < 15$	2850 ± 32	2851 ± 32	2923 ± 54	1.03

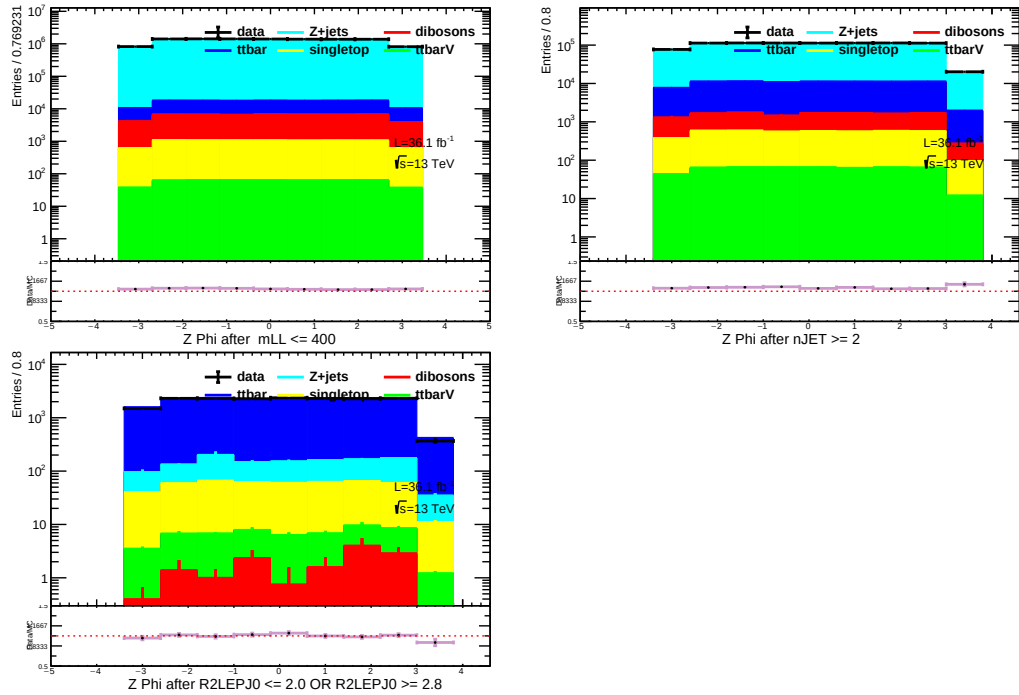


Figure 4.11: Z boson ϕ distribution in the ee channel in the $t\bar{t}$ control region at various levels of the analysis algorithm. (*Top-left*) after preselections, (*top-right*) after cut #2 and (*bottom-left*) after cut #7 (see Table 4.3) .

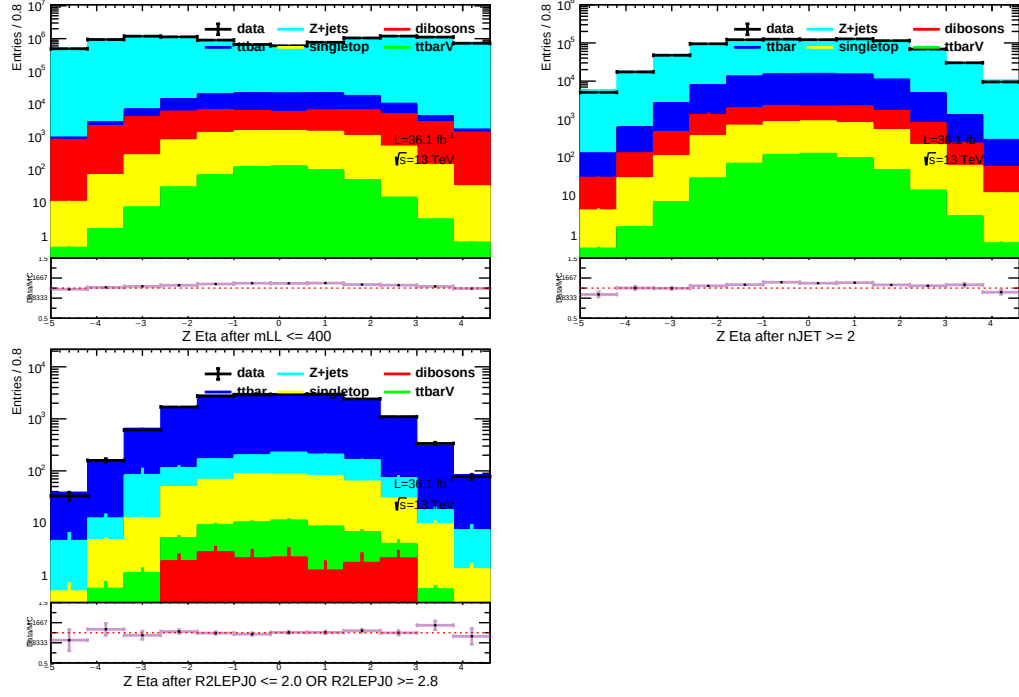


Figure 4.12: Z boson η distribution in the ee channel in the $t\bar{t}$ control region at various levels of the analysis algorithm. (*Top-left*) after preselections, (*top-right*) after cut #2 and (*bottom-left*) after cut #7 (see Table 4.3) .

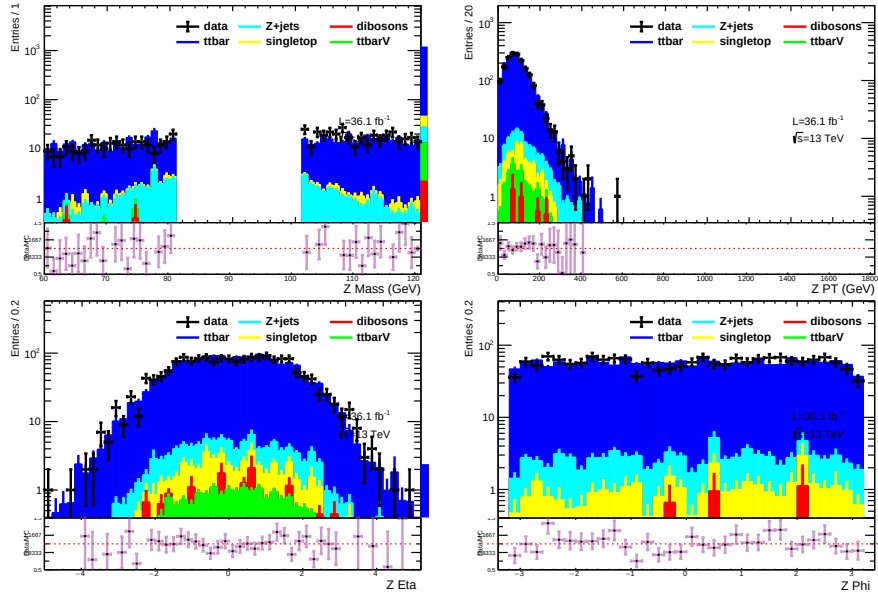


Figure 4.13: Kinematic distributions ((*top-left*) mass distribution, (*top-right*) P_T distribution, (*bottom-left*) η distribution, (*bottom-right*) ϕ distribution) of Z boson in the ee channel for one b-tagged case in the $t\bar{t}$ control region after all cuts (cut #9 in Table 4.3).

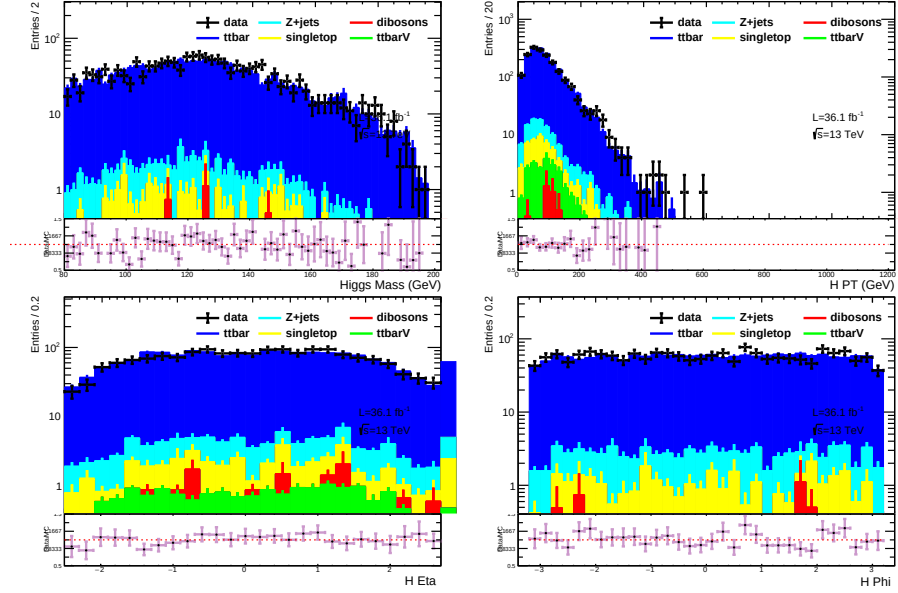


Figure 4.14: Kinematic distributions ((*top-left*) mass distribution, (*top-right*) P_T distribution, (*bottom-left*) η distribution, (*bottom-right*) ϕ distribution) of H boson in the ee channel for one b-tagged case in the $t\bar{t}$ control region after all cuts (cut #9 in Table 4.3).

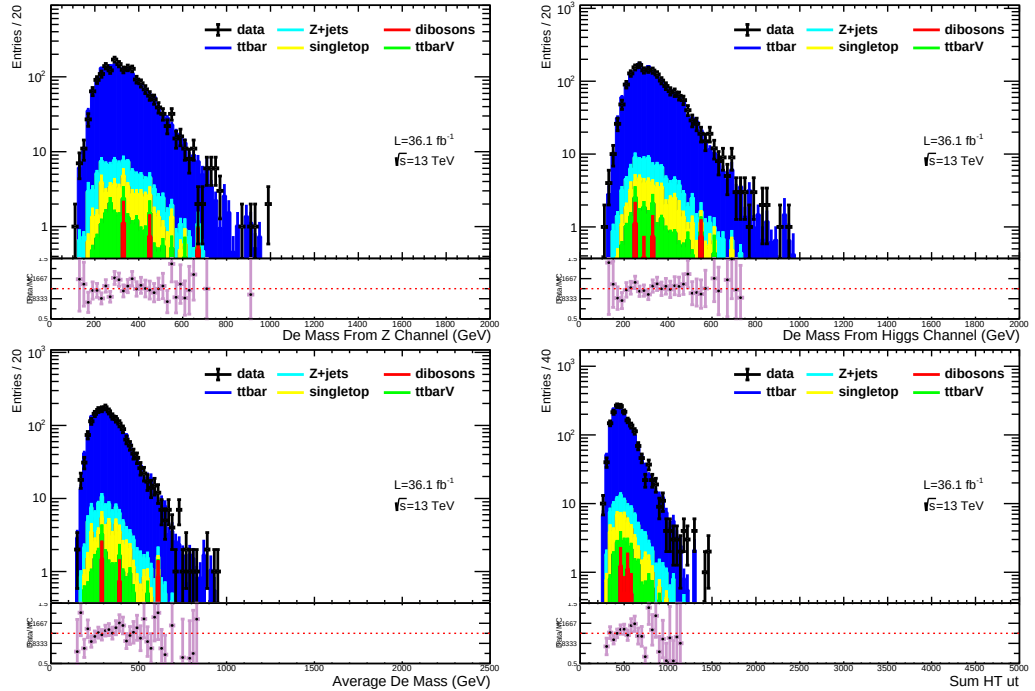


Figure 4.15: D quark mass reconstructed from a Z boson (*top-left*), D quark mass reconstructed from a H boson (*top-right*), average reconstructed D quark mass (*bottom-left*) and Sum H_T distributions (*bottom-right*) in case of one-btagged in the ee channel in the $t\bar{t}$ control region after all cuts (cut #9 in Table 4.3) .

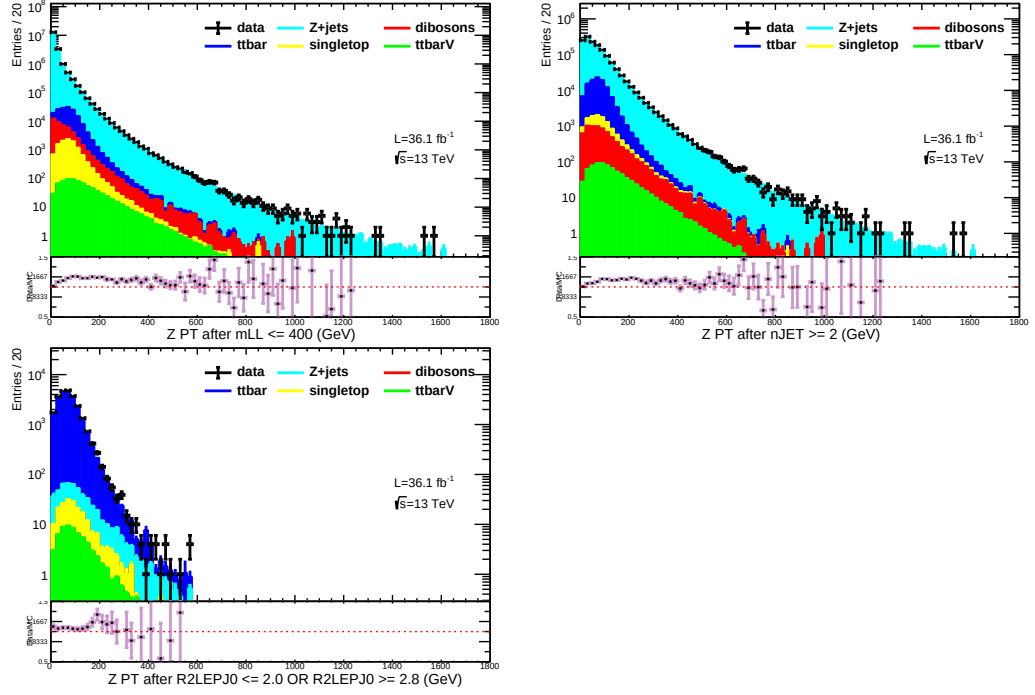


Figure 4.16: Z boson P_T distribution in the $\mu\mu$ channel in the $t\bar{t}$ control region at various levels of the analysis algorithm. (*Top-left*) after preselections, (*top-right*) after cut #2 and (*bottom-left*) after cut #7 (see Table 4.3) .

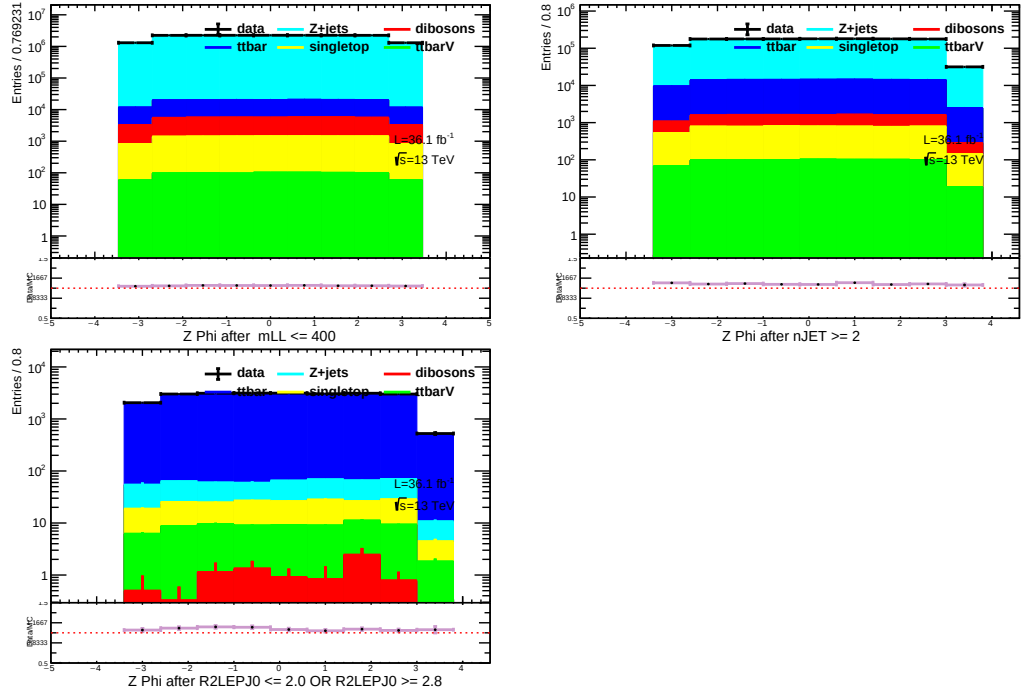


Figure 4.17: Z boson ϕ distribution in the $\mu\mu$ channel in the $t\bar{t}$ control region at various levels of the analysis algorithm. (*Top-left*) after preselections, (*top-right*) after cut #2 and (*bottom-left*) after cut #7 (see Table 4.3) .

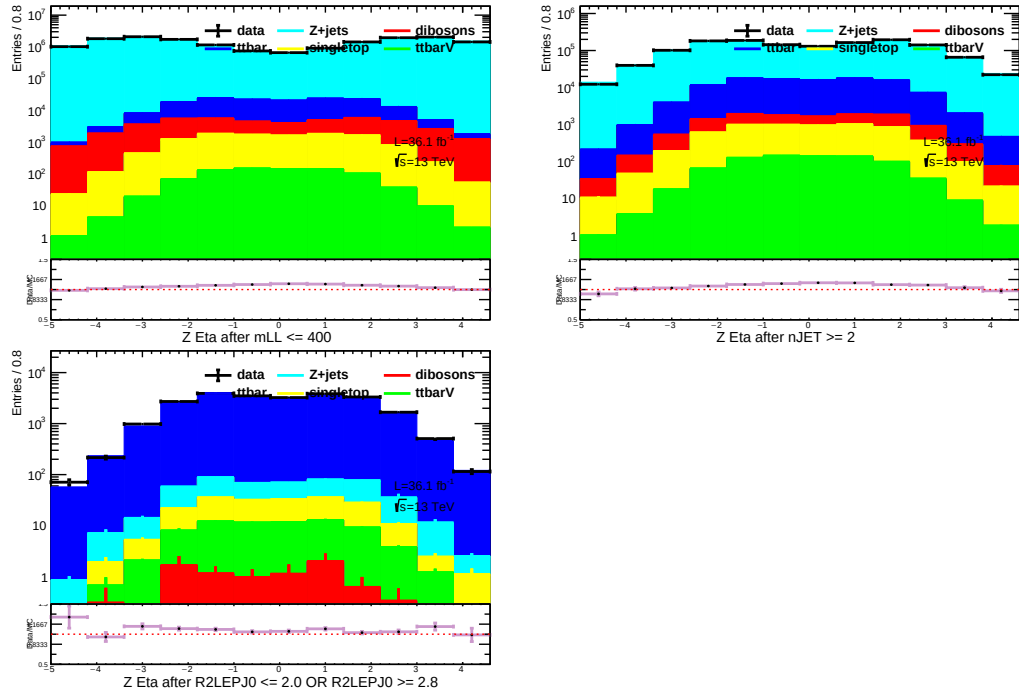


Figure 4.18: Z boson η distribution in the $\mu\mu$ channel in the $t\bar{t}$ control region at various levels of the analysis algorithm. (*Top-left*) after preselection, (*top-right*) after cut #2 and (*bottom-left*) after cut #7 (see Table 4.3) .

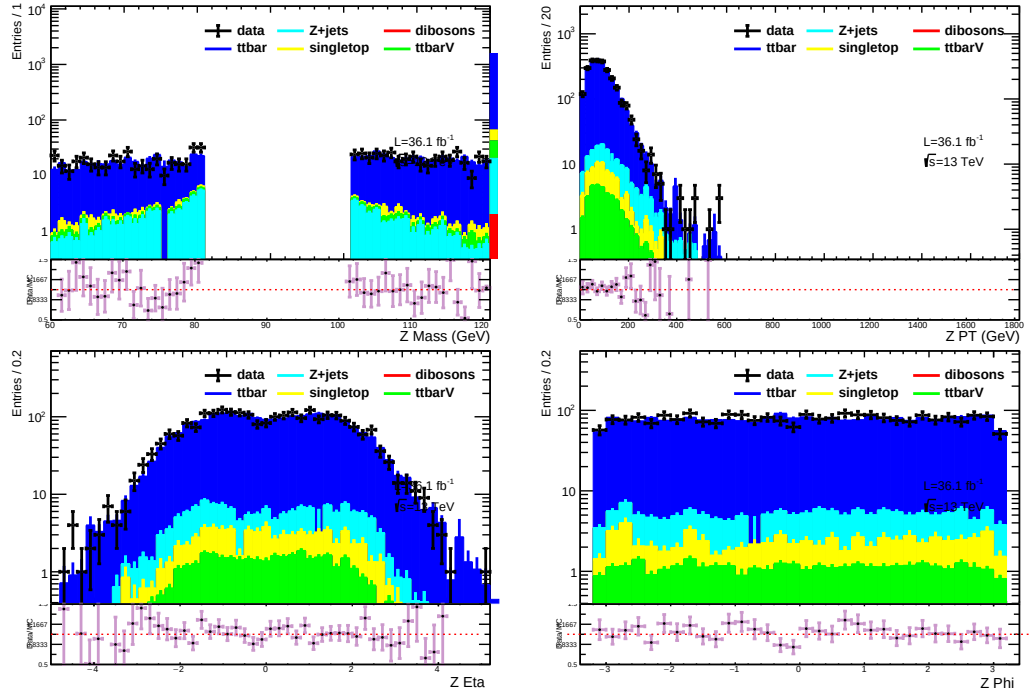


Figure 4.19: Kinematic distribution ((*top-left*) mass distribution, (*top-right*) P_T distribution, (*bottom-left*) η distribution, (*bottom-right*) ϕ distribution) of Z boson in the $\mu\mu$ channel in the $t\bar{t}$ control region for one b-tagged case after all cuts (cut #9 in Table 4.3).

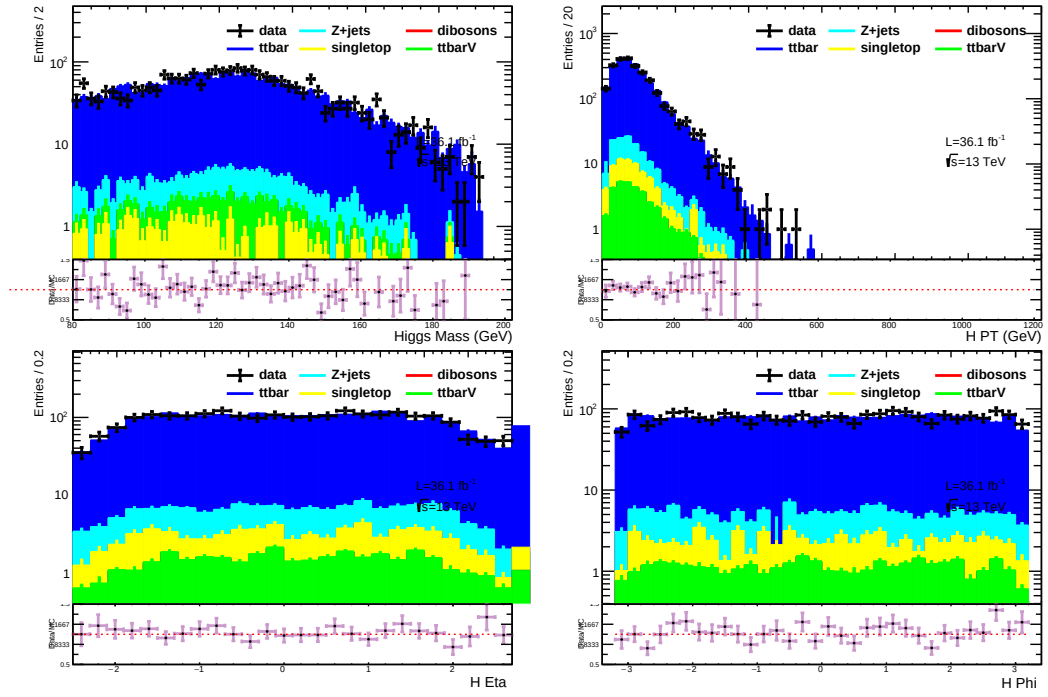


Figure 4.20: Kinematic distribution (*top-left*) mass distribution, (*top-right*) P_T distribution, (*bottom-left*) η distribution, (*bottom-right*) ϕ distribution) of H boson in the $\mu\mu$ channel in the $t\bar{t}$ control region for one b-tagged case after all cuts (cut #9 in Table 4.3).

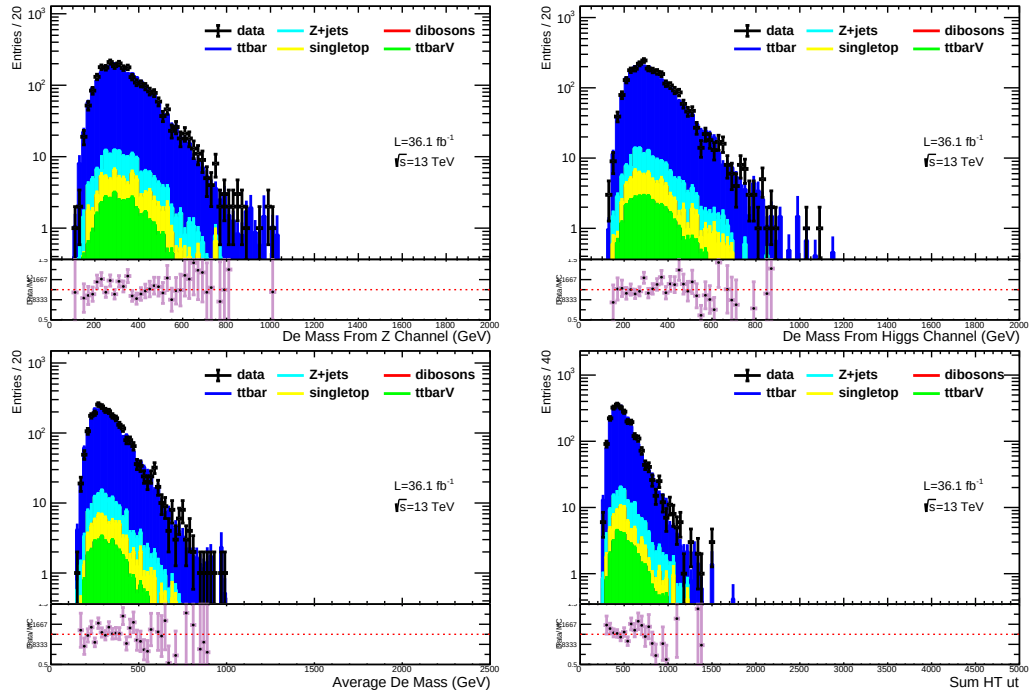


Figure 4.21: D quark mass reconstructed from a Z boson (*top-left*), D quark mass reconstructed from a H boson (*top-right*), average reconstructed D quark mass (*bottom-left*) and Sum H_T distributions (*bottom-right*) in the $\mu\mu$ channel in the $t\bar{t}$ control region for one-btagged case after all cuts (cut #9 in Table 4.3).

4.3.5.2. Z +jets Control Region. The Z +jets control region is defined with the same selection criteria as the signal region for the Z reconstruction, but using a maximum $H_T(jets)$ to make sure no signal contamination remains. We also require two b -tagged jets, to be able to compare our yields with those of reference [73]. Figures 4.22-4.33 show the kinematics for all the relevant physics objects, particularly those that pertain the Z boson. Relatively good agreement is observed throughout, particularly as the selection requirements become closer and closer to our signal selection criteria. In particular, it is comforting to see that requiring four jets in the event improves the agreement. Also, in order to make sure that Z +jets control region and signal region are orthogonal, we vetoed an event if there exist a b -tagged jet in Higgs-daughter jets.

We should note that while the ee channel has an almost perfect agreement between data and simulation, the $\mu\mu$ channel seems to have a normalization issue of around 10/20%. This issue had also been observed in reference [73], and the reason is not clear, but it seems only to affect the Z +jets background prediction as it is not visible in the $t\bar{t}$ control-region and in the early cuts of the signal-region analysis.

Tables 4.10, and 4.11 show the event yields for the different background processes, signal and data. This CR is $\sim 84\%$ pure in the Z +jets process, with a significant contribution from $t\bar{t}$ events. The modeling of $t\bar{t}$, however, has already been checked in the $t\bar{t}$ CR.

Table 4.10: Signal and background yields in the Z +jets control region; electron channel.

	Signal (1 TeV)	Z +jets	$t\bar{t}$
PreSelection	167.4 ± 1.2	$(1087 \pm 1.389) \times 10^4$	87460 ± 173
nLEP=2	167.4 ± 1.2	$(1087 \pm 1.389) \times 10^4$	87460 ± 173
nJET ≥ 2	167.3 ± 1.2	$(7564 \pm 27.20) \times 10^2$	72330 ± 157
nBJET ≥ 1	144.2 ± 1.1	98870 ± 892	64780 ± 150
$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	142.5 ± 1.1	87750 ± 850	8754 ± 55
HT(Jets) $< 1150 \text{ GeV}$	26.8 ± 0.5	87590 ± 850	8742 ± 55
nJET ≥ 4	21.6 ± 0.4	12070 ± 131	2020 ± 26
$\chi^2 < 15$	17.9 ± 0.4	3872 ± 31	801 ± 17
b-tagged jet veto	4.9 ± 0.2	2124 ± 18	334 ± 11
	$t\bar{t} + V$	singletop	dibosons
PreSelection	503 ± 2	7908 ± 36	$(44.4 \pm 0.3) \times 10^3$
nLEP == 2	503 ± 2	7908 ± 36	$(44.4 \pm 0.3) \times 10^3$
nJET ≥ 2	492 ± 2	3867 ± 25	8408 ± 246
nBJET ≥ 1	429 ± 2	3116 ± 23	820 ± 28
$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	281 ± 1	509.4 ± 8.3	460 ± 25
HT(Jets) $< 1150 \text{ GeV}$	277 ± 1	508.7 ± 8.3	456 ± 24
nJET ≥ 4	222 ± 1	94 ± 3	121 ± 16
$\chi^2 < 15$	138 ± 1	34 ± 2	46 ± 5
b-tagged jet veto	66 ± 1	16 ± 1	28 ± 4

Table 4.10: Signal and background yields in the Z +jets control region; electron channel (cont.).

	Total SM bkg	Signal + SM bkg	Data
PreSelection	$(1101 \pm 1.389) \times 10^4$	$(1101 \pm 1.389) \times 10^4$	$(1144 \pm 0.3) \times 10^4$
nLEP=2	$(1101 \pm 1.389) \times 10^4$	$(1101 \pm 1.389) \times 10^4$	$(1144 \pm 0.3) \times 10^4$
nJET ≥ 2	$(8414 \pm 27.35) \times 10^2$	$(8416 \pm 27.35) \times 10^2$	$(8899 \pm 9.43) \times 10^2$
nBJET ≥ 1	$(16.8 \pm 0.09) \times 10^4$	$(16.8 \pm 0.09) \times 10^4$	$(17.7 \pm 4.2) \times 10^2$
$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	97760 ± 852	97900 ± 852	$(10.4 \pm 3.2) \times 10^2$
HT(Jets) $< 1150 \text{ GeV}$	97580 ± 852	97600 ± 852	$(10.4 \pm 3.2) \times 10^2$
nJET ≥ 4	14530 ± 134	14550 ± 134	14470 ± 120
$\chi^2 < 15$	4892 ± 35	4910 ± 35	4476 ± 67
b-tagged jet veto	2567 ± 22	2572 ± 22	2279 ± 48

	data/mc
PreSelection	1.04
nLEP == 2	1.04
nJET ≥ 2	1.06
nBJET ≥ 1	1.05
$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	1.06
HT(Jets) $< 1150 \text{ GeV}$	1.07
nJET ≥ 4	0.996
$\chi^2 < 15$	0.915
b-tagged jet veto	0.888

Table 4.11: Signal and background yields in the Z +jets control region; muon channel.

	Signal(1 TeV)	Z +jets	$t\bar{t}$
PreSelection	163.3 ± 1.1	$(1743 \pm 2) \times 10^4$	$(114.4 \pm 0.2) \times 10^3$
nLEP = 2	163.3 ± 1.1	$(1743 \pm 2) \times 10^4$	$(114.4 \pm 0.2) \times 10^3$
nJET ≥ 2	163.3 ± 1.1	$(1198 \pm 4) \times 10^3$	$(95.44 \pm 0.18) \times 10^3$
nBJET ≥ 1	141.9 ± 1.0	$(147.6 \pm 1.3) \times 10^3$	$(857.1 \pm 1.7) \times 10^2$
$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	129.6 ± 1.0	$(130.3 \pm 1.2) \times 10^3$	11870 ± 65
HT(Jets) < 1150 GeV	23.0 ± 0.4	$(130.0 \pm 1.2) \times 10^3$	11850 ± 65
nJET ≥ 4	19.5 ± 0.4	19040 ± 293	2916 ± 32
$\chi^2 < 15$	16.1 ± 0.3	5704 ± 118	1069 ± 20
b-tagged jet veto	4.5 ± 0.2	3128 ± 28	467 ± 13
	$t\bar{t} + V$	singletop	dibosons
PreSelection	781.1 ± 2.9	10370 ± 41	33000 ± 134.2
nLEP=2	781.1 ± 2.9	10370 ± 41	33000 ± 134.2
nJET ≥ 2	759.4 ± 2.8	5210 ± 29	6222 ± 46.21
nBJET ≥ 1	667 ± 3	4182 ± 26	605 ± 17
$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	359 ± 2	701 ± 10	334 ± 14
HT(Jets) < 1150 GeV	354 ± 2	700 ± 10	330 ± 14
nJET ≥ 4	283 ± 1	138 ± 4	90 ± 5
$\chi^2 < 15$	171 ± 1	50 ± 2	33 ± 3
b-tagged jet veto	81 ± 1	24 ± 1	20 ± 2

Table 4.11: Signal and background yields in the Z +jets control region; muon channel
(cont.).

	Total SM bkg	Signal + SM bkg	Data
PreSelection	$(1759 \pm 1.7) \times 10^4$	$(1759 \pm 1.7) \times 10^4$	$(1832 \pm 0.4) \times 10^4$
nLEP == 2	$(1759 \pm 1.7) \times 10^4$	$(1759 \pm 1.7) \times 10^4$	$(1832 \pm 0.4) \times 10^4$
nJET ≥ 2	$(1306 \pm 35.4) \times 10^3$	$(1306 \pm 37.1) \times 10^3$	$(1399 \pm 1.2) \times 10^3$
nBJET ≥ 1	$(238.8 \pm 1.3) \times 10^3$	$(238.9 \pm 1.3) \times 10^3$	$(256.3 \pm 0.5) \times 10^3$
$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	$(143.5 \pm 12.0) \times 10^2$	$(143.7 \pm 12.0) \times 10^2$	$(156.2 \pm 0.4) \times 10^2$
HT(Jets) < 1150 GeV	$(143.3 \pm 12.0) \times 10^2$	$(143.3 \pm 12.0) \times 10^2$	$(155.9 \pm 0.4) \times 10^2$
nJET ≥ 4	$(2246 \pm 29.4) \times 10^1$	$(2248 \pm 29.4) \times 10^1$	$(2263 \pm 15.0) \times 10^1$
$\chi^2 < 15$	7027 ± 120	7044 ± 120	6721 ± 82
b-tagged jet veto	3720 ± 31	3725 ± 31	3478 ± 59

	data/mc
PreSelection	1.05
nLEP == 2	1.05
nJET ≥ 2	1.07
nBJET ≥ 1	1.07
$ m_{\ell\ell} - m_Z < 10 \text{ GeV}$	1.09
HT(Jets) < 1150 GeV	1.09
nJET ≥ 4	1.01
$\chi^2 < 15$	0.956
b-tagged jet veto	0.935

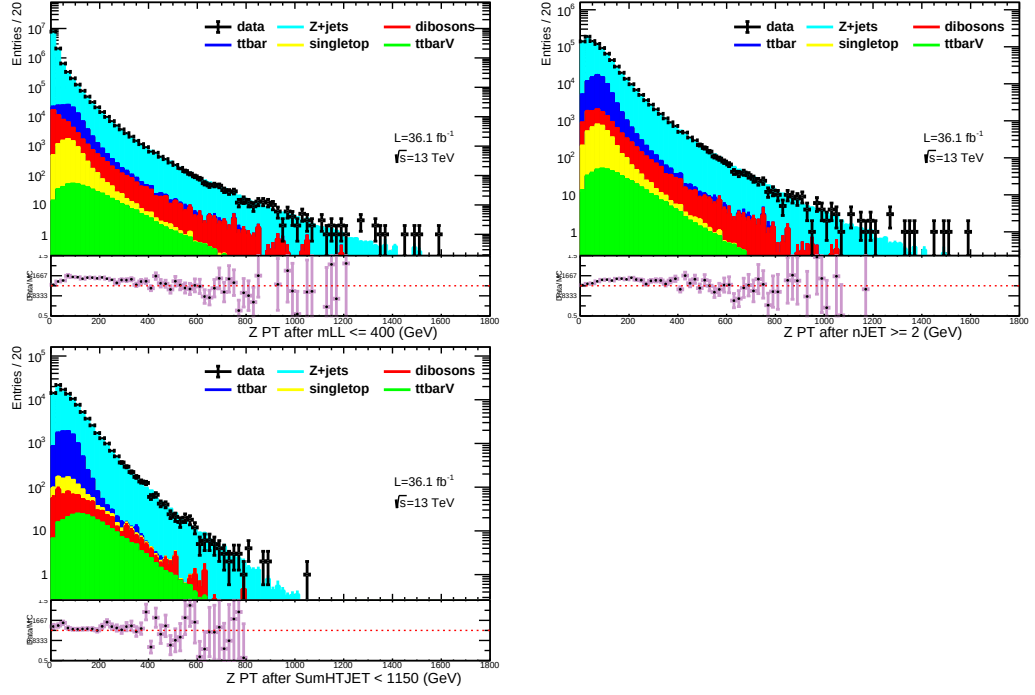


Figure 4.22: Z boson P_T distribution in the ee channel in the Z +jets control region at various levels of the analysis algorithm. (*Top-left*) after preselection, (*top-left*) after cut #2 and (*bottom-left*) after cut #5 (see Table 4.4).

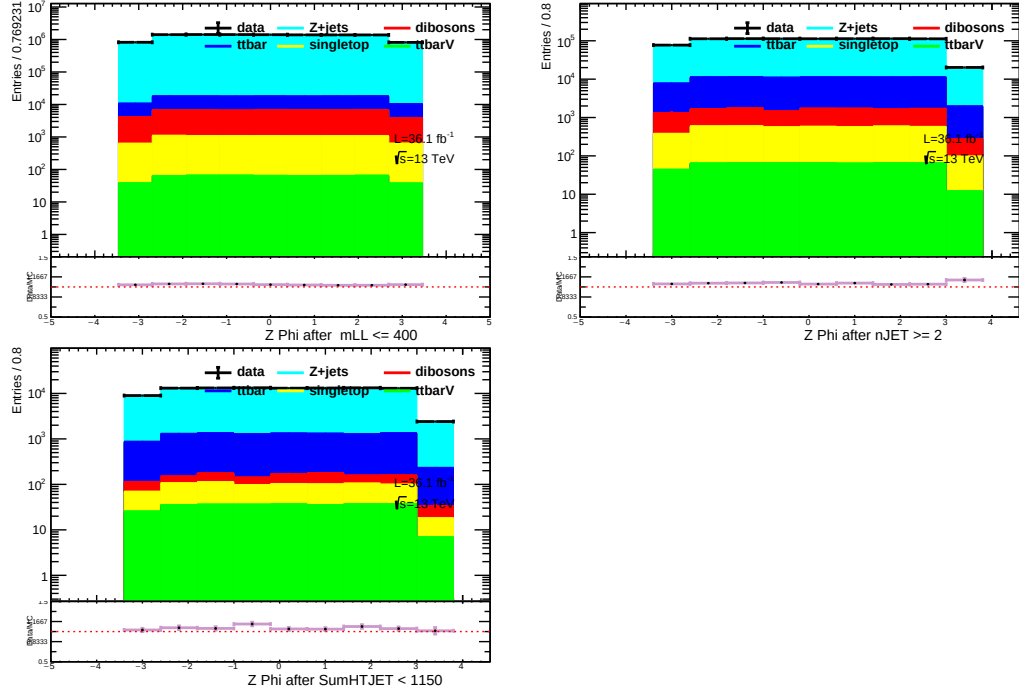


Figure 4.23: Z boson ϕ distribution in the ee channel in the Z +jets control region at various levels of the analysis algorithm. (*Top-left*) after preselections, (*top-right*) after cut #2 and (*bottom-left*) after cut #5 (see Table 4.4).

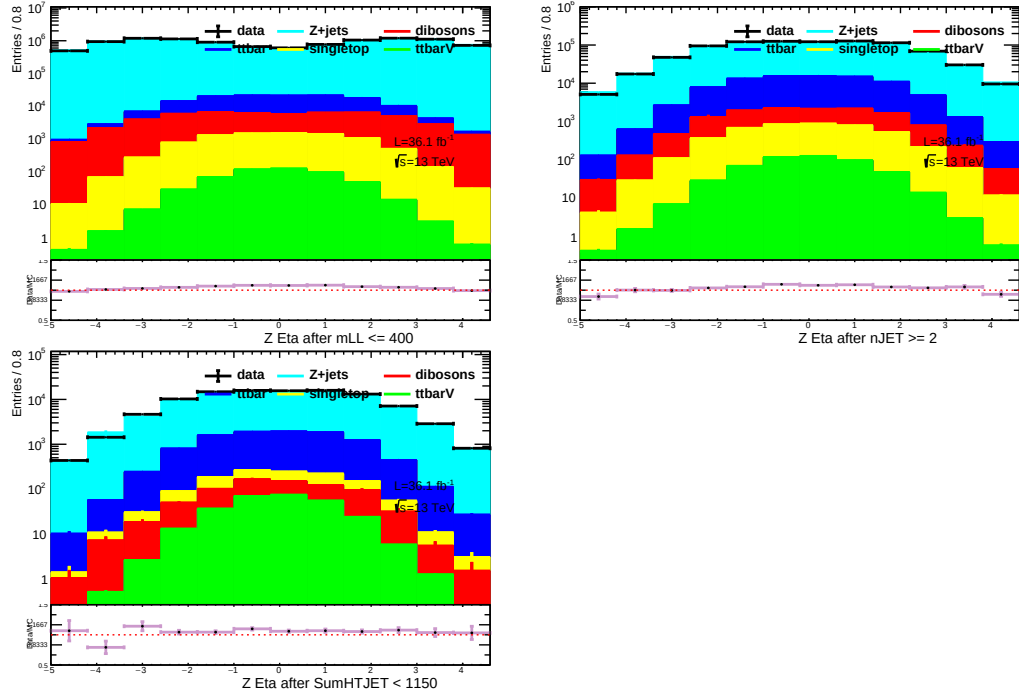


Figure 4.24: Z boson η distribution in the ee channel in the Z +jets control region at various levels of the analysis algorithm. (*Top-left*) after preselections, (*top-right*) after cut #2 and (*bottom-left*) after cut #5 (see Table 4.4).

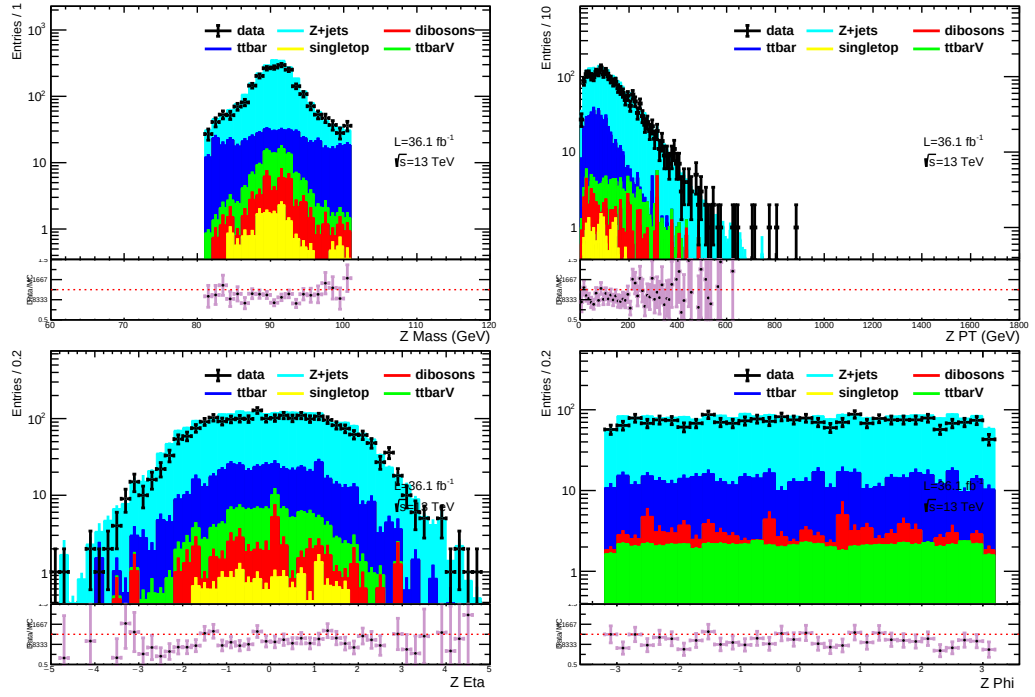


Figure 4.25: Kinematic distributions ((*top-left*) mass distribution, (*top-right*) P_T distribution, (*bottom-left*) η distribution, (*bottom-right*) ϕ distribution) of Z boson in the ee channel in the Z +jets control region for b-veto in Higgs-daughter jets case after all cuts (cut #7 in Table 4.4).

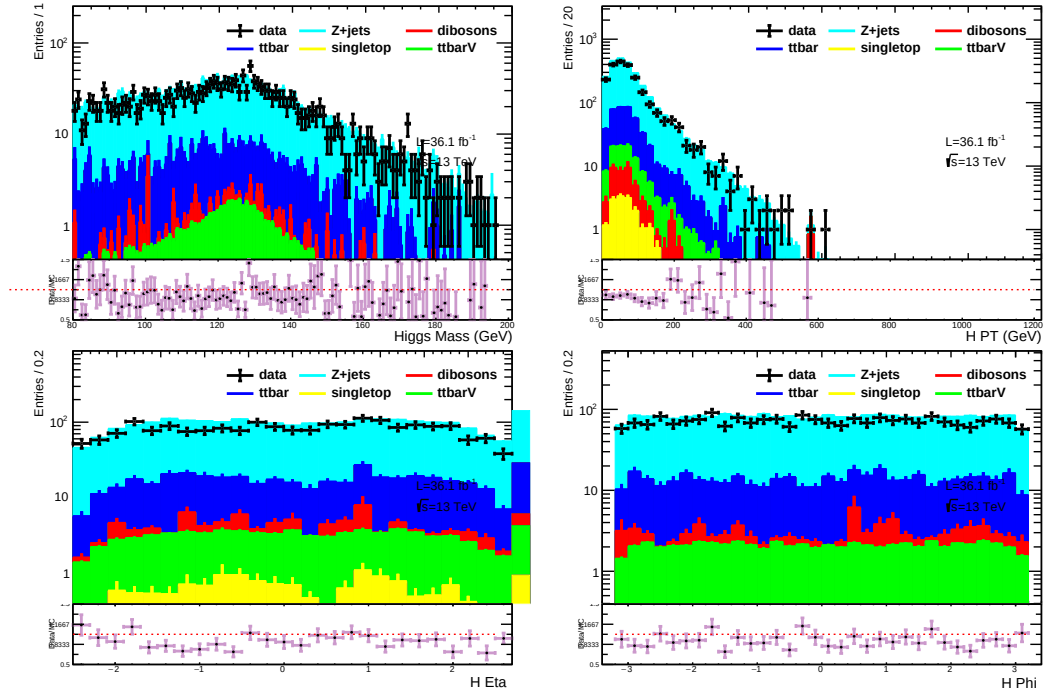


Figure 4.26: Kinematic distributions ((*top-left*) mass distribution, (*top-right*) P_T distribution, (*bottom-left*) η distribution, (*bottom-right*) ϕ distribution) of H boson in the ee channel in the Z +jets control region for b-veto in Higgs-daughter jets case after all cuts (cut #7 in Table 4.4).

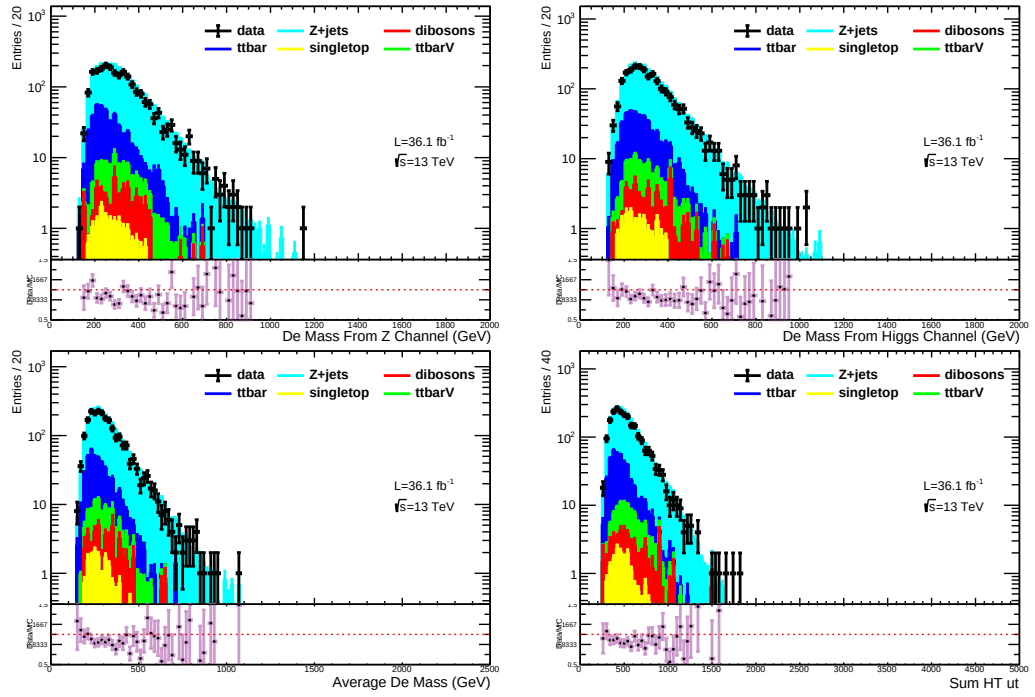


Figure 4.27: D quark mass reconstructed from a Z boson (*top-left*), D quark mass reconstructed from a H boson (*top-right*), average reconstructed D quark mass (*bottom-left*) and Sum H_T distributions (*bottom-right*) when b-tagged jets are vetoed in Higgs-daughters in the ee channel in the Z +jets control region after all cuts (cut #7 in Table 4.4) .

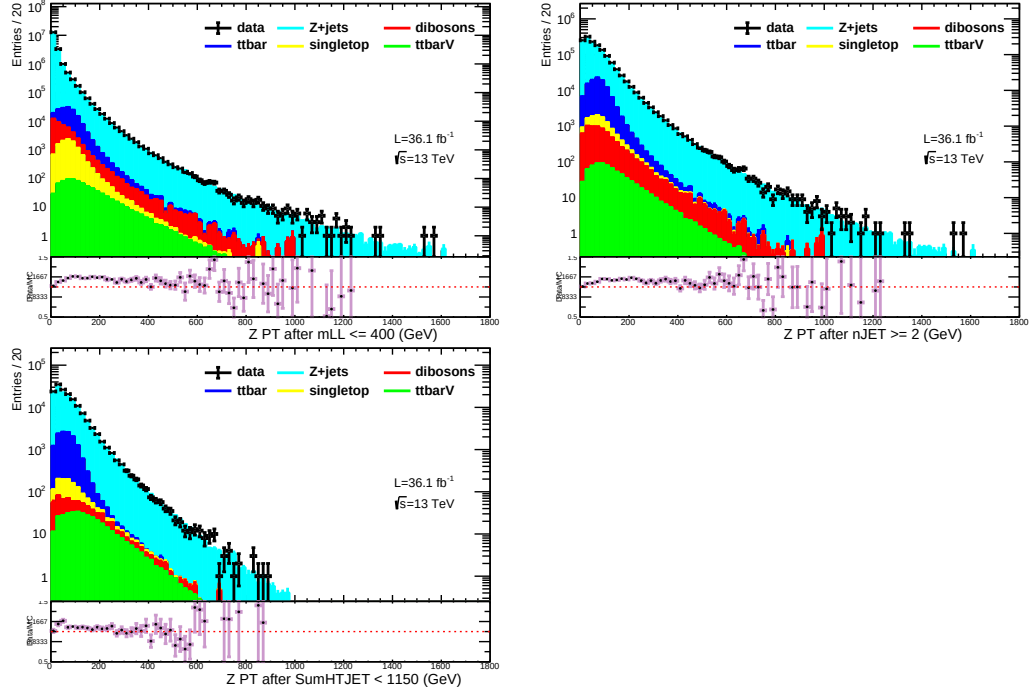


Figure 4.28: Z boson P_T distribution in the $\mu\mu$ channel in the Z +jets control region at various levels of the analysis algorithm. (*Top-left*) after preselections, (*top-right*) after cut #2 and (*bottom-left*) after cut #5 (see Table 4.4).

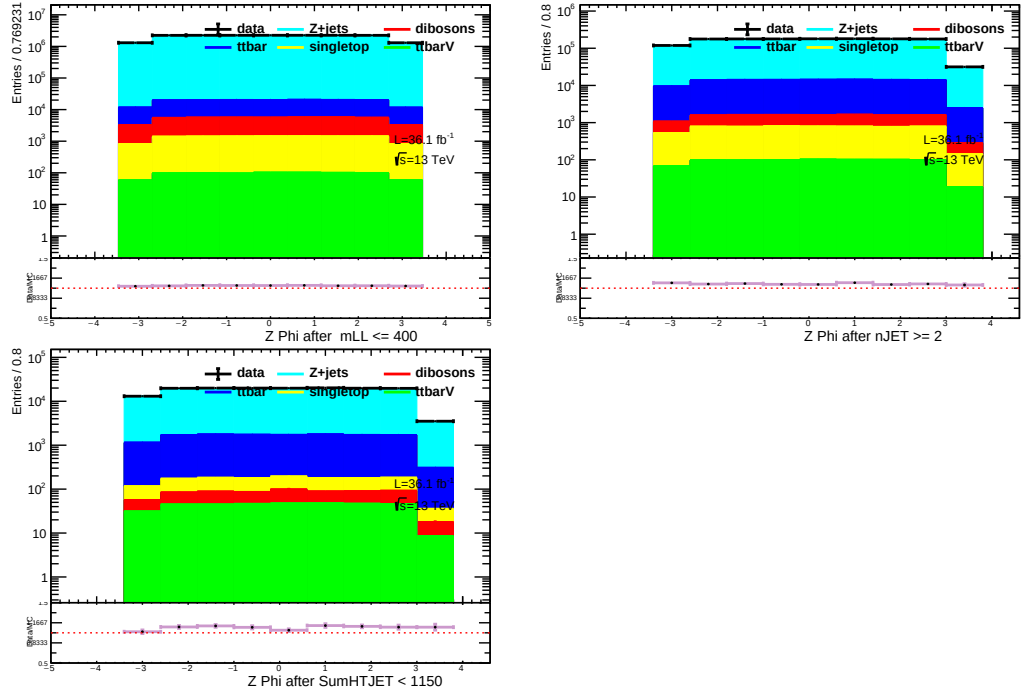


Figure 4.29: Z boson ϕ distribution in the $\mu\mu$ channel in the Z +jets control region at various levels of the analysis algorithm. (*Top-left*) after preselections, (*top-right*) after cut #2 and (*bottom-left*) after cut #5 (see Table 4.4).

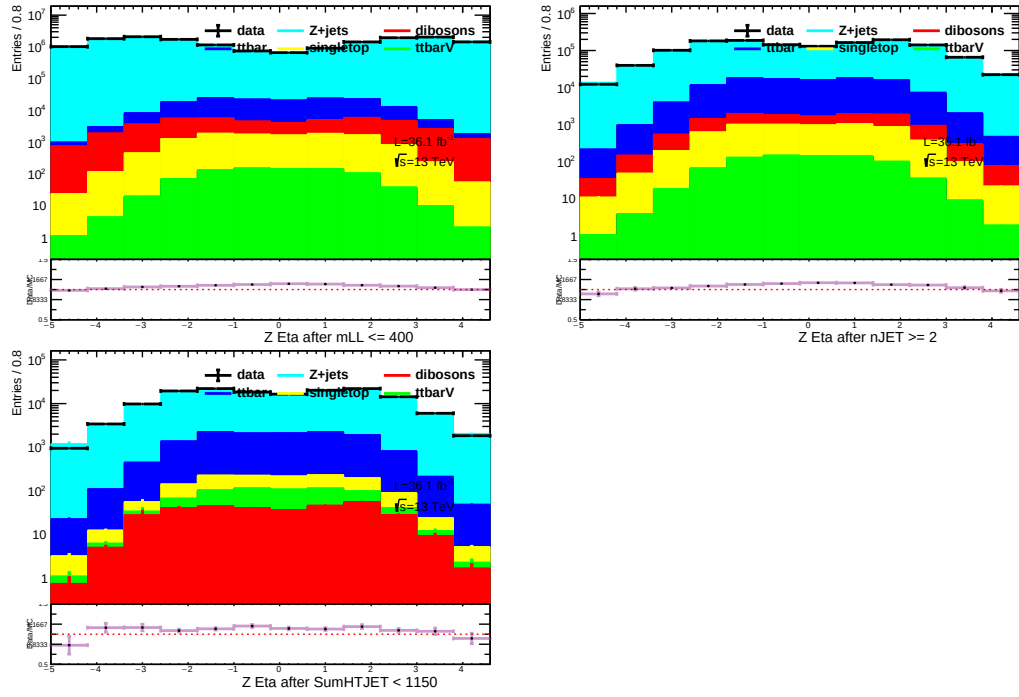


Figure 4.30: Z boson η distribution in the $\mu\mu$ channel in the Z +jets control region at various levels of the analysis algorithm. (*Top-left*) after preselections, (*top-right*) after cut #2 and (*bottom-left*) after cut #5 (see Table 4.4).

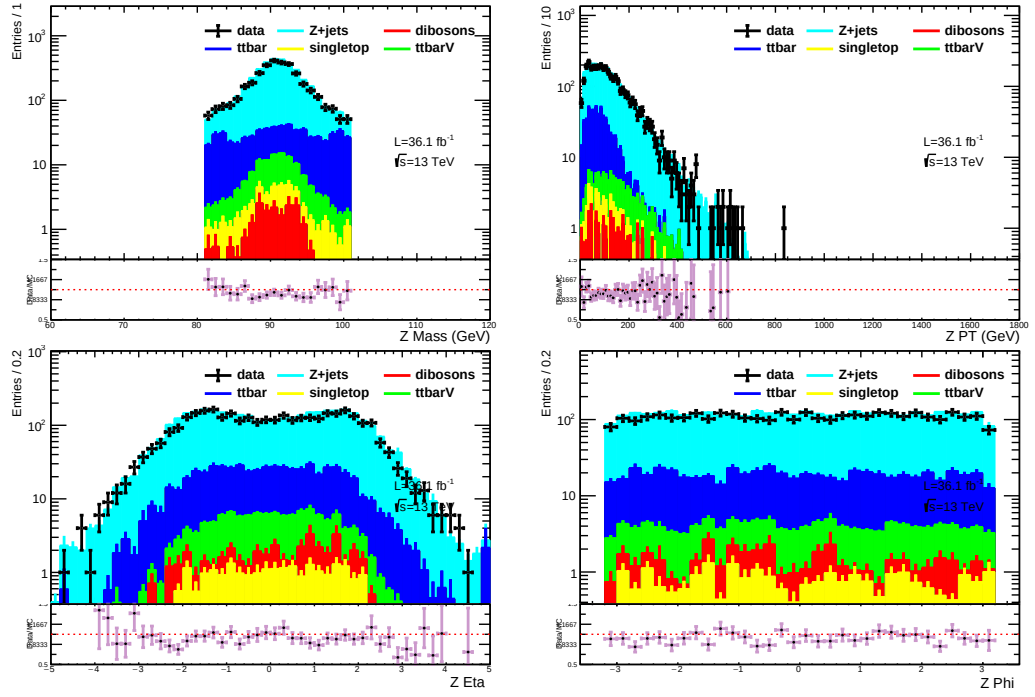


Figure 4.31: Kinematic distribution (*(top-left)* mass distribution, (*top-right*) P_T distribution, (*bottom-left*) η distribution, (*bottom-right*) ϕ distribution) of Z boson in the $\mu\mu$ channel in the Z +jets control region for b-veto in Higgs-daughter jets case after all cuts (cut #7 in Table 4.4).

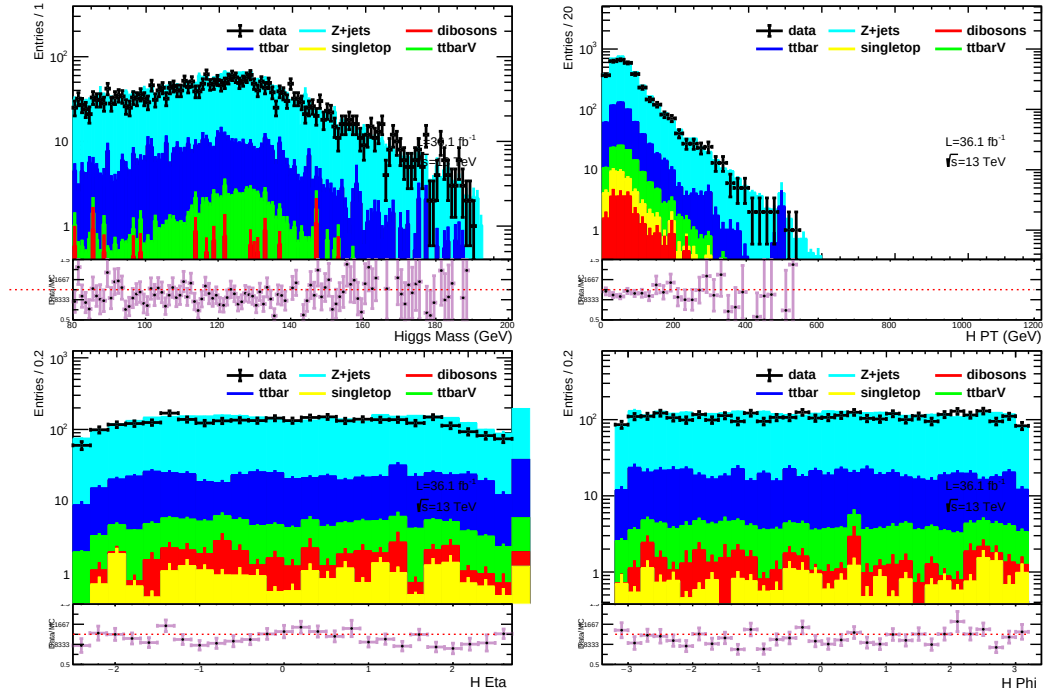


Figure 4.32: Kinematic distribution (*(top-left)* mass distribution, (*top-right*) P_T distribution, (*bottom-left*) η distribution, (*bottom-right*) ϕ distribution) of H boson in the $\mu\mu$ channel in the Z +jets control region for b-veto in Higgs-daughter jets case after all cuts (cut #7 in Table 4.4).

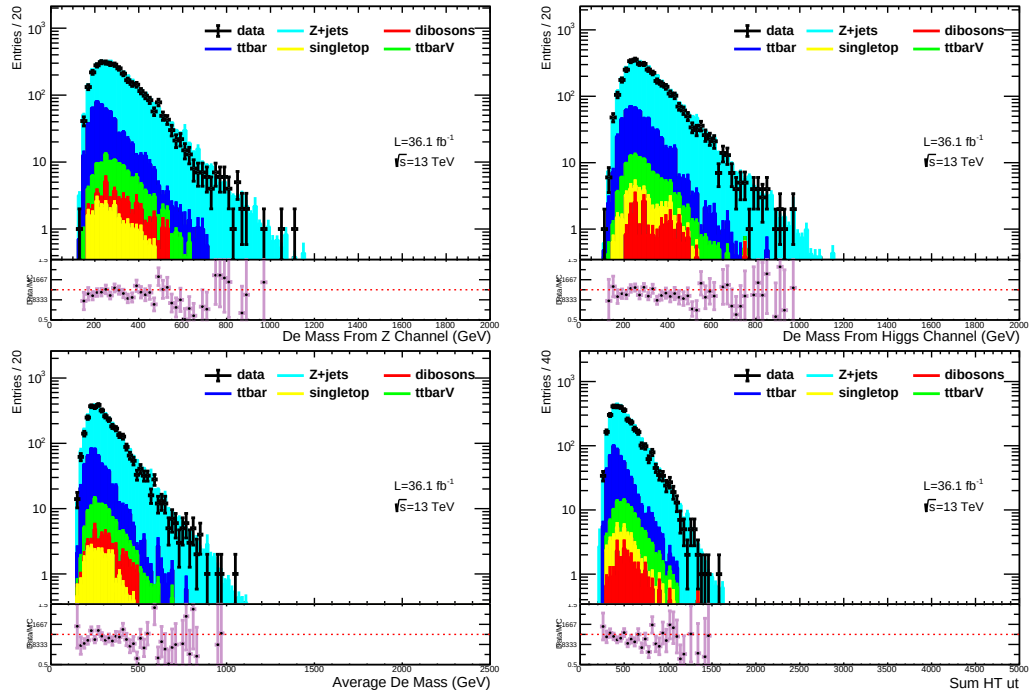


Figure 4.33: D quark mass reconstructed from a Z boson (*top-left*), D quark mass reconstructed from a H boson (*top-right*), average reconstructed D quark mass (*bottom-left*) and Sum H_T distributions (*bottom-right*) when b-tagged jets are vetoed in Higgs-daughters in the $\mu\mu$ channel in the Z +jets control region after all cuts (cut #7 in Table 4.4).

4.3.6. Signal Region Distributions

Here we give the distributions of the major kinematic variables as well as the different final discriminants in the signal region after all the selection criteria have been applied. Since the analysis is blinded, distributions which might in any way give clues about the presence or absence of an actual signal are shown only for the Monte Carlo samples. For such distributions, the signal histograms are also provided for comparison. Appendix A.3 shows plots from early injection tests performed using these histograms.

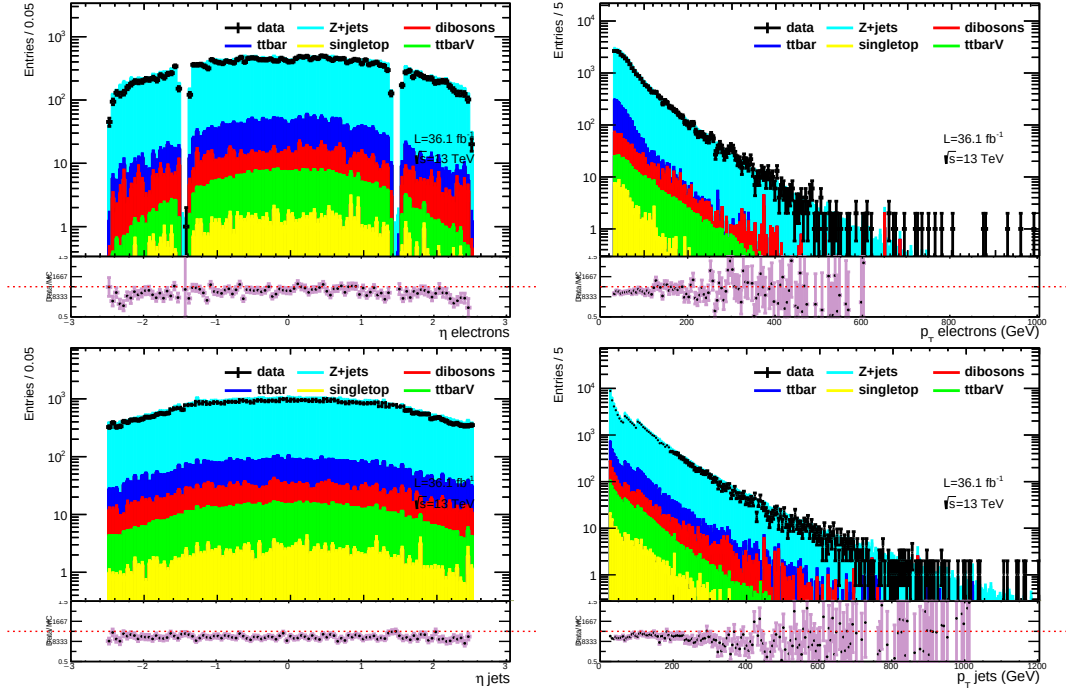


Figure 4.34: P_T , η distributions of electrons and jets in the ee channel in the signal region before b-tagging requirement (before cut #11 in Table 4.2).

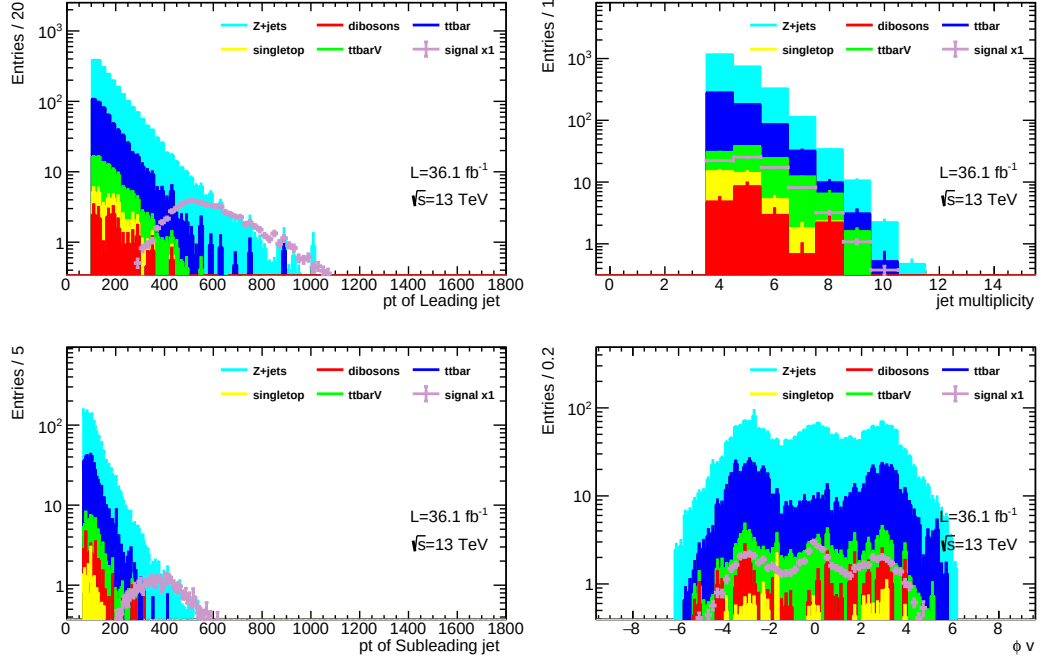


Figure 4.35: P_T of leading jet, jet multiplicity, P_T of subleading jet and ϕ of MET minus ϕ of leading jet distributions in the ee channel in the signal region after b-tagging requirement (after cut #11 in Table 4.2). Data is blinded at this level.

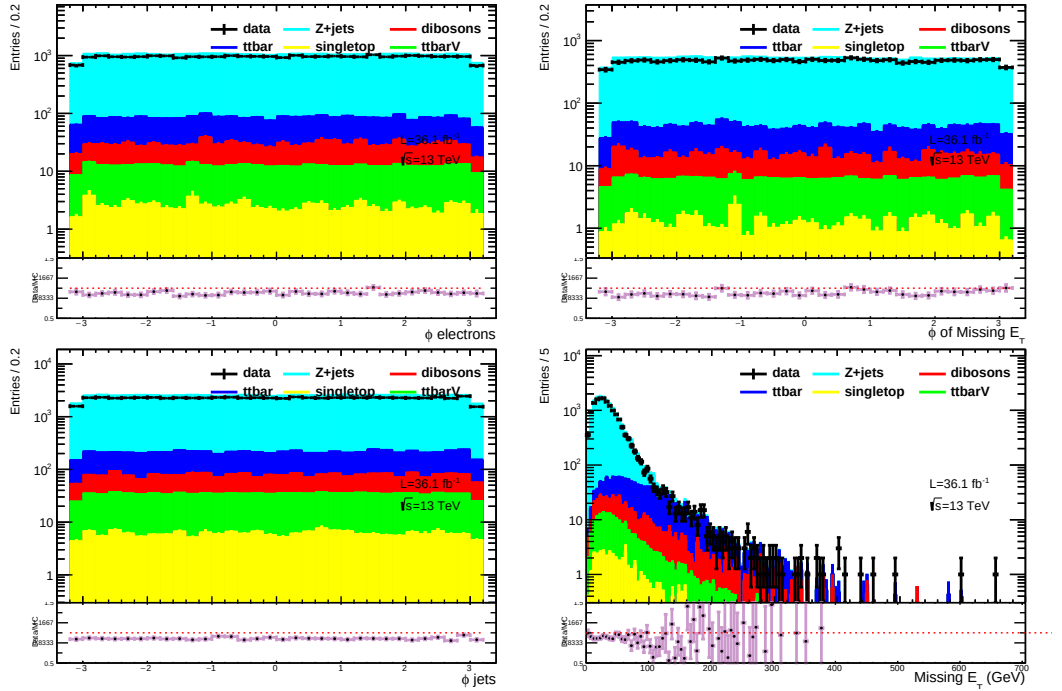


Figure 4.36: ϕ distributions of electrons, jets and MET and MET distribution in the ee channel in the signal region before b-tagging requirement (before cut #11 in Table 4.2).

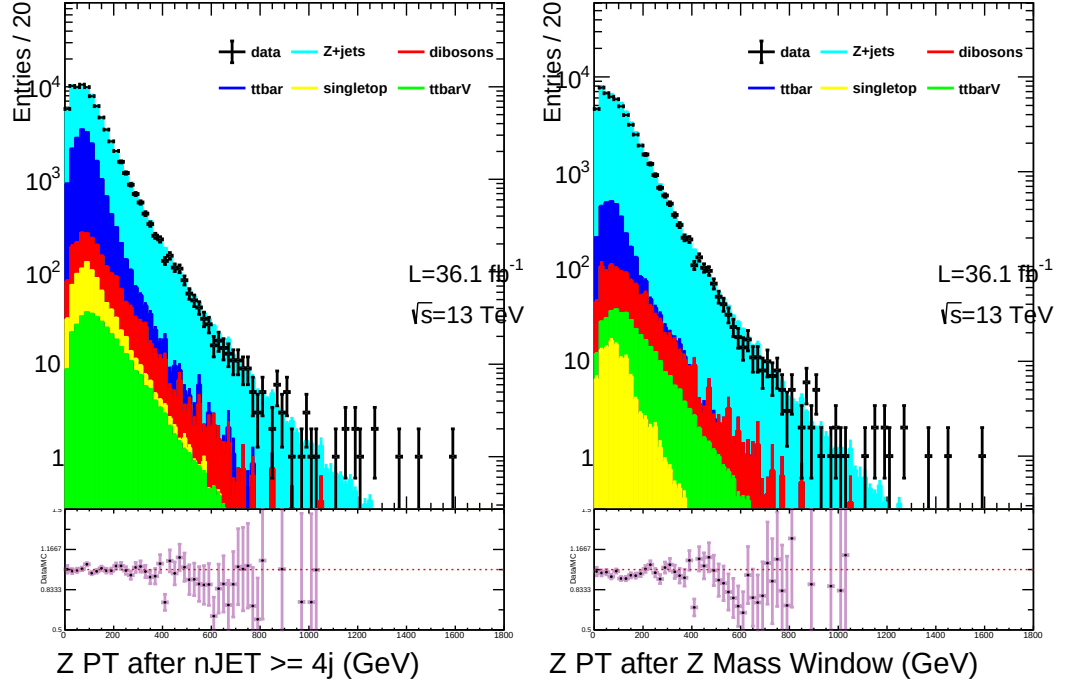


Figure 4.37: Z boson P_T distribution in the ee channel in the signal region at various levels of the analysis algorithm. (*Left*) after cut #6 and (*right*) after cut #7 (see Table 4.2).

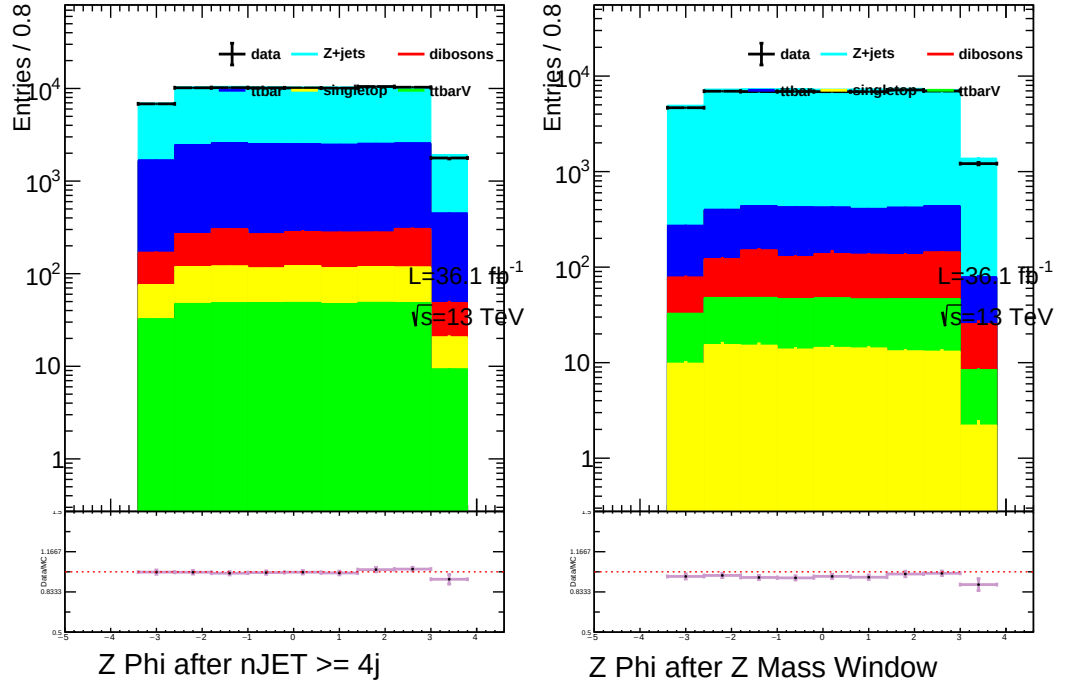


Figure 4.38: Z boson ϕ distribution in the ee channel in the signal region at various levels of the analysis algorithm. (*Left*) after cut #6 and (*right*) after cut #7 (see Table 4.2).

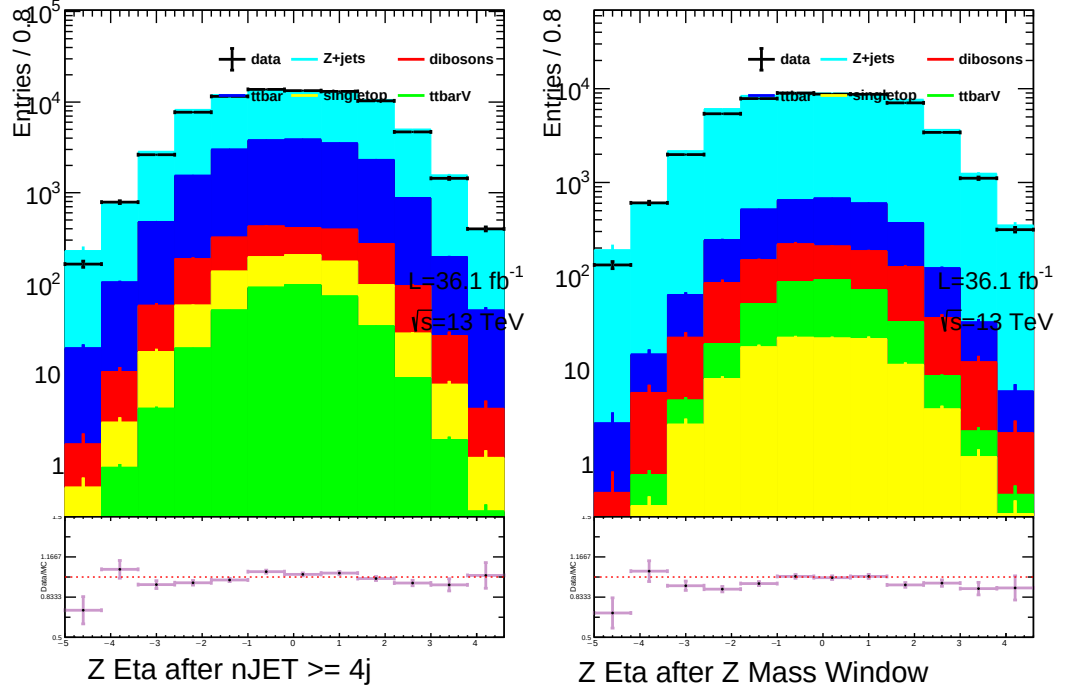


Figure 4.39: Z boson η distribution in the ee channel in the signal region at various levels of the analysis algorithm. (*Left*) after cut #6 and (*right*) after cut #7 (see Table 4.2).

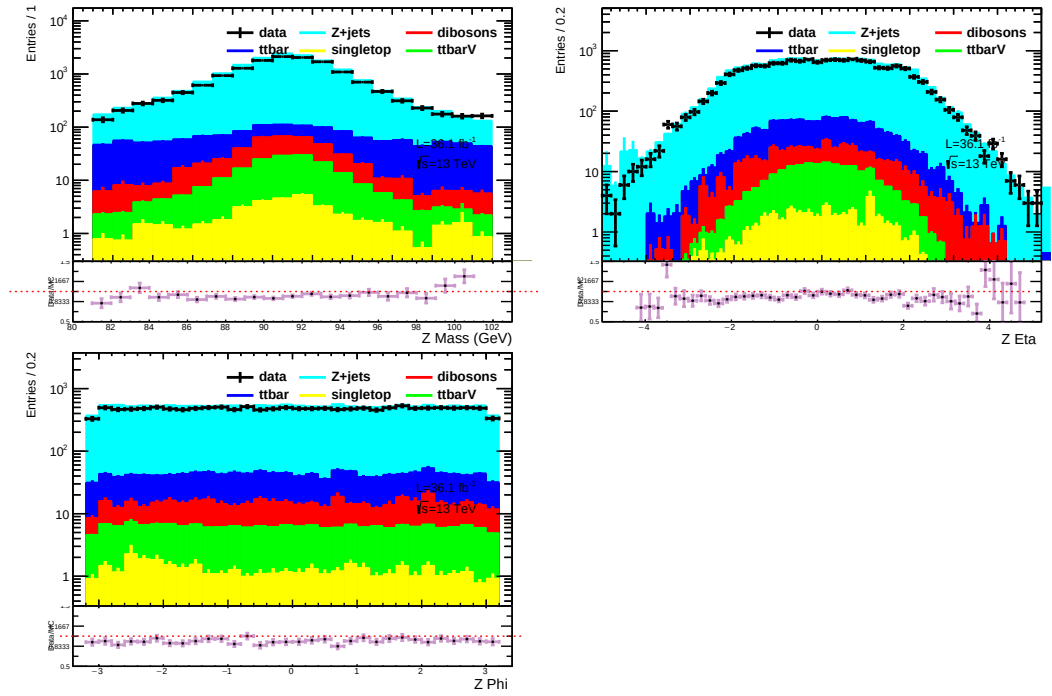


Figure 4.40: Kinematic distributions of Z boson for the ee channel in the signal region before b-tagging requirement (before cut #11 in Table 4.2).

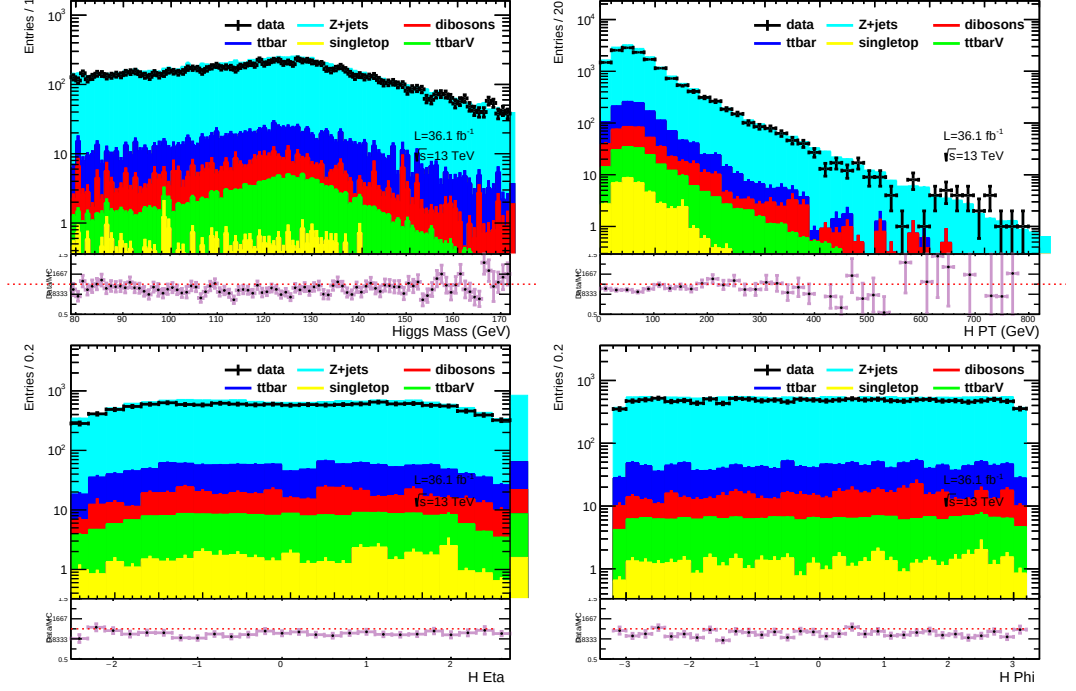


Figure 4.41: Kinematic distributions of H boson for the ee channel in the signal region before b-tagging requirement (before cut #11 in Table 4.2).

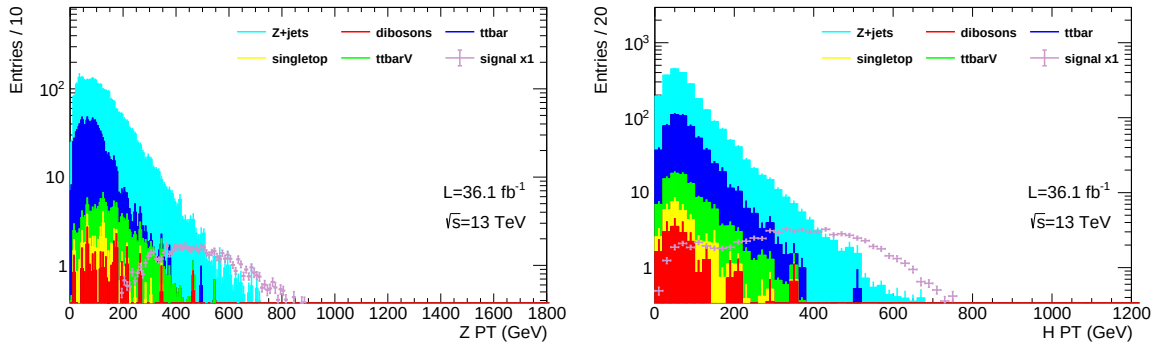


Figure 4.42: P_T distribution of Z boson (*left*) and P_T distribution of Higgs boson (*right*) in the ee channel in the signal region after b-tagging requirement (after cut #11 in Table 4.2). Data is blinded at this level.

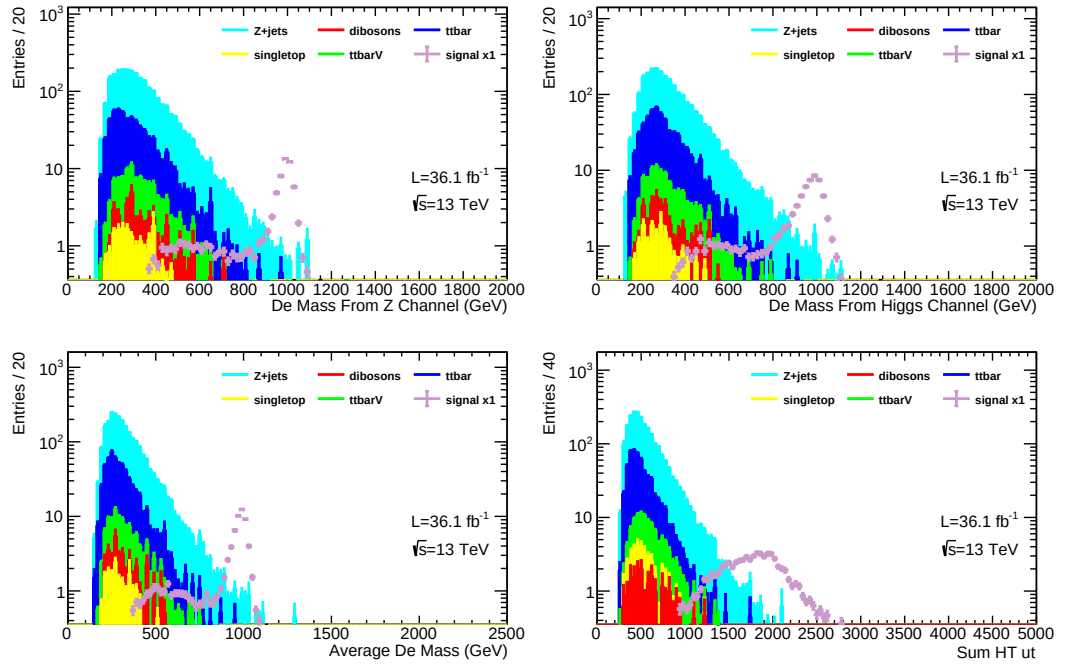


Figure 4.43: D quark mass reconstructed from a Z boson (*top-left*), D quark mass reconstructed from a H boson (*top-right*), average reconstructed D quark mass (*bottom-left*) and Sum H_T distributions (*bottom-right*) when one b-tagged jet is requested in Higgs-daughter jets in the ee channel in the signal region (after cut #11 in Table 4.2). Data is blinded at this level.

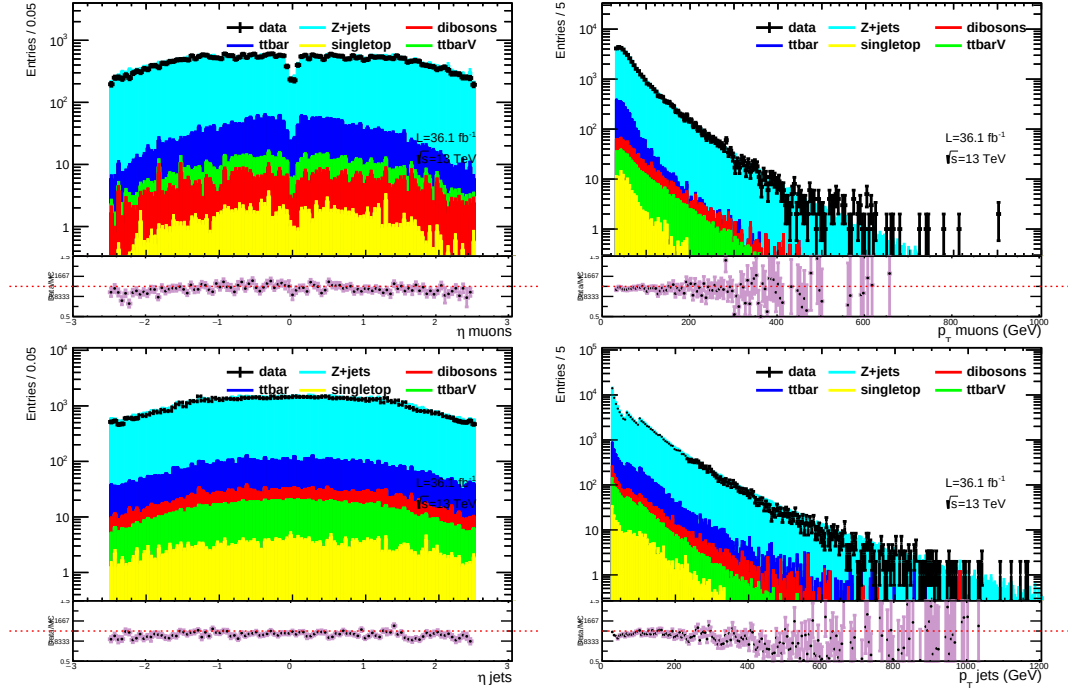


Figure 4.44: P_T , η distributions of muons and jets in the $\mu\mu$ channel in the signal region before b-tagging requirement (before cut #11 in Table 4.2).

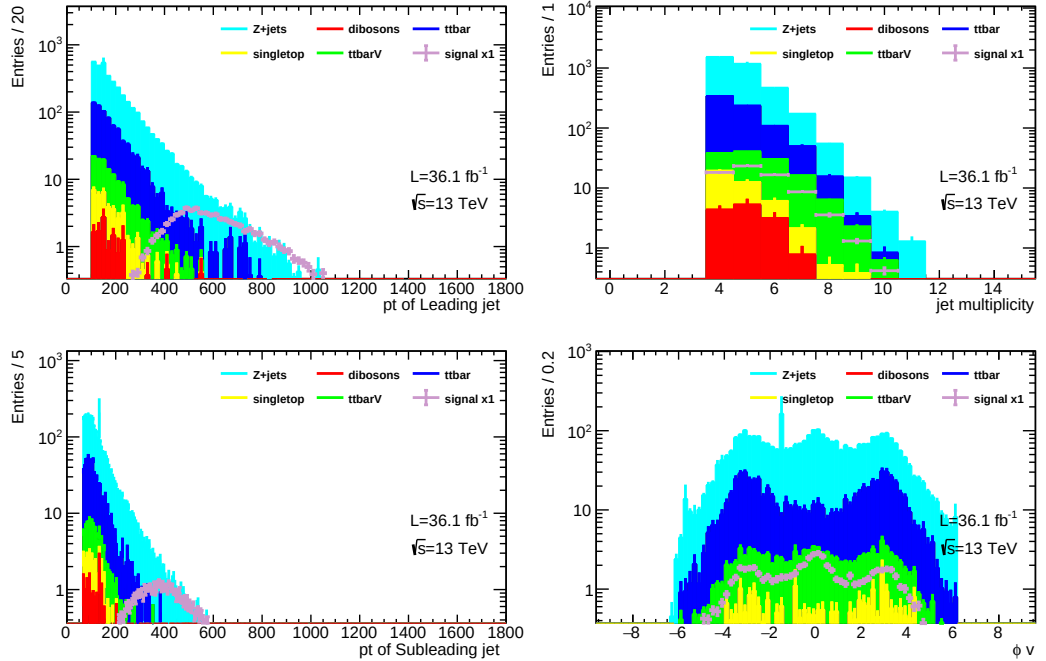


Figure 4.45: P_T of leading jet, jet multiplicity, P_T of subleading jet and ϕ of MET minus ϕ of leading jet distributions in the $\mu\mu$ channel in the signal region after b-tagging requirement (after cut #11 in Table 4.2). Data is blinded at this level.

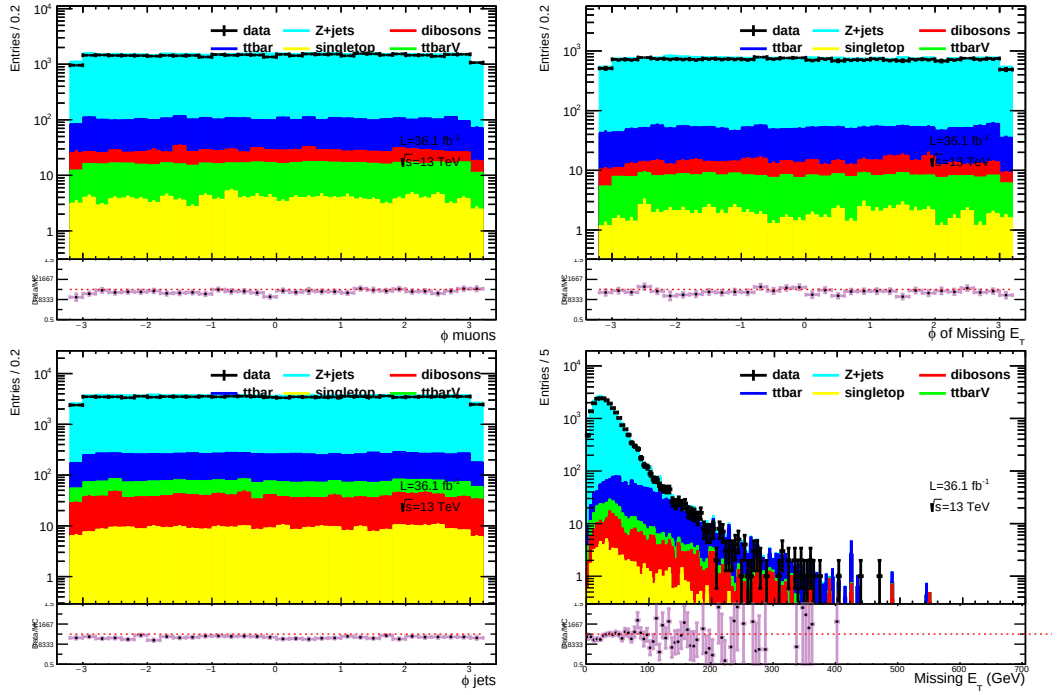


Figure 4.46: ϕ of muons, jets and MET and MET distribution in the $\mu\mu$ channel in the signal region before b-tagging requirement (before cut #11 in Table 4.2).

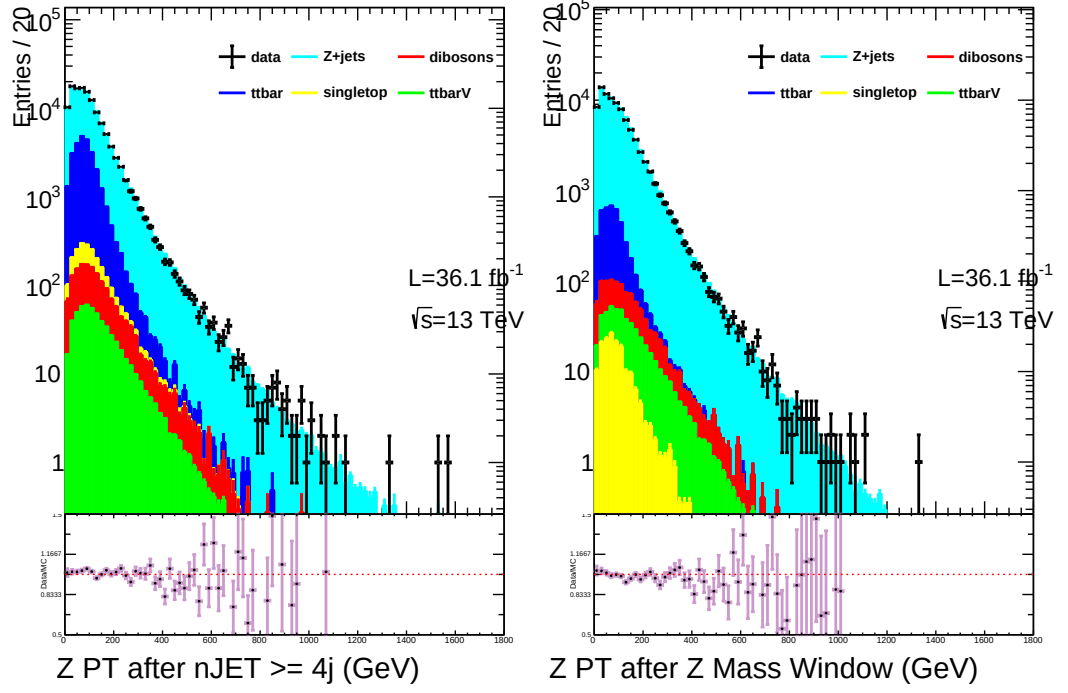


Figure 4.47: Z boson P_T distribution in the $\mu\mu$ channel in the signal region at various levels of the analysis algorithm. (Left) after cut #6 and (right) after cut #7 (see Table 4.2).

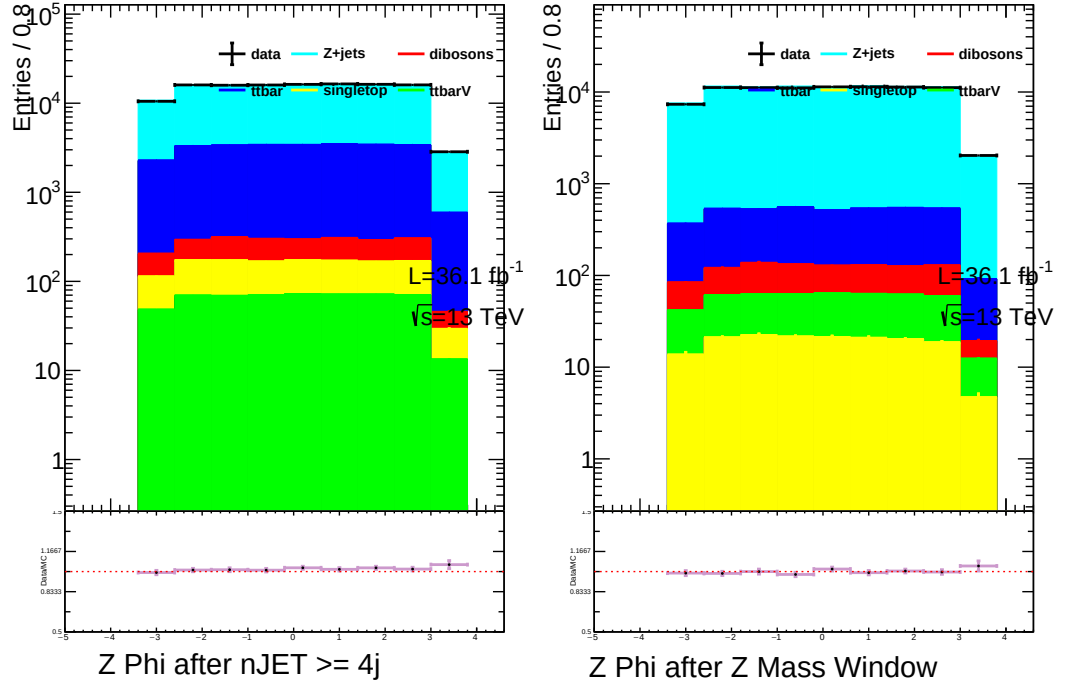


Figure 4.48: Z boson ϕ distribution in the $\mu\mu$ channel in the signal region at various levels of the analysis algorithm. (Left) after cut #6 and (right) after cut #7 (see Table 4.2).

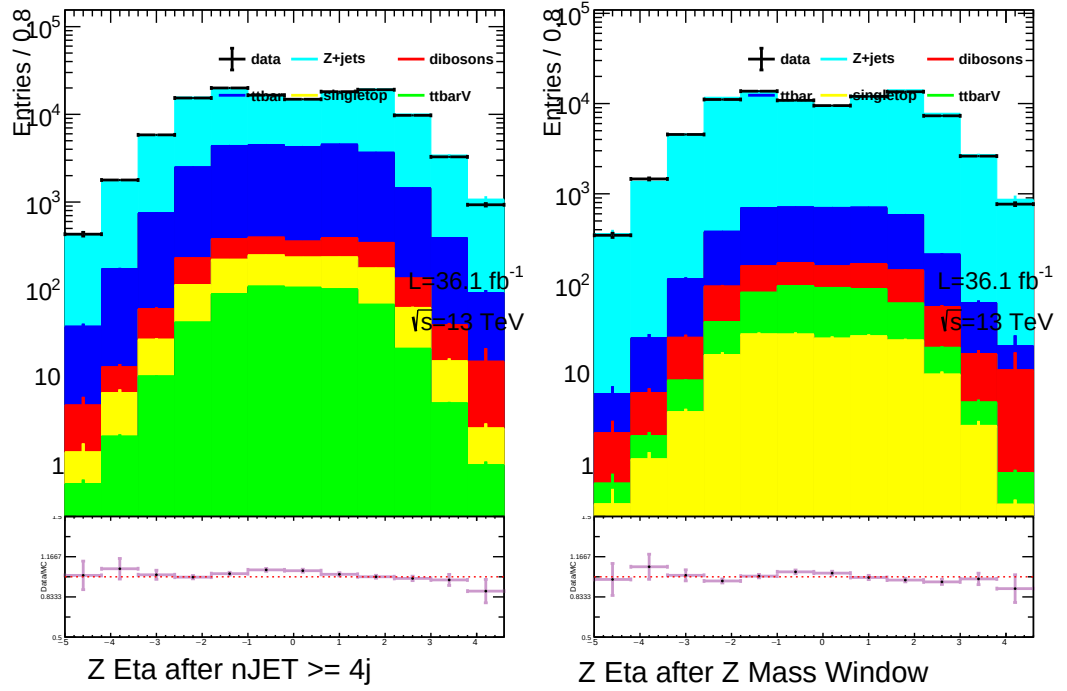


Figure 4.49: Z boson η distribution in the $\mu\mu$ channel in the signal region at various levels of the analysis algorithm. (Left) after cut #6 and (right) after cut #7 (see Table 4.2).

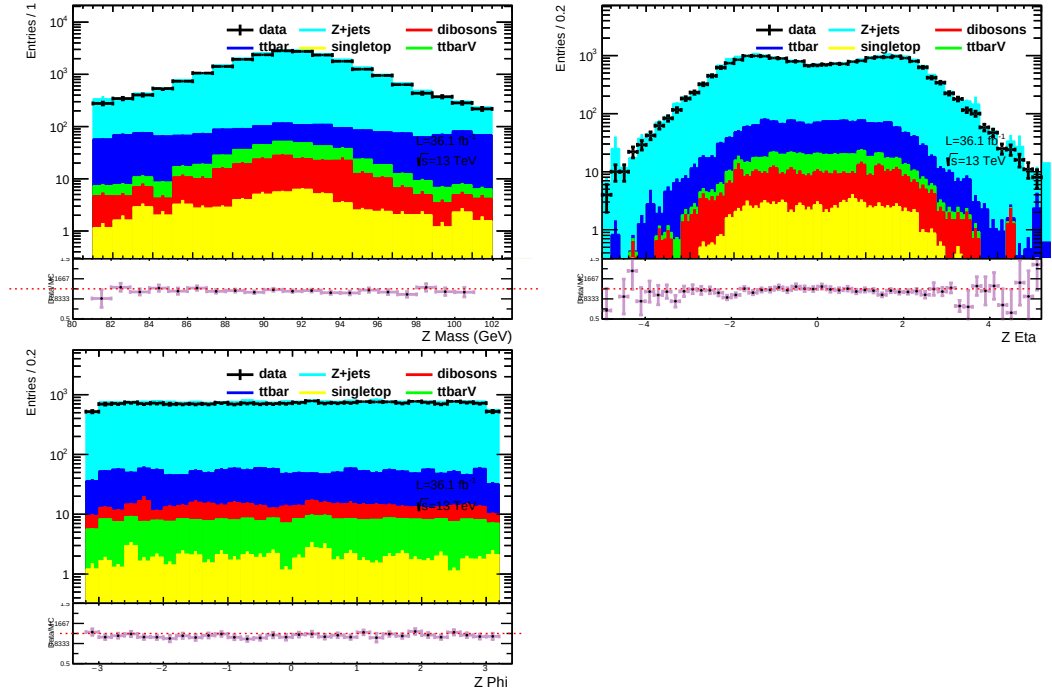


Figure 4.50: Kinematic distributions of Z boson in the $\mu\mu$ channel in the signal region before b-tagging requirement (before cut #11 in Table 4.2).

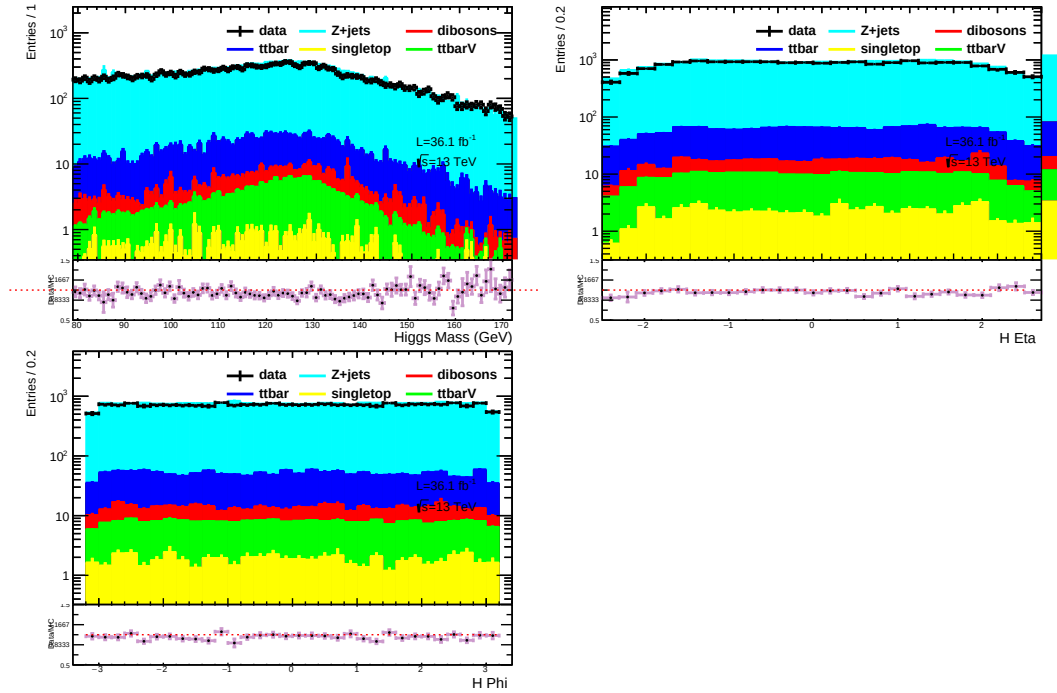


Figure 4.51: Kinematic distributions of H boson in the $\mu\mu$ channel in the signal region before b-tagging requirement (before cut #11 in Table 4.2).

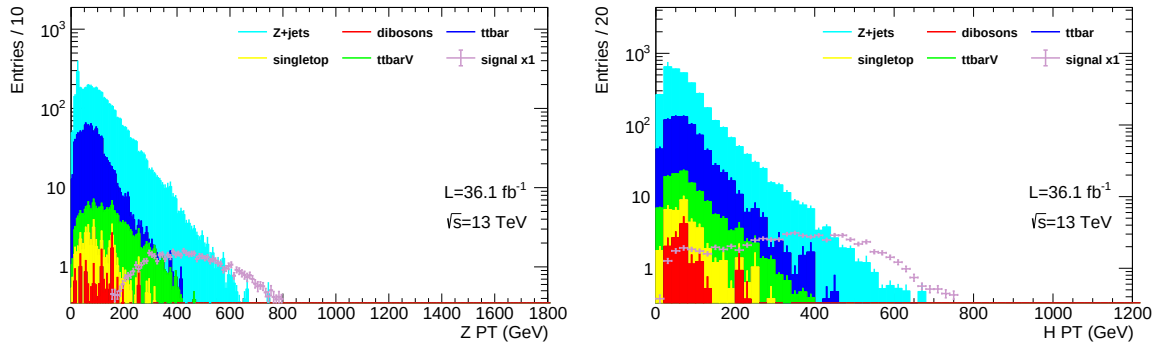


Figure 4.52: P_T distribution of Z boson (*left*) and P_T distribution of H boson (*right*) in the $\mu\mu$ channel in the signal region after b-tagging requirement (after cut #11 in Table 4.2). Data is blinded at this level.

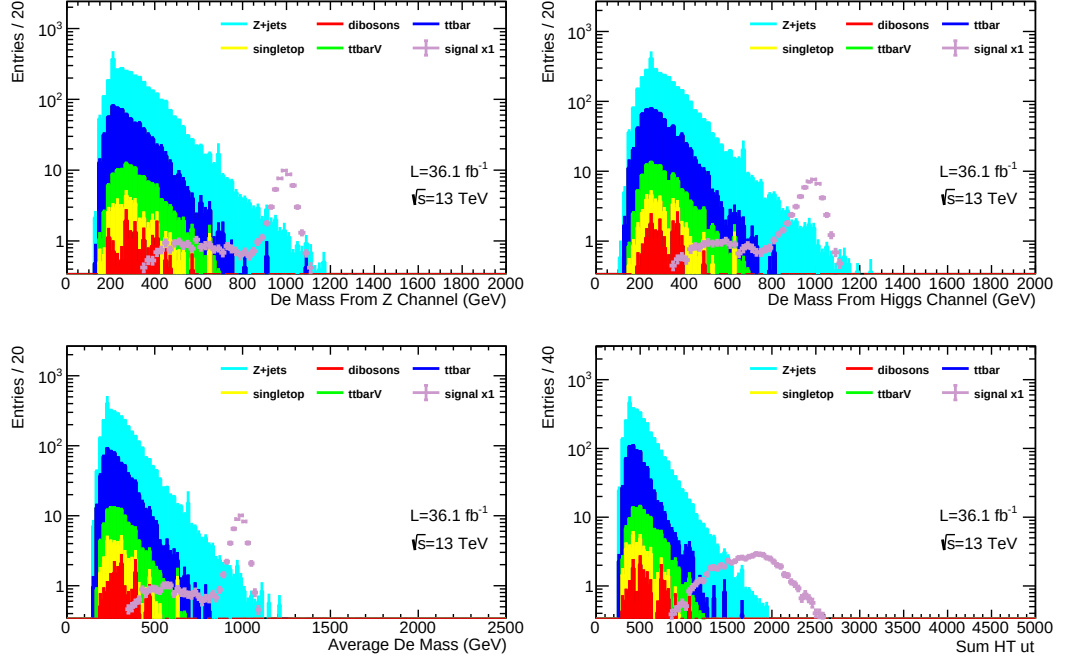


Figure 4.53: D quark mass reconstructed from a Z boson (*top-left*), D quark mass reconstructed from a H boson (*top-right*), average reconstructed D quark mass (*bottom-left*) and Sum H_T distributions (*bottom-right*) when one b-tagged jet is requested in Higgs-daughter jets in the $\mu\mu$ channel in the signal region (after cut #11 in Table 4.2). Data is blinded at this level.

4.4. Systematic Uncertainties

There are a number of sources of systematic uncertainties studied in the analysis. Some are detector-related and affect the physics objects used in the analysis: jet energy smearing, jet energy scaling, muon scale factor, muon P_T smearing, trigger efficiency, electron energy scaling, electron scale factors. Others are due to imperfections in theory and modelling: namely the background uncertainties (pdf, cross-section, generator). We also include the uncertainty in the integrated luminosity ($\pm 2.2\%$), as well as uncertainties related to the pile-up reweighting. The full list of uncertainties and their contributions can be found in Tables 4.13 - 4.18. We note that these tables provide the full list of factors contributing to various effects we study; for example, the jet energy scale uncertainty is handled through a globally reduced set of 21 nuisance parameters (NP) (8 from the in-situ analyses of Z +jet, γ +jet and multijet balance, and others coming from eta-intercalibration, pile-up and high- P_T jets among other factors).

While the object uncertainties are derived from AnalysisTop following the recommendations by the different performance groups, it is worth summarizing the modeling uncertainties. For each of the backgrounds, we consider cross-section uncertainties as listed in Table 4.12. For the two dominant backgrounds, Z +jets and $t\bar{t}$, we also consider the impact of variations in the renormalization and factorization scales (halved, nominal, doubled combinations for the two scales). For this purpose, we change the internal weights of the background samples and produce variations of the final discriminant histogram. Then for each bin, we determine the maximum positive and negative difference of the variations from the nominal version and construct an envelope. We apply the same procedure also for determining the PDF uncertainties, with the variations this time obtained by reweighting through different PDF sets. (We also consider variations within the nominal PDF set, but these are much smaller.)

Finally, for our most dominant background, Z +jets, we consider the effect of using an alternative generator Madgraph, instead of our default SHERPA 2.2.1 samples. Apart from coming from a completely different generator, the Madgraph samples

differ also in the way the events are sliced: H_T slicing as opposed to SHERPA samples' $\max(p_T(Z), H_T)$. However it is worth noting that the Madgraph samples are somewhat limited in statistics (about 3 times larger statistical uncertainty after all cuts applied), so we perform smoothing later while running the statistical analysis with the TRexFitter.

Table 4.12: Cross-section uncertainties for the background processes in the different channels.

Process	Uncertainty (%)	Reference
$Z + \text{Jets}$	12	[93]
$t\bar{t}$	6	[94]
Diboson	6	[95]
$t\bar{t} + W$	12	[96]
$t\bar{t} + Z$	12	[96]
$t\bar{t} + \ell\ell$	12	[96]
Singletop	5	[97]

Table 4.13: Systematic uncertainties (%) per sample in the signal region for electron channel.

	Z+jets	Diboson	$t\bar{t}$	Singletop	$t\bar{t} + V$	Signal (1000)
Pile-up	0.22 / 0.22	-5.16 / -5.16	2.27 / 2.27	6.23 / 6.23	-0.429 / -0.429	nan / nan
EL Trigger	0.0145 / 0.0145	0.028 / 0.028	0.0131 / 0.0131	0.0162 / 0.0162	0.00756 / 0.00756	nan / nan
EL Reco.	0.325 / 0.325	0.353 / 0.353	0.235 / 0.235	0.268 / 0.268	0.355 / 0.355	nan / nan
EL ID	1.76 / 1.76	2.2 / 2.2	1.21 / 1.21	1.49 / 1.49	1.95 / 1.95	nan / nan
EL Isol.	0.723 / 0.723	0.977 / 0.977	0.187 / 0.187	0.577 / 0.577	1.26 / 1.26	nan / nan
Muon Trig. Stat	0 / 0	8.7e-06 / 8.7e-06	0 / 0	-1.29e-06 / -1.29e-06	1.52e-05 / 1.29e-05	nan / nan
Muon Trig. Syst.	0 / 0	2.83e-05 / 2.83e-05	0 / 0	-1.29e-06 / -1.29e-06	1.67e-05 / 1.67e-05	nan / nan
Muon ID Stat	4.16e-06 / 4.16e-06	0.0196 / 0.0196	0 / 0	0.00176 / 0.00176	0.0185 / 0.0185	nan / nan
Muon ID Syst	6.09e-06 / 6.09e-06	0.116 / 0.116	0 / 0	0.0063 / 0.0063	0.0784 / 0.0784	nan / nan
Muon ID Stat (low pt)	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Muon ID Syst (low pt)	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Muon Isol. Stat	4.06e-07 / 4.06e-07	0.00535 / 0.00535	0 / 0	0.000361 / 0.000361	0.00322 / 0.00322	nan / nan
Muon Isol. Syst	4.06e-07 / 4.06e-07	0.00903 / 0.00903	0 / 0	0.000489 / 0.000489	0.00902 / 0.00902	nan / nan
Muon TTVA Stat	4.06e-07 / 4.06e-07	0.00822 / 0.00822	0 / 0	0.000786 / 0.000786	0.0075 / 0.0075	nan / nan
Muon TTVA Syst	0 / 0	0.0075 / 0.0075	0 / 0	0.00123 / 0.00123	0.00816 / 0.00816	nan / nan
Btag extrP.	0.0542 / 0.0542	-0.171 / -0.171	0.0411 / 0.0411	0.163 / 0.163	0.0882 / 0.0882	nan / nan
Btag extraP from charm	0.000383 / 0.000383	2.28 / 2.28	0 / 0	0.0252 / 0.0252	0.0712 / 0.0712	nan / nan
Btag b 100	-1.78 / -1.78	-1.68 / -1.68	-3 / -3	-2.57 / -2.57	-2.59 / -2.59	nan / nan
Btag b 200	-0.299 / -0.299	-0.0241 / -0.0241	-0.927 / -0.927	-0.879 / -0.879	-0.84 / -0.84	nan / nan
Btag b 300	0.207 / 0.207	0.297 / 0.297	0.437 / 0.437	0.253 / 0.253	0.317 / 0.317	nan / nan
Btag b 400	-0.0232 / -0.0231	0.0749 / 0.0749	0.109 / 0.109	-0.095 / -0.095	0.00554 / 0.00554	nan / nan
Btag b 500	5.33e-05 / 5.33e-05	0.0244 / 0.0244	-0.0162 / -0.0162	-0.053 / -0.053	-0.0194 / -0.0194	nan / nan
Btag b 600	-0.000947 / -0.000949	0.00168 / 0.00168	-0.00337 / -0.00337	-0.000279 / -0.000279	8.96e-05 / 8.96e-05	nan / nan
Btag c 100	-1.24 / -1.24	-8.9 / -8.9	-0.802 / -0.802	-0.628 / -0.628	-1.14 / -1.14	nan / nan
Btag c 200	0.0265 / 0.0265	0.0101 / 0.0101	-0.272 / -0.272	-0.109 / -0.109	-0.262 / -0.262	nan / nan
Btag c 300	0.0325 / 0.0325	0.21 / 0.21	-0.0525 / -0.0525	-0.00672 / -0.00672	-0.0371 / -0.0371	nan / nan
Btag light 100	-4.86 / -4.86	-5.07 / -5.07	-0.147 / -0.147	-0.794 / -0.794	-0.518 / -0.518	nan / nan
Btag light 200	1.74 / 1.74	1.11 / 1.11	0.0973 / 0.0973	0.197 / 0.197	0.139 / 0.139	nan / nan
Btag light 300	1.38 / 1.38	1.41 / 1.41	0.0215 / 0.0215	0.00109 / 0.00109	0.103 / 0.103	nan / nan
Btag light 400	0.387 / 0.387	-0.256 / -0.256	-0.0307 / -0.0307	-0.162 / -0.162	0.0281 / 0.0281	nan / nan
Btag light 500	-0.947 / -0.947	-0.183 / -0.183	-0.0256 / -0.0256	-0.0479 / -0.0479	-0.0128 / -0.0128	nan / nan
Btag light 600	0.401 / 0.401	-0.026 / -0.026	-0.0182 / -0.0182	-0.034 / -0.034	-0.00229 / -0.00229	nan / nan
Btag light 700	0.244 / 0.244	-0.123 / -0.123	0.027 / 0.027	0.0607 / 0.0607	-0.00171 / -0.00171	nan / nan
Btag light 800	0.151 / 0.151	-0.0228 / -0.0228	-0.00301 / -0.00301	0.00168 / 0.00168	-0.00778 / -0.00778	nan / nan
Btag light 900	0.325 / 0.325	0.473 / 0.473	-0.0126 / -0.0126	-0.0853 / -0.0853	0.0252 / 0.0252	nan / nan
Btag light 1000	-0.00652 / -0.00652	0.209 / 0.209	0.0308 / 0.0308	-0.00769 / -0.00769	0.00269 / 0.00269	nan / nan
Btag light 1100	-0.0865 / -0.0865	-0.135 / -0.135	0.00093 / 0.000931	-0.0077 / -0.0077	0.00613 / 0.00613	nan / nan
Btag light 1200	-0.0149 / -0.0149	0.0197 / 0.0197	-0.00632 / -0.00632	-0.0146 / -0.0146	0.00348 / 0.00348	nan / nan
Btag light 1300	-0.046 / -0.046	0.0307 / 0.0307	-0.00968 / -0.00968	0.018 / 0.018	-0.00153 / -0.00152	nan / nan
Btag light 1400	0.0146 / 0.0146	-0.0879 / -0.0879	-0.00664 / -0.00664	0.0069 / 0.0069	0.00191 / 0.00191	nan / nan
Btag light 1500	-0.0126 / -0.0126	-0.0236 / -0.0236	0.00143 / 0.00143	-0.00208 / -0.00208	0.000323 / 0.000326	nan / nan
Btag light 1600	-0.0058 / -0.0058	-0.0254 / -0.0254	-0.00812 / -0.00812	0.00669 / 0.00669	0.000728 / 0.000727	nan / nan
Jet JVT eff.	0.254 / 0.254	0.719 / 0.719	0.0982 / 0.0982	-0.0659 / -0.0659	-0.0265 / -0.0265	nan / nan
Z+jets scalevar SR	29.7 / 29.7	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Z+jets PDF SR	13.8 / 13.8	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
EG Resolution	0.00405 / 0.00405	1.12 / 1.12	-0.14 / -0.14	-0.867 / -0.867	0.105 / 0.105	nan / nan
EG Scale	0.031 / 0.031	2.04 / 2.04	-0.314 / -0.314	-1.09 / -1.09	0.0528 / 0.0528	nan / nan
Muon ID	5.69e-05 / 5.69e-05	0.000794 / 0.000794	0.000118 / 0.000118	-6.98e-05 / -7.23e-05	0.000398 / 0.000397	nan / nan
Muon ResBias	-3.32e-05 / -3.32e-05	1.44e-05 / 1.44e-05	0.000233 / 0.000233	1.53e-05 / 1.53e-05	-6.53e-05 / -6.53e-05	nan / nan
Muo Rho	6.45e-05 / 6.45e-05	1.51e-05 / 1.51e-05	-1.23e-05 / -1.43e-05	-3.4e-06 / -5.98e-06	-5.54e-05 / -5.43e-05	nan / nan
Muon Scale	-4.01e-06 / -5.63e-06	0.000105 / 0.000105	0.000309 / 0.000309	-0.000105 / -0.000107	0.00068 / 0.000679	nan / nan

Table 4.13: Systematic uncertainties (%) per sample in the signal region for electron channel (cont.).

	Z+jets	Diboson	$t\bar{t}$	Singletop	$t\bar{t} + V$	Signal (1000)
JET Flavor Response	0.431 / 0.431	1.02 / 1.02	-0.105 / -0.105	0.082 / 0.082	0.293 / 0.293	nan / nan
JET Effective NP1	2.47 / 2.47	9.2 / 9.2	1.61 / 1.61	0 / 0	0.558 / 0.558	nan / nan
JET Effective NP2	-0.295 / -0.295	-2.16 / -2.16	0.119 / 0.119	0 / 0	0.447 / 0.447	nan / nan
JET Effective NP3	-0.0791 / -0.0791	1.08 / 1.08	-0.521 / -0.521	-0.161 / -0.161	-0.296 / -0.296	nan / nan
JET Effective NP4	0.116 / 0.116	-1.08 / -1.08	0.342 / 0.342	0.103 / 0.103	0.229 / 0.229	nan / nan
JET Effective NP5	-0.0208 / -0.0208	1.08 / 1.08	0.0388 / 0.0388	0.237 / 0.237	0.047 / 0.047	nan / nan
JET Effective NP6	0.0717 / 0.0717	1.08 / 1.08	-0.117 / -0.117	0.0398 / 0.0398	-0.0971 / -0.0971	nan / nan
JET Effective NP7	-0.179 / -0.179	0.00076 / 0.00076	-0.178 / -0.178	-0.0289 / -0.0289	-0.0461 / -0.0461	nan / nan
JET NP8 RestTerm	0.105 / 0.105	-1.09 / -1.09	0.287 / 0.287	0.0419 / 0.0419	-0.0073 / -0.00731	nan / nan
JET EtaIntercalibration Modelling	1.29 / 1.29	2.08 / 2.08	0.684 / 0.684	-0.123 / -0.123	0.652 / 0.652	nan / nan
JET EtaIntercalibration NonClosure	-0.441 / -0.441	1.24 / 1.24	-1.15 / -1.15	-0.918 / -0.918	-0.517 / -0.517	nan / nan
JET EtaIntercalibration TotalStat	0.541 / 0.541	0.0238 / 0.0238	0.262 / 0.262	-1.29 / -1.29	0.294 / 0.294	nan / nan
JET Flavor Composition	4.97 / 4.97	8.64 / 8.64	3.35 / 3.35	7.15 / 7.15	1.37 / 1.37	nan / nan
JET PU Offset Mu	-0.176 / -0.176	-4.27 / -4.27	-0.781 / -0.781	1.69 / 1.69	-0.173 / -0.173	nan / nan
JET PU Offset NPV	0.516 / 0.516	1.34 / 1.34	0.202 / 0.202	1.18 / 1.18	0.221 / 0.221	nan / nan
JET PU Pt Term	0.494 / 0.494	-2.18 / -2.18	0.326 / 0.326	-1.05 / -1.05	0.532 / 0.532	nan / nan
JET Punch Through	0.00381 / 0.00381	6.39e-05 / 6.39e-05	0.000234 / 0.000234	-0.000189 / -0.000189	-0.00317 / -0.00317	nan / nan
JET Single Particle High Pt	2.7e-05 / 2.7e-05	2.54e-05 / 2.54e-05	0.000142 / 0.000142	1.89e-05 / 1.89e-05	-6.62e-05 / -6.51e-05	nan / nan
JET JER SINGLE NP	-13.3 / -13.3	-3.16 / -3.16	-0.232 / -0.235	3.1 / 3.1	-0.648 / -0.648	nan / nan
MET Reso Para	-13.3 / -13.3	-0.000149 / -0.000153	0.00175 / 0.00175	3.28e-05 / 3.02e-05	-0.000109 / -0.000111	nan / nan
MET Reso Perp	-13.3 / -13.3	-0.00015 / -0.000154	0.0019 / 0.0019	-4.09e-05 / -4.13e-05	-0.000109 / -0.000111	nan / nan
MET Scale	-7.37e-05 / -7.37e-05	-6.8e-06 / -8.97e-06	-0.000125 / -0.000128	-5.24e-05 / -5.26e-05	-8.62e-05 / -8.62e-05	nan / nan
Z+jets cross section	5 / 5	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Luminosity	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	nan / nan
Z+jets generator SR	-12 / -12	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Diboson cross section	0 / 0	6 / 6	0 / 0	0 / 0	0 / 0	nan / nan
$t\bar{t}$ scalevar SR	0 / 0	0 / 0	7.72 / 7.72	0 / 0	0 / 0	nan / nan
$t\bar{t}$ PDF SR	0 / 0	0 / 0	6.76 / 6.76	0 / 0	0 / 0	nan / nan
$t\bar{t}$ cross section	0 / 0	0 / 0	6 / 6	0 / 0	0 / 0	nan / nan
Singletop cross section	0 / 0	0 / 0	0 / 0	5 / 5	0 / 0	nan / nan
$t\bar{t}$ V cross section	0 / 0	0 / 0	0 / 0	0 / 0	12 / 12	nan / nan
SigXsecOverSM	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	inf / inf

Table 4.14: Systematic uncertainties (%) per sample in the signal region for muon channel.

	Z+jets	Diboson	$t\bar{t}$	Singletop	$t\bar{t} + V$	Signal (1000)
Pile-up	1.28 / 1.28	-5.98 / -5.98	-1.17 / -1.17	1.35 / 1.35	0.261 / 0.261	nan / nan
EL Trigger	0 / 0	0.000135 / 0.000132	5.69e-06 / 5.69e-06	-7.4e-06 / -7.4e-06	0.000544 / 0.000544	nan / nan
EL Reco.	1.01e-05 / 1.01e-05	0.0141 / 0.0141	7.48e-05 / 7.48e-05	0.00196 / 0.00196	0.013 / 0.013	nan / nan
EL ID	2.71e-05 / 2.71e-05	0.0871 / 0.0871	0.000872 / 0.000872	0.0107 / 0.0107	0.0638 / 0.0638	nan / nan
EL Isol.	6.69e-05 / 6.69e-05	0.0731 / 0.0731	4.23e-05 / 4.23e-05	0.00271 / 0.00271	0.0196 / 0.0196	nan / nan
Muon Trig. Stat	0.214 / 0.214	0.107 / 0.107	0.248 / 0.248	0.235 / 0.235	0.214 / 0.214	nan / nan
Muon Trig. Syst.	0.345 / 0.345	0.337 / 0.337	0.396 / 0.396	0.388 / 0.388	0.335 / 0.335	nan / nan
Muon ID Stat	0.373 / 0.373	0.399 / 0.399	0.391 / 0.391	0.349 / 0.349	0.41 / 0.41	nan / nan
Muon ID Syst	1.79 / 1.79	2.12 / 2.12	1.44 / 1.44	1.65 / 1.65	2.15 / 2.15	nan / nan
Muon ID Stat (low pt)	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Muon ID Syst (low pt)	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Muon Isol. Stat	0.0649 / 0.0649	0.073 / 0.073	0.0628 / 0.0628	0.0622 / 0.0622	0.0698 / 0.0698	nan / nan
Muon Isol. Syst	0.2 / 0.2	0.283 / 0.283	0.124 / 0.124	0.181 / 0.181	0.278 / 0.278	nan / nan
Muon TTVA Stat	0.153 / 0.153	0.172 / 0.172	0.161 / 0.161	0.149 / 0.149	0.169 / 0.169	nan / nan
Muon TTVA Syst	0.0994 / 0.0994	0.15 / 0.15	0.186 / 0.186	0.146 / 0.146	0.181 / 0.181	nan / nan
Btag extrP.	0.0672 / 0.0672	-0.0521 / -0.0521	-0.0275 / -0.0275	0.111 / 0.111	0.0452 / 0.0452	nan / nan
Btag extraP from charm	-0.000113 / -0.000112	2.07 / 2.07	-0.0032 / -0.0032	0.0215 / 0.0215	0.0767 / 0.0767	nan / nan
Btag b 100	-1.73 / -1.73	-2.41 / -2.41	-2 / -2	-3.5 / -3.5	-2.71 / -2.71	nan / nan
Btag b 200	-0.3 / -0.3	-0.245 / -0.245	-0.72 / -0.72	-1.12 / -1.12	-0.845 / -0.845	nan / nan
Btag b 300	0.204 / 0.204	0.387 / 0.387	0.388 / 0.388	0.38 / 0.38	0.358 / 0.358	nan / nan
Btag b 400	-0.0275 / -0.0275	-0.076 / -0.076	0.103 / 0.103	0.0935 / 0.0935	0.0321 / 0.0321	nan / nan
Btag b 500	-9.1e-05 / -9.21e-05	0.027 / 0.027	-0.0335 / -0.0335	-0.0399 / -0.0399	-0.0231 / -0.0231	nan / nan
Btag b 600	-0.00111 / -0.00111	-0.00875 / -0.00876	-0.00266 / -0.00266	-0.00865 / -0.00865	-0.00123 / -0.00123	nan / nan
Btag c 100	-1.25 / -1.25	-8.2 / -8.2	-0.137 / -0.137	-0.707 / -0.707	-1.16 / -1.16	nan / nan
Btag c 200	0.0421 / 0.0421	0.335 / 0.335	0.173 / 0.173	-0.515 / -0.515	-0.0893 / -0.0893	nan / nan
Btag c 300	0.0355 / 0.0355	1.14 / 1.14	0.0461 / 0.0461	-0.152 / -0.152	0.0321 / 0.0321	nan / nan
Btag light 100	-5.05 / -5.05	-4.85 / -4.85	-1.09 / -1.09	0.192 / 0.192	-0.345 / -0.345	nan / nan
Btag light 200	1.77 / 1.77	1.69 / 1.69	0.17 / 0.17	-0.0353 / -0.0353	0.0861 / 0.0861	nan / nan
Btag light 300	1.17 / 1.17	1.06 / 1.06	0.0405 / 0.0405	-0.0607 / -0.0607	0.0263 / 0.0263	nan / nan
Btag light 400	0.266 / 0.266	1.32 / 1.32	-0.165 / -0.165	-0.0158 / -0.0158	-0.0012 / -0.0012	nan / nan
Btag light 500	-1.07 / -1.07	-0.075 / -0.075	-0.0296 / -0.0296	0.00336 / 0.00336	-0.00649 / -0.00649	nan / nan
Btag light 600	0.43 / 0.43	0.285 / 0.285	-0.00427 / -0.00427	-0.00555 / -0.00555	-0.012 / -0.012	nan / nan
Btag light 700	0.277 / 0.277	0.274 / 0.274	0.0332 / 0.0332	-0.0295 / -0.0295	-0.016 / -0.016	nan / nan
Btag light 800	0.219 / 0.219	0.317 / 0.317	0.0223 / 0.0223	-0.014 / -0.014	-0.0168 / -0.0168	nan / nan
Btag light 900	0.32 / 0.32	-0.337 / -0.337	-0.0411 / -0.0411	0.0462 / 0.0462	0.0226 / 0.0226	nan / nan
Btag light 1000	-0.00691 / -0.00691	0.205 / 0.205	0.0339 / 0.0339	-0.000468 / -0.000468	0.00282 / 0.00282	nan / nan
Btag light 1100	-0.0748 / -0.0748	-0.241 / -0.241	-0.0073 / -0.0073	-0.00196 / -0.00196	0.00631 / 0.00631	nan / nan
Btag light 1200	-0.0398 / -0.0398	-0.317 / -0.317	-0.0341 / -0.0341	-0.00221 / -0.00221	-0.0015 / -0.0015	nan / nan
Btag light 1300	-0.0287 / -0.0287	0.233 / 0.233	-0.0034 / -0.0034	0.00268 / 0.00268	-0.00404 / -0.00404	nan / nan
Btag light 1400	0.0201 / 0.0201	0.125 / 0.125	0.00781 / 0.00781	-0.00111 / -0.00111	-0.00109 / -0.00109	nan / nan
Btag light 1500	-0.0067 / -0.0067	-0.0164 / -0.0164	0.00382 / 0.00382	-0.00238 / -0.00238	0.00102 / 0.00102	nan / nan
Btag light 1600	-0.00456 / -0.00456	0.0794 / 0.0794	-0.00601 / -0.00601	-0.000968 / -0.000969	-0.0017 / -0.0017	nan / nan
Jet JVT eff.	0.238 / 0.238	0.617 / 0.617	0.0942 / 0.0942	-0.16 / -0.16	-0.0834 / -0.0834	nan / nan
Z+jets scalevar SR	30.4 / 30.4	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Z+jets PDF SR	1.85 / 1.85	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
EG Resolution	6.83e-05 / 6.83e-05	4.74e-05 / 4.72e-05	-5.98e-05 / -5.97e-05	-5.46e-05 / -5.46e-05	0.0134 / 0.0134	nan / nan
EG Scale	-3.72e-05 / -3.75e-05	-0.000892 / -0.000892	-0.000314 / -0.000314	7.03e-05 / 6.99e-05	0.00276 / 0.00276	nan / nan
Muon ID	0.129 / 0.129	-0.547 / -0.547	-0.171 / -0.171	-0.141 / -0.141	0.05 / 0.05	nan / nan
Muon ResBias	6.6e-05 / 6.6e-05	4.14e-06 / 4.23e-06	-0.000119 / -0.000119	-4.8e-05 / -4.84e-05	-6.55e-06 / -6.55e-06	nan / nan
Muo Rho	-3.74e-05 / -3.78e-05	1.06e-05 / 1.06e-05	0.000238 / 0.000238	-3.42e-05 / -3.61e-05	-3.1e-05 / -3.2e-05	nan / nan
Muon Scale	0.0356 / 0.0356	-0.0938 / -0.0938	0.353 / 0.353	-0.138 / -0.138	0.0911 / 0.0911	nan / nan

Table 4.14: Systematic uncertainties (%) per sample in the signal region for muon channel (cont.).

	Z+jets	Diboson	$t\bar{t}$	Singletop	$t\bar{t} + V$	Signal (1000)
JET Flavor Response	0.47 / 0.47	-0.689 / -0.689	0.858 / 0.858	1.49 / 1.49	0.316 / 0.316	nan / nan
JET Effective NP1	1.83 / 1.83	0.863 / 0.863	1.23 / 1.23	0 / 0	0.646 / 0.646	nan / nan
JET Effective NP2	-0.193 / -0.193	0.749 / 0.749	0.00355 / 0.00355	0 / 0	0.101 / 0.101	nan / nan
JET Effective NP3	-0.0849 / -0.0849	-0.74 / -0.74	-0.223 / -0.223	0.117 / 0.117	-0.188 / -0.188	nan / nan
JET Effective NP4	0.0976 / 0.0976	0.743 / 0.743	0.321 / 0.321	0.0357 / 0.0357	0.24 / 0.24	nan / nan
JET Effective NP5	-0.00293 / -0.00293	-0.00116 / -0.00117	-0.005 / -0.005	-0.379 / -0.379	0.023 / 0.023	nan / nan
JET Effective NP6	0.077 / 0.077	0.00421 / 0.00421	0.184 / 0.184	0.678 / 0.678	0.051 / 0.051	nan / nan
JET Effective NP7	-0.105 / -0.105	-0.00513 / -0.00513	0.209 / 0.209	-0.659 / -0.659	-0.0313 / -0.0313	nan / nan
JET NP8 RestTerm	0.0299 / 0.0299	0.00175 / 0.00175	-0.082 / -0.082	0.315 / 0.315	0.079 / 0.079	nan / nan
JET EtaIntercalibration Modelling	1.03 / 1.03	0.105 / 0.105	0.384 / 0.384	1.17 / 1.17	0.48 / 0.48	nan / nan
JET EtaIntercalibration NonClosure	-0.67 / -0.67	0.854 / 0.854	-0.151 / -0.151	-0.579 / -0.579	-0.405 / -0.405	nan / nan
JET EtaIntercalibration TotalStat	0.357 / 0.357	-0.01 / -0.01	0.199 / 0.199	1.02 / 1.02	0.246 / 0.246	nan / nan
JET Flavor Composition	3.59 / 3.59	5.25 / 5.25	1.68 / 1.68	4.23 / 4.23	1.41 / 1.41	nan / nan
JET PU Offset Mu	-0.163 / -0.163	-0.744 / -0.744	-0.302 / -0.302	-0.713 / -0.713	-0.181 / -0.181	nan / nan
JET PU Offset NPV	0.485 / 0.485	1.51 / 1.51	0.288 / 0.288	-0.203 / -0.203	0.196 / 0.196	nan / nan
JET PU Pt Term	0.496 / 0.496	1.31 / 1.31	-0.2 / -0.2	0.291 / 0.291	0.655 / 0.655	nan / nan
JET Punch Through	0.00143 / 0.00143	1e-05 / 1e-05	0.000202 / 0.000202	0.000327 / 0.000327	0.0172 / 0.0172	nan / nan
JET Single Particle High Pt	1.21e-05 / 1.21e-05	1.52e-05 / 1.52e-05	-9.2e-06 / -1.01e-05	1.35e-05 / 1.31e-05	-7.14e-05 / -7.17e-05	nan / nan
JET JER SINGLE NP	-13.5 / -13.5	5.3 / 5.3	0.681 / 0.681	0.0355 / 0.0355	-0.618 / -0.618	nan / nan
MET Reso Para	-13.5 / -13.5	-3.47 / -3.47	-1.07 / -1.07	-1.09 / -1.09	-0.886 / -0.886	nan / nan
MET Reso Perp	-13.5 / -13.5	-3.47 / -3.47	-1.07 / -1.07	-1.09 / -1.09	-0.887 / -0.887	nan / nan
MET Scale	-1.91e-05 / -1.91e-05	2.67e-06 / 2.67e-06	-0.000123 / -0.000121	-4.55e-05 / -4.88e-05	-1.28e-05 / -1.28e-05	nan / nan
Z+jets cross section	5 / 5	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Luminosity	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	nan / nan
Z+jets generator SR	-10.7 / -10.7	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Diboson cross section	0 / 0	6 / 6	0 / 0	0 / 0	0 / 0	nan / nan
$t\bar{t}$ PDF SR	0 / 0	0 / 0	6.33 / 6.33	0 / 0	0 / 0	nan / nan
$t\bar{t}$ scalevar SR	0 / 0	0 / 0	9.63 / 9.63	0 / 0	0 / 0	nan / nan
$t\bar{t}$ cross section	0 / 0	0 / 0	6 / 6	0 / 0	0 / 0	nan / nan
Singletop cross section	0 / 0	0 / 0	0 / 0	5 / 5	0 / 0	nan / nan
$t\bar{t}$ V cross section	0 / 0	0 / 0	0 / 0	0 / 0	12 / 12	nan / nan
SigXsecOverSM	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	inf / inf

Table 4.15: Systematic uncertainties (%) per sample in the Z +jets CR region for electron channel.

	Z+jets	Diboson	$t\bar{t}$	Singletop	$t\bar{t} + V$	Signal (1 TeV)
Pile-up	0.66 / 0.66	-0.366 / -0.366	-1.44 / -1.44	-3.97 / -3.97	1.19 / 1.19	nan / nan
EL Trigger	0.0132 / 0.0132	0.00355 / 0.00355	0.0185 / 0.0185	0.0217 / 0.0217	0.00804 / 0.00804	nan / nan
EL Reco.	0.329 / 0.329	0.338 / 0.338	0.255 / 0.255	0.333 / 0.333	0.36 / 0.36	nan / nan
EL ID	1.81 / 1.81	2.5 / 2.5	1.34 / 1.34	1.65 / 1.65	2.03 / 2.03	nan / nan
EL Isol.	0.801 / 0.801	1.92 / 1.92	0.215 / 0.215	0.677 / 0.677	1.47 / 1.47	nan / nan
Muon Trig. Stat	0 / 0	-1.52e-06 / -1.52e-06	0 / 0	-1.77e-06 / -3.35e-06	5.72e-07 / 5.72e-07	nan / nan
Muon Trig. Syst.	0 / 0	-1.74e-06 / -1.74e-06	0 / 0	-6.13e-06 / -6.13e-06	8.59e-06 / 8.59e-06	nan / nan
Muon ID Stat	1.35e-05 / 1.35e-05	0.0351 / 0.0351	0 / 0	0.00169 / 0.00169	0.0167 / 0.0167	nan / nan
Muon ID Syst	4.8e-05 / 4.8e-05	0.109 / 0.109	0 / 0	0.00751 / 0.00751	0.0842 / 0.0842	nan / nan
Muon ID Stat (low pt)	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Muon ID Syst (low pt)	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Muon Isol. Stat	3.05e-06 / 3.05e-06	0.00477 / 0.00477	0 / 0	0.000423 / 0.000423	0.00326 / 0.00326	nan / nan
Muon Isol. Syst	2.69e-06 / 2.69e-06	0.0071 / 0.0071	0 / 0	0.000944 / 0.000944	0.00894 / 0.00894	nan / nan
Muon TTVA Stat	4.64e-06 / 4.64e-06	0.0102 / 0.0102	0 / 0	0.000854 / 0.000854	0.00715 / 0.00715	nan / nan
Muon TTVA Syst	0 / 0	0.00487 / 0.00487	0 / 0	0.000993 / 0.000993	0.00675 / 0.00675	nan / nan
Btag extrP.	0.371 / 0.371	0.519 / 0.519	0.112 / 0.112	0.0739 / 0.0739	0.0696 / 0.0696	nan / nan
Btag extraP from charm	0.00218 / 0.00218	1.06 / 1.06	0 / 0	-0.0533 / -0.0533	-0.0493 / -0.0493	nan / nan
Btag b 100	-0.269 / -0.269	-0.605 / -0.605	1.5 / 1.5	2.06 / 2.06	0.967 / 0.967	nan / nan
Btag b 200	-0.317 / -0.317	-0.288 / -0.288	0.238 / 0.238	-0.241 / -0.241	0.088 / 0.088	nan / nan
Btag b 300	-0.123 / -0.123	-0.085 / -0.085	-0.565 / -0.565	-0.336 / -0.336	-0.223 / -0.223	nan / nan
Btag b 400	0.03 / 0.03	-0.145 / -0.145	0.104 / 0.104	0.018 / 0.018	0.0782 / 0.0782	nan / nan
Btag b 500	-0.00993 / -0.00993	-0.067 / -0.067	0.029 / 0.029	-0.0819 / -0.0819	0.0063 / 0.0063	nan / nan
Btag b 600	-0.00201 / -0.00201	0.00657 / 0.00657	-0.00558 / -0.00558	0.00716 / 0.00716	-0.00389 / -0.00389	nan / nan
Btag c 100	-1.49 / -1.49	-5.18 / -5.18	0.154 / 0.154	0.602 / 0.602	0.407 / 0.407	nan / nan
Btag c 200	-0.853 / -0.853	-3.3 / -3.3	-0.272 / -0.272	-0.305 / -0.305	-0.248 / -0.248	nan / nan
Btag c 300	-0.557 / -0.557	-0.97 / -0.97	-0.159 / -0.159	-0.18 / -0.18	-0.0722 / -0.0722	nan / nan
Btag light 100	-6.03 / -6.03	-4.74 / -4.74	-0.174 / -0.174	-1.25 / -1.25	0.232 / 0.232	nan / nan
Btag light 200	1.56 / 1.56	-0.229 / -0.229	-0.0102 / -0.0102	0.275 / 0.275	-0.158 / -0.158	nan / nan
Btag light 300	-0.338 / -0.338	2.53 / 2.53	0.463 / 0.463	1.14 / 1.14	0.108 / 0.108	nan / nan
Btag light 400	-0.67 / -0.67	0.762 / 0.762	-0.0333 / -0.0333	0.0286 / 0.0286	-0.0704 / -0.0704	nan / nan
Btag light 500	0.306 / 0.306	0.227 / 0.227	-0.0304 / -0.0304	-0.0739 / -0.0739	0.00899 / 0.00899	nan / nan
Btag light 600	0.534 / 0.534	0.511 / 0.511	-0.0191 / -0.0191	-0.0311 / -0.0311	0.0135 / 0.0135	nan / nan
Btag light 700	0.247 / 0.247	-0.104 / -0.104	0.0922 / 0.0922	-0.129 / -0.129	-0.00188 / -0.00188	nan / nan
Btag light 800	-0.0603 / -0.0603	0.378 / 0.378	0.0304 / 0.0304	-0.056 / -0.056	0.0201 / 0.0201	nan / nan
Btag light 900	-0.221 / -0.221	0.0535 / 0.0535	-0.163 / -0.163	0.319 / 0.319	-0.00728 / -0.00728	nan / nan
Btag light 1000	-0.104 / -0.104	-0.444 / -0.444	-0.0433 / -0.0433	0.00229 / 0.00229	-0.00901 / -0.00901	nan / nan
Btag light 1100	0.151 / 0.151	-0.223 / -0.223	0.0164 / 0.0164	-0.089 / -0.089	-0.0129 / -0.0129	nan / nan
Btag light 1200	0.0919 / 0.0919	0.245 / 0.245	0.0239 / 0.0239	0.139 / 0.139	0.000454 / 0.000456	nan / nan
Btag light 1300	0.0261 / 0.0261	0.132 / 0.132	-0.0222 / -0.0222	0.0354 / 0.0354	0.00592 / 0.00593	nan / nan
Btag light 1400	0.013 / 0.013	0.0886 / 0.0886	0.00293 / 0.00293	-0.139 / -0.139	0.000923 / 0.000923	nan / nan
Btag light 1500	0.00574 / 0.00574	0.04 / 0.04	0.00612 / 0.00612	-0.0479 / -0.0479	-0.000974 / -0.000974	nan / nan
Btag light 1600	0.00303 / 0.00303	0.0793 / 0.0793	0.000741 / 0.000741	-0.0204 / -0.0204	0.000469 / 0.00047	nan / nan
Jet JVT eff.	0.316 / 0.316	0.813 / 0.813	-0.0946 / -0.0946	0.203 / 0.203	0.125 / 0.125	nan / nan
Z+jets scalevar	30.3 / 30.3	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Z+jets PDF	14 / 14	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
EG Resolution	0.00576 / 0.00576	-0.183 / -0.183	-0.423 / -0.423	0.615 / 0.615	-0.09 / -0.09	nan / nan
EG Scale	0.0595 / 0.0595	-0.253 / -0.253	-0.932 / -0.932	-0.746 / -0.746	0.39 / 0.39	nan / nan
Muon ID	3.47e-05 / 3.47e-05	0.00602 / 0.00602	6.61e-05 / 6.61e-05	3.95e-05 / 3.95e-05	-0.000836 / -0.000836	nan / nan
Muon ResBias	-6.41e-05 / -6.41e-05	3.13e-05 / 3.13e-05	6.9e-05 / 6.9e-05	-0.000145 / -0.000145	-4.13e-05 / -4.13e-05	nan / nan
Muo Rho	5.24e-05 / 5.24e-05	-1.91e-05 / -1.91e-05	2.52e-05 / 2.52e-05	-3.09e-05 / -3.09e-05	-1.53e-05 / -1.58e-05	nan / nan
Muon Scale	2.24e-05 / 2.24e-05	0.000718 / 0.000718	0.000118 / 0.000118	2.34e-05 / 2.34e-05	0.000584 / 0.000584	nan / nan

Table 4.15: Systematic uncertainties (%) per sample in the Z +jets CR region for electron channel (cont.) .

	Z +jets	Diboson	$t\bar{t}$	Singletop	$t\bar{t} + V$	Signal (1 TeV)
JET Flavor Response	0.279 / 0.279	8.85 / 8.85	0.87 / 0.87	-0.325 / -0.325	0.24 / 0.24	nan / nan
JET Effective NP1	2.58 / 2.58	14.6 / 14.6	1.78 / 1.78	0 / 0	2.15 / 2.15	nan / nan
JET Effective NP2	-0.165 / -0.165	1.87 / 1.87	-0.406 / -0.406	0 / 0	-0.479 / -0.479	nan / nan
JET Effective NP3	-0.151 / -0.151	-1.88 / -1.88	-0.588 / -0.588	-0.226 / -0.226	0.0813 / 0.0813	nan / nan
JET Effective NP4	0.166 / 0.166	0.00639 / 0.00639	0.775 / 0.775	0.331 / 0.331	0.0761 / 0.0761	nan / nan
JET Effective NP5	-0.0266 / -0.0266	0.00226 / 0.00226	-0.13 / -0.13	-0.226 / -0.226	-0.0851 / -0.0851	nan / nan
JET Effective NP6	0.101 / 0.101	-0.000555 / -0.000552	0.874 / 0.874	-0.136 / -0.136	0.18 / 0.18	nan / nan
JET Effective NP7	-0.116 / -0.116	0.000265 / 0.000264	-1.33 / -1.33	0.227 / 0.227	-0.0903 / -0.0903	nan / nan
JET NP8 RestTerm	0.0853 / 0.0853	-0.000224 / -0.000224	0.792 / 0.792	-0.336 / -0.336	0.129 / 0.129	nan / nan
JET EtaIntercalibration Modelling	1.1 / 1.1	-0.0664 / -0.0664	0.489 / 0.489	-0.0312 / -0.0312	1.09 / 1.09	nan / nan
JET EtaIntercalibration NonClosure	-0.411 / -0.411	0.784 / 0.784	0.461 / 0.461	0.139 / 0.139	-0.319 / -0.319	nan / nan
JET EtaIntercalibration TotalStat	0.573 / 0.573	0.032 / 0.032	1.44 / 1.44	-0.381 / -0.381	0.511 / 0.511	nan / nan
JET Flavor Composition	5.91 / 5.91	15.9 / 15.9	6.13 / 6.13	6.9 / 6.9	4.75 / 4.75	nan / nan
JET PU Offset Mu	-0.284 / -0.284	-0.011 / -0.011	0.406 / 0.406	-0.947 / -0.947	-0.235 / -0.235	nan / nan
JET PU Offset NPV	0.724 / 0.724	1.2 / 1.2	1.11 / 1.11	-1.27 / -1.27	0.528 / 0.528	nan / nan
JET PU Pt Term	0.586 / 0.586	9.77 / 9.77	0.029 / 0.029	0.381 / 0.381	0.946 / 0.946	nan / nan
JET Punch Through	-0.00427 / -0.00427	-5.76e-05 / -6.11e-05	-0.00154 / -0.00154	-9.83e-05 / -9.83e-05	-0.0115 / -0.0115	nan / nan
JET Single Particle High Pt	4e-05 / 4e-05	-1.97e-05 / -1.97e-05	0.000105 / 0.000105	-4.79e-06 / -6.32e-06	7.51e-06 / 7.51e-06	nan / nan
JET JER SINGLE NP	-12.3 / -12.3	-16.3 / -16.3	-2.3 / -2.3	4.64 / 4.64	3.31 / 3.31	nan / nan
MET Reso Para	-13.6 / -13.6	-0.000106 / -0.000107	0.0022 / 0.0022	-8.57e-05 / -8.61e-05	0.000205 / 0.000199	nan / nan
MET Reso Perp	-13.6 / -13.6	-3.32e-05 / -3.7e-05	0.00229 / 0.00229	-9.45e-05 / -9.55e-05	-8.76e-05 / -8.42e-05	nan / nan
MET Scale	3.17e-05 / 3.17e-05	-7.83e-06 / -7.83e-06	-5.18e-05 / -5.01e-05	-6.66e-05 / -6.67e-05	-7.22e-05 / -7.22e-05	nan / nan
Z +jets cross section	5 / 5	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Luminosity	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	nan / nan
Z +jets generator	-26.1 / -26.1	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Diboson cross section	0 / 0	6 / 6	0 / 0	0 / 0	0 / 0	nan / nan
$t\bar{t}$ PDF ZJets	0 / 0	0 / 0	8.06 / 8.06	0 / 0	0 / 0	nan / nan
$t\bar{t}$ scalevar ZJets	0 / 0	0 / 0	9.61 / 9.61	0 / 0	0 / 0	nan / nan
$t\bar{t}$ cross section	0 / 0	0 / 0	6 / 6	0 / 0	0 / 0	nan / nan
Singletop cross section	0 / 0	0 / 0	0 / 0	5 / 5	0 / 0	nan / nan
$t\bar{t} V$ cross section	0 / 0	0 / 0	0 / 0	0 / 0	12 / 12	nan / nan
SigXsecOverSM	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	inf / inf

Table 4.16: Systematic uncertainties (%) per sample in the Z +jets CR region for muon channel.

	Z+jets	Diboson	$t\bar{t}$	Singletop	$t\bar{t} + V$	Signal (1 TeV)
Pile-up	1.29 / 1.29	6.45 / 6.45	3.96 / 3.96	-3.34 / -3.34	0.563 / 0.563	nan / nan
EL Trigger	-6.84e-07 / -1.37e-06	0.000183 / 0.000183	0 / 0	4e-05 / 4e-05	0.00053 / 0.00053	nan / nan
EL Reco.	1.26e-05 / 1.26e-05	0.0466 / 0.0466	0.000173 / 0.000173	0.000821 / 0.000821	0.0151 / 0.0151	nan / nan
EL ID	0.000152 / 0.000152	0.173 / 0.173	0.000774 / 0.000774	0.00531 / 0.00531	0.066 / 0.066	nan / nan
EL Isol.	0.000182 / 0.000182	0.152 / 0.152	8.91e-05 / 8.91e-05	0.000362 / 0.000362	0.0279 / 0.0279	nan / nan
Muon Trig. Stat	0.211 / 0.211	0.14 / 0.14	0.218 / 0.218	0.278 / 0.278	0.195 / 0.195	nan / nan
Muon Trig. Syst.	0.337 / 0.337	0.256 / 0.256	0.4 / 0.4	0.434 / 0.434	0.317 / 0.317	nan / nan
Muon ID Stat	0.373 / 0.373	0.398 / 0.398	0.376 / 0.376	0.375 / 0.375	0.409 / 0.409	nan / nan
Muon ID Syst	1.86 / 1.86	2.2 / 2.2	1.39 / 1.39	1.7 / 1.7	2.26 / 2.26	nan / nan
Muon ID Stat (low pt)	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Muon ID Syst (low pt)	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Muon Isol. Stat	0.0659 / 0.0659	0.0681 / 0.0681	0.0596 / 0.0596	0.0659 / 0.0659	0.0714 / 0.0714	nan / nan
Muon Isol. Syst	0.214 / 0.214	0.306 / 0.306	0.131 / 0.131	0.188 / 0.188	0.299 / 0.299	nan / nan
Muon TTVA Stat	0.151 / 0.151	0.159 / 0.159	0.155 / 0.155	0.158 / 0.158	0.167 / 0.167	nan / nan
Muon TTVA Syst	0.0936 / 0.0936	0.168 / 0.168	0.19 / 0.19	0.149 / 0.149	0.176 / 0.176	nan / nan
Btag extrP.	0.366 / 0.366	0.511 / 0.511	-0.0462 / -0.0462	0.0161 / 0.0161	0.0577 / 0.0577	nan / nan
Btag extraP from charm	-0.000133 / -0.000135	1.25 / 1.25	0 / 0	-0.029 / -0.029	-0.0569 / -0.0569	nan / nan
Btag b 100	-0.249 / -0.249	-0.595 / -0.595	1.08 / 1.08	0.864 / 0.864	0.947 / 0.947	nan / nan
Btag b 200	-0.337 / -0.337	-0.231 / -0.231	0.201 / 0.201	-0.138 / -0.138	0.0999 / 0.0999	nan / nan
Btag b 300	-0.113 / -0.113	-0.0902 / -0.0902	-0.0218 / -0.0218	-0.469 / -0.469	-0.256 / -0.256	nan / nan
Btag b 400	0.038 / 0.038	0.0102 / 0.0102	0.0685 / 0.0685	0.0402 / 0.0402	0.0397 / 0.0397	nan / nan
Btag b 500	-0.00906 / -0.00906	-0.0253 / -0.0253	-0.0175 / -0.0175	0.0265 / 0.0265	0.00129 / 0.00129	nan / nan
Btag b 600	-0.0022 / -0.00221	-0.00744 / -0.00744	-0.00331 / -0.00331	-0.00335 / -0.00335	-0.00333 / -0.00332	nan / nan
Btag c 100	-1.45 / -1.45	-8.03 / -8.03	0.0626 / 0.0626	-0.127 / -0.127	0.363 / 0.363	nan / nan
Btag c 200	-0.847 / -0.847	-4.09 / -4.09	-0.272 / -0.272	-0.239 / -0.239	-0.174 / -0.174	nan / nan
Btag c 300	-0.531 / -0.531	-1.19 / -1.19	-0.0805 / -0.0805	0.187 / 0.187	-0.0995 / -0.0995	nan / nan
Btag light 100	-5.79 / -5.79	-6.28 / -6.28	0.636 / 0.636	0.188 / 0.188	0.223 / 0.223	nan / nan
Btag light 200	1.5 / 1.5	-0.219 / -0.219	-0.299 / -0.299	0.0891 / 0.0891	-0.133 / -0.133	nan / nan
Btag light 300	-0.294 / -0.294	2.76 / 2.76	0.0671 / 0.0671	0.0356 / 0.0356	0.0283 / 0.0283	nan / nan
Btag light 400	-0.625 / -0.625	0.981 / 0.981	0.0529 / 0.0529	0.202 / 0.202	0.00736 / 0.00736	nan / nan
Btag light 500	0.344 / 0.344	0.323 / 0.323	0.0527 / 0.0527	0.00618 / 0.00618	0.0237 / 0.0237	nan / nan
Btag light 600	0.52 / 0.52	0.651 / 0.651	0.0527 / 0.0527	0.00392 / 0.00392	0.0214 / 0.0214	nan / nan
Btag light 700	0.285 / 0.285	-0.331 / -0.331	-0.0076 / -0.0076	-0.0313 / -0.0313	-0.0179 / -0.0179	nan / nan
Btag light 800	0.0781 / 0.0781	0.483 / 0.483	0.0313 / 0.0313	-0.0175 / -0.0175	0.0151 / 0.0151	nan / nan
Btag light 900	-0.266 / -0.266	0.248 / 0.248	0.000611 / 0.000611	0.0533 / 0.0533	0.0057 / 0.0057	nan / nan
Btag light 1000	-0.0748 / -0.0748	-0.288 / -0.288	-0.00224 / -0.00224	-0.00618 / -0.00618	-0.000131 / -0.000131	nan / nan
Btag light 1100	0.16 / 0.16	-0.216 / -0.216	0.0094 / 0.0094	0.00603 / 0.00603	0.00103 / 0.00103	nan / nan
Btag light 1200	0.0719 / 0.0719	0.118 / 0.118	0.000812 / 0.000813	-0.00161 / -0.00161	-0.00686 / -0.00686	nan / nan
Btag light 1300	0.0237 / 0.0237	0.0573 / 0.0573	0.00276 / 0.00276	-0.00536 / -0.00536	-0.00611 / -0.00611	nan / nan
Btag light 1400	0.0176 / 0.0176	0.0168 / 0.0168	0.0103 / 0.0103	0.00991 / 0.00991	0.00335 / 0.00335	nan / nan
Btag light 1500	0.00537 / 0.00537	-0.00616 / -0.00616	-0.0011 / -0.0011	0.00409 / 0.00409	0.00197 / 0.00197	nan / nan
Btag light 1600	-0.00389 / -0.00389	0.0372 / 0.0372	0.00316 / 0.00316	0.000943 / 0.000943	-0.00108 / -0.00108	nan / nan
Jet JVT eff.	0.308 / 0.308	0.475 / 0.475	0.198 / 0.198	0.3 / 0.3	0.0733 / 0.0733	nan / nan
Z+jets scalevar	30.8 / 30.8	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Z+jets PDF	1.93 / 1.93	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
EG Resolution	2.95e-05 / 2.95e-05	-0.000321 / -0.000321	0.000292 / 0.000292	0.000224 / 0.000224	0.00182 / 0.00182	nan / nan
EG Scale	-2.98e-05 / -2.91e-05	-0.000804 / -0.000803	-0.000133 / -0.000133	0.00135 / 0.00135	-0.0091 / -0.0091	nan / nan
Muon ID	0.296 / 0.296	0.806 / 0.806	0.542 / 0.542	0.164 / 0.164	0.173 / 0.173	nan / nan
Muon ResBias	3.32e-05 / 3.32e-05	-6.25e-06 / -6.58e-06	-0.000183 / -0.000188	-7.67e-05 / -7.67e-05	0.000124 / 0.000124	nan / nan
Muon Rho	9.03e-05 / 9.03e-05	-1.32e-05 / -1.32e-05	7.24e-05 / 7.24e-05	-4.1e-05 / -4.1e-05	5.31e-05 / 5.31e-05	nan / nan
Muon Scale	0.00993 / 0.00993	-0.09 / -0.09	-0.647 / -0.647	0.0731 / 0.0731	0.102 / 0.102	nan / nan

Table 4.16: Systematic uncertainties (%) per sample in the Z +jets CR region for muon channel (cont.).

	Z +jets	Diboson	$t\bar{t}$	Singletop	$t\bar{t} + V$	Signal (1 TeV)
JET Flavor Response	0.216 / 0.216	0.524 / 0.524	0.419 / 0.419	-0.509 / -0.509	0.335 / 0.335	nan / nan
JET Effective NP1	2.73 / 2.73	-0.0623 / -0.0623	5.98 / 5.98	0 / 0	1.05 / 1.05	nan / nan
JET Effective NP2	-0.455 / -0.455	-0.0618 / -0.0618	2.4 / 2.4	0 / 0	0.0379 / 0.0379	nan / nan
JET Effective NP3	-0.0982 / -0.0982	0.784 / 0.784	-2.53 / -2.53	-0.902 / -0.902	-0.135 / -0.135	nan / nan
JET Effective NP4	0.157 / 0.157	-0.776 / -0.776	1.13 / 1.13	0.642 / 0.642	0.0821 / 0.0821	nan / nan
JET Effective NP5	-0.0232 / -0.0232	-0.0215 / -0.0215	0.138 / 0.138	-0.174 / -0.174	-0.057 / -0.057	nan / nan
JET Effective NP6	0.0259 / 0.0259	0.0204 / 0.0204	0.00818 / 0.00818	-1.53 / -1.53	0.0998 / 0.0998	nan / nan
JET Effective NP7	-0.166 / -0.166	-0.00643 / -0.00643	-0.00707 / -0.00707	1.58 / 1.58	-0.136 / -0.136	nan / nan
JET NP8 RestTerm	0.0859 / 0.0859	0.00318 / 0.00318	-0.138 / -0.138	-0.511 / -0.511	0.15 / 0.15	nan / nan
JET EtaIntercalibration Modelling	1.52 / 1.52	0.209 / 0.209	2.25 / 2.25	-0.549 / -0.549	0.814 / 0.814	nan / nan
JET EtaIntercalibration NonClosure	-0.344 / -0.344	-1.02 / -1.02	-0.529 / -0.529	-1.9 / -1.9	-0.294 / -0.294	nan / nan
JET EtaIntercalibration TotalStat	0.724 / 0.724	0.0596 / 0.0596	1.64 / 1.64	-1.53 / -1.53	0.384 / 0.384	nan / nan
JET Flavor Composition	6.21 / 6.21	4.95 / 4.95	9.89 / 9.89	10.2 / 10.2	2.52 / 2.52	nan / nan
JET PU Offset Mu	-0.168 / -0.168	0.77 / 0.77	0.865 / 0.865	-0.174 / -0.174	-0.134 / -0.134	nan / nan
JET PU Offset NPV	0.65 / 0.65	1.67 / 1.67	3.41 / 3.41	-1.88 / -1.88	0.368 / 0.368	nan / nan
JET PU Pt Term	0.532 / 0.532	0.629 / 0.629	2.76 / 2.76	2.83 / 2.83	0.459 / 0.459	nan / nan
JET Punch Through	0.00195 / 0.00195	-0.000113 / -0.000114	0.000283 / 0.000283	0.000399 / 0.000399	-0.0463 / -0.0463	nan / nan
JET Single Particle High Pt	-3.62e-05 / -3.64e-05	-2.44e-05 / -2.44e-05	-3.15e-05 / -3.15e-05	-5.26e-05 / -5.29e-05	0 / 0	nan / nan
JET JER SINGLE NP	-6.27 / -6.27	8.42 / 5.9	3.72 / 3.61	0.0701 / 0.0701	0.65 / 0.65	nan / nan
MET Reso Para	-6.88 / -6.88	-4.56e-05 / -4.59e-05	0.001 / 0.001	-9.51e-05 / -9.33e-05	2.61e-05 / 2.61e-05	nan / nan
MET Reso Perp	-6.88 / -6.88	-4.39e-05 / -4.39e-05	0.000712 / 0.000712	-0.000176 / -0.000176	5.92e-05 / 5.92e-05	nan / nan
MET Scale	-1.27e-05 / -1.27e-05	-2.81e-05 / -2.85e-05	1.34e-05 / 1.34e-05	8.15e-06 / 8.15e-06	2.43e-05 / 2.43e-05	nan / nan
Z +jets cross section	5 / 5	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Luminosity	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	nan / nan
Z +jets generator	-14.1 / -14.1	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Diboson cross section	0 / 0	6 / 6	0 / 0	0 / 0	0 / 0	nan / nan
$t\bar{t}$ PDF ZJets	0 / 0	0 / 0	8.28 / 8.28	0 / 0	0 / 0	nan / nan
$t\bar{t}$ scalevar ZJets	0 / 0	0 / 0	9.39 / 9.39	0 / 0	0 / 0	nan / nan
$t\bar{t}$ cross section	0 / 0	0 / 0	6 / 6	0 / 0	0 / 0	nan / nan
Singletop cross section	0 / 0	0 / 0	0 / 0	5 / 5	0 / 0	nan / nan
$t\bar{t}$ V cross section	0 / 0	0 / 0	0 / 0	0 / 0	12 / 12	nan / nan
SigXsecOverSM	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	inf / inf

Table 4.17: Systematic uncertainties (%) per sample in the $t\bar{t}$ CR region for electron channel.

	Z+jets	Diboson	$t\bar{t}$	Singletop	$t\bar{t} + V$	Signal (1 TeV)
Pile-up	-0.0303 / -0.0303	-23.1 / -23.1	1.28 / 1.28	-0.965 / -0.965	-0.562 / -0.562	nan / nan
EL Trigger	0.0154 / 0.0154	0.0058 / 0.0058	0.0127 / 0.0127	0.0113 / 0.0113	0.0117 / 0.0117	nan / nan
EL Reco.	0.315 / 0.315	0.3 / 0.3	0.289 / 0.289	0.297 / 0.297	0.315 / 0.315	nan / nan
EL ID	1.74 / 1.74	1.55 / 1.55	1.47 / 1.47	1.51 / 1.51	1.64 / 1.64	nan / nan
EL Isol.	0.606 / 0.606	0.586 / 0.586	0.37 / 0.37	0.538 / 0.538	0.601 / 0.601	nan / nan
Muon Trig. Stat	0 / 0	0 / 0	0 / 0	0 / 0	-2.69e-06 / -5.38e-06	nan / nan
Muon Trig. Syst.	0 / 0	0 / 0	0 / 0	0 / 0	-4.03e-06 / -6.72e-06	nan / nan
Muon ID Stat	0 / 0	0 / 0	0.000154 / 0.000154	0.000921 / 0.000921	0.00878 / 0.00878	nan / nan
Muon ID Syst	0 / 0	0 / 0	0.000713 / 0.000713	0.0121 / 0.0121	0.0433 / 0.0433	nan / nan
Muon ID Stat (low pt)	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Muon ID Syst (low pt)	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Muon Isol. Stat	0 / 0	0 / 0	3.31e-05 / 3.31e-05	0.000395 / 0.000395	0.00168 / 0.00168	nan / nan
Muon Isol. Syst	0 / 0	0 / 0	6.98e-05 / 6.98e-05	0.00101 / 0.00101	0.00472 / 0.00472	nan / nan
Muon TTVA Stat	0 / 0	0 / 0	5.14e-05 / 5.14e-05	0.00042 / 0.00042	0.00397 / 0.00397	nan / nan
Muon TTVA Syst	0 / 0	0 / 0	0 / 0	5.38e-05 / 5.38e-05	0.00467 / 0.00467	nan / nan
Btag extrP.	0.237 / 0.237	0.444 / 0.444	0.038 / 0.038	0.13 / 0.13	0.108 / 0.108	nan / nan
Btag extraP from charm	0 / 0	0 / 0	-0.000224 / -0.000224	-0.00103 / -0.00103	0.246 / 0.246	nan / nan
Btag b 100	-4.71 / -4.71	-3.04 / -3.04	-5.04 / -5.04	-5.53 / -5.53	-4.48 / -4.48	nan / nan
Btag b 200	-1.23 / -1.23	-1.16 / -1.16	-1.82 / -1.82	-1.8 / -1.8	-1.48 / -1.48	nan / nan
Btag b 300	0.417 / 0.417	0.588 / 0.588	0.599 / 0.599	0.455 / 0.455	0.417 / 0.417	nan / nan
Btag b 400	0.0648 / 0.0648	0.179 / 0.179	0.235 / 0.235	0.113 / 0.113	0.146 / 0.146	nan / nan
Btag b 500	-0.0194 / -0.0194	-0.0329 / -0.0329	-0.028 / -0.028	-0.0225 / -0.0225	-0.0133 / -0.0133	nan / nan
Btag b 600	-0.00615 / -0.00615	-0.0229 / -0.0229	-0.00461 / -0.00461	0.00187 / 0.00187	-0.00391 / -0.00391	nan / nan
Btag c 100	-6.83 / -6.83	-16.3 / -16.3	-0.747 / -0.747	-1.59 / -1.59	-1.92 / -1.92	nan / nan
Btag c 200	-1.97 / -1.97	-1.4 / -1.4	-0.171 / -0.171	-0.288 / -0.288	-0.277 / -0.277	nan / nan
Btag c 300	-0.475 / -0.475	1.71 / 1.71	-0.0292 / -0.0292	-0.185 / -0.185	0.00437 / 0.00437	nan / nan
Btag light 100	-3.95 / -3.95	-20.4 / -20.4	-0.645 / -0.645	-0.936 / -0.936	-0.826 / -0.826	nan / nan
Btag light 200	0.826 / 0.826	-1.56 / -1.56	0.185 / 0.185	0.113 / 0.113	0.15 / 0.15	nan / nan
Btag light 300	0.696 / 0.696	-7.17 / -7.17	0.0281 / 0.0281	-0.0917 / -0.0917	0.154 / 0.154	nan / nan
Btag light 400	0.089 / 0.089	-9.97 / -9.97	0.0359 / 0.0359	-0.355 / -0.355	-0.115 / -0.115	nan / nan
Btag light 500	-0.051 / -0.051	-0.0399 / -0.0399	-0.0126 / -0.0126	-0.0406 / -0.0406	-0.0326 / -0.0326	nan / nan
Btag light 600	-0.0265 / -0.0265	-0.405 / -0.405	-0.00259 / -0.00259	-0.0497 / -0.0497	-0.0273 / -0.0273	nan / nan
Btag light 700	-0.12 / -0.12	-0.544 / -0.544	0.00142 / 0.00142	-0.0708 / -0.0708	0.00733 / 0.00733	nan / nan
Btag light 800	-0.0803 / -0.0803	-0.108 / -0.108	-0.00739 / -0.00739	-0.0522 / -0.0522	-0.00595 / -0.00595	nan / nan
Btag light 900	0.234 / 0.234	0.193 / 0.193	0.0172 / 0.0172	0.159 / 0.159	-0.0247 / -0.0247	nan / nan
Btag light 1000	0.0624 / 0.0624	0.0819 / 0.0819	0.0217 / 0.0217	0.00376 / 0.00376	-0.0338 / -0.0338	nan / nan
Btag light 1100	0.0333 / 0.0333	-0.044 / -0.044	0.00663 / 0.00663	-0.0171 / -0.0171	-0.0054 / -0.0054	nan / nan
Btag light 1200	-0.0541 / -0.0541	-0.166 / -0.166	-0.00961 / -0.00961	0.0425 / 0.0425	0.00202 / 0.00202	nan / nan
Btag light 1300	-0.00953 / -0.00953	0.071 / 0.071	-0.00233 / -0.00233	0.00373 / 0.00373	-0.0002 / -0.000196	nan / nan
Btag light 1400	0.0366 / 0.0366	-0.0636 / -0.0636	0.00262 / 0.00262	-0.0313 / -0.0313	0.0115 / 0.0115	nan / nan
Btag light 1500	0.00455 / 0.00455	0.00793 / 0.00793	0.000478 / 0.000478	-0.0079 / -0.0079	0.00477 / 0.00477	nan / nan
Btag light 1600	0.00451 / 0.00451	0.0173 / 0.0173	-0.000827 / -0.000827	-0.00546 / -0.00546	0.00127 / 0.00127	nan / nan
Jet JVT eff.	0.136 / 0.136	1.44 / 1.44	0.209 / 0.209	0.466 / 0.466	-0.0621 / -0.0621	nan / nan
EG Resolution	0.52 / 0.52	3.59 / 3.59	0.108 / 0.108	0.068 / 0.068	-0.22 / -0.22	nan / nan
EG Scale	0.726 / 0.726	2.27 / 2.27	-0.138 / -0.138	0.868 / 0.868	0.0379 / 0.0379	nan / nan
Muon ID	3.51e-05 / 3.51e-05	0.0066 / 0.0066	0.000105 / 0.000105	-1.73e-06 / -1.73e-06	0.000412 / 0.000412	nan / nan
Muon ResBias	-2.03e-05 / -2.03e-05	2.05e-05 / 2.05e-05	-0.000132 / -0.000132	-3.99e-05 / -3.99e-05	1.21e-05 / 1.21e-05	nan / nan
Muon Rho	-3.69e-06 / -3.69e-06	5.21e-06 / 5.21e-06	-6.06e-05 / -6.43e-05	1.56e-05 / 1.56e-05	-9.41e-06 / -1.21e-05	nan / nan
Muon Scale	5.54e-06 / 5.54e-06	0.000827 / 0.000827	-7.16e-05 / -7.16e-05	0 / 0	-9.55e-05 / -9.28e-05	nan / nan

Table 4.17: Systematic uncertainties (%) per sample in the $t\bar{t}$ CR region for electron channel (cont).

	Z+jets	Diboson	$t\bar{t}$	Singletop	$t\bar{t} + V$	Signal (1 TeV)
JET Flavor Response	1.22 / 1.22	0.207 / 0.207	0.789 / 0.789	0.689 / 0.689	0.604 / 0.604	nan / nan
JET Effective NP1	3.63 / 3.63	0.0638 / 0.0638	2.64 / 2.64	0 / 0	0.848 / 0.848	nan / nan
JET Effective NP2	-0.749 / -0.749	0.0131 / 0.0131	-0.459 / -0.459	0 / 0	0.214 / 0.214	nan / nan
JET Effective NP3	-0.149 / -0.149	0.00688 / 0.00688	-0.0758 / -0.0758	-0.862 / -0.862	-0.3 / -0.3	nan / nan
JET Effective NP4	0.175 / 0.175	0.225 / 0.225	0.187 / 0.187	0.857 / 0.857	0.189 / 0.189	nan / nan
JET Effective NP5	-0.0739 / -0.0739	0.00193 / -0.234	-0.0855 / -0.0855	-0.00941 / -0.00941	-0.0139 / -0.0139	nan / nan
JET Effective NP6	0.0334 / 0.0334	-0.00413 / -0.00413	0.009 / 0.009	-0.358 / -0.358	-0.0105 / -0.0105	nan / nan
JET Effective NP7	-0.0516 / -0.0516	0.000426 / 0.000426	-0.142 / -0.142	-0.14 / -0.14	0.00563 / 0.00563	nan / nan
JET NP8 RestTerm	0.0322 / 0.0322	-0.000743 / -0.00074	0.111 / 0.111	0.34 / 0.34	0.122 / 0.122	nan / nan
JET EtaIntercalibration Modelling	1.62 / 1.62	0.214 / 0.214	1.29 / 1.29	0.136 / 0.136	0.207 / 0.207	nan / nan
JET EtaIntercalibration NonClosure	-0.968 / -0.968	0.254 / 0.254	-0.522 / -0.522	0.46 / 0.46	0.11 / 0.11	nan / nan
JET EtaIntercalibration TotalStat	0.789 / 0.789	0.221 / 0.221	0.738 / 0.738	1.06 / 1.06	0.279 / 0.279	nan / nan
JET Flavor Composition	5.18 / 5.18	11.6 / 11.6	4.13 / 4.13	3.03 / 3.03	1.63 / 1.63	nan / nan
JET PU Offset Mu	-0.611 / -0.611	-0.00213 / -0.238	-0.232 / -0.232	-0.306 / -0.306	0.116 / 0.116	nan / nan
JET PU Offset NPV	0.236 / 0.236	-0.0613 / -0.295	0.645 / 0.645	0.478 / 0.478	-0.0162 / -0.0162	nan / nan
JET PU Pt Term	0.295 / 0.295	-0.0125 / -0.0125	0.532 / 0.532	0.622 / 0.622	0.41 / 0.41	nan / nan
JET Punch Through	-3.32e-05 / -3.32e-05	5.77e-05 / 5.73e-05	-0.000114 / -0.000118	9.54e-05 / 9.54e-05	-0.00497 / -0.00497	nan / nan
JET Single Particle High Pt	0 / 0	-7.3e-06 / -7.3e-06	4.96e-05 / 4.96e-05	-1.56e-05 / -1.56e-05	-1.21e-05 / -1.21e-05	nan / nan
JET JER SINGLE NP	0.433 / 0.433	12.9 / 12.9	0.204 / 0.204	1.39 / 1.39	-1.27 / -1.27	nan / nan
MET Reso Para	0.0433 / 0.0433	4.31e-05 / 4.03e-05	0.00339 / 0.00339	-1.02 / -1.02	0.198 / 0.198	nan / nan
MET Reso Perp	0.00696 / 0.00696	-6.15e-05 / -5.59e-05	0.104 / 0.104	-2.25e-05 / -1.91e-05	0.156 / 0.156	nan / nan
MET Scale	0.00347 / 0.00347	6.6e-06 / 6.6e-06	0.0565 / 0.0565	0.348 / 0.348	0.108 / 0.108	nan / nan
Z+jets cross section	5 / 5	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Luminosity	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	nan / nan
Diboson cross section	0 / 0	6 / 6	0 / 0	0 / 0	0 / 0	nan / nan
$t\bar{t}$ scalevar	0 / 0	0 / 0	9.27 / 9.27	0 / 0	0 / 0	nan / nan
$t\bar{t}$ PDF	0 / 0	0 / 0	5.8 / 5.8	0 / 0	0 / 0	nan / nan
$t\bar{t}$ cross section	0 / 0	0 / 0	6 / 6	0 / 0	0 / 0	nan / nan
Singletop cross section	0 / 0	0 / 0	0 / 0	5 / 5	0 / 0	nan / nan
$t\bar{t} V$ cross section	0 / 0	0 / 0	0 / 0	0 / 0	12 / 12	nan / nan
SigXsecOverSM	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	inf / inf

Table 4.18: Systematic uncertainties (%) per sample in the $t\bar{t}$ CR region for muon channel.

	Z +jets	Diboson	$t\bar{t}$	Singletop	$t\bar{t} + V$	Signal (1 TeV)
Pile-up	-0.287 / -0.287	-20.2 / -20.2	0.466 / 0.466	-0.471 / -0.471	2.54 / 2.54	nan / nan
EL Trigger	0 / 0	0 / 0	5.55e-06 / 5.55e-06	1.01e-05 / 1.01e-05	0.000275 / 0.000275	nan / nan
EL Reco.	4.29e-05 / 4.29e-05	0 / 0	4.58e-05 / 4.58e-05	0.000253 / 0.000253	0.00591 / 0.00591	nan / nan
EL ID	0.000215 / 0.000215	0 / 0	0.000309 / 0.000309	0.000732 / 0.000732	0.0306 / 0.0306	nan / nan
EL Isol.	9.54e-06 / 9.54e-06	0 / 0	0.000262 / 0.000262	8.59e-05 / 8.59e-05	0.00841 / 0.00841	nan / nan
Muon Trig. Stat	0.239 / 0.239	0.209 / 0.209	0.238 / 0.238	0.254 / 0.254	0.211 / 0.211	nan / nan
Muon Trig. Syst.	0.368 / 0.368	0.189 / 0.189	0.38 / 0.38	0.421 / 0.421	0.331 / 0.331	nan / nan
Muon ID Stat	0.393 / 0.393	0.323 / 0.323	0.385 / 0.385	0.41 / 0.41	0.385 / 0.385	nan / nan
Muon ID Syst	1.8 / 1.8	2.66 / 2.66	1.62 / 1.62	1.69 / 1.69	1.73 / 1.73	nan / nan
Muon ID Stat (low pt)	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Muon ID Syst (low pt)	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Muon Isol. Stat	0.0664 / 0.0664	0.0974 / 0.0974	0.0588 / 0.0588	0.0602 / 0.0602	0.0615 / 0.0615	nan / nan
Muon Isol. Syst	0.21 / 0.21	0.308 / 0.308	0.18 / 0.18	0.203 / 0.203	0.209 / 0.209	nan / nan
Muon TTVA Stat	0.148 / 0.148	0.167 / 0.167	0.159 / 0.159	0.161 / 0.161	0.158 / 0.158	nan / nan
Muon TTVA Syst	0.113 / 0.113	0.125 / 0.125	0.165 / 0.165	0.174 / 0.174	0.159 / 0.159	nan / nan
Btag extrP.	0.302 / 0.302	1.95 / 1.95	0.0647 / 0.0647	0.0945 / 0.0945	0.123 / 0.123	nan / nan
Btag extraP from charm	-0.000115 / -0.00011	0 / 0	-0.00215 / -0.00215	-0.0177 / -0.0177	0.123 / 0.123	nan / nan
Btag b 100	-5.26 / -5.26	-5.26 / -5.26	-5.02 / -5.02	-5.46 / -5.46	-4.05 / -4.05	nan / nan
Btag b 200	-1.32 / -1.32	-1.08 / -1.08	-1.89 / -1.89	-1.78 / -1.78	-1.51 / -1.51	nan / nan
Btag b 300	0.411 / 0.411	0.152 / 0.152	0.586 / 0.586	0.471 / 0.471	0.412 / 0.412	nan / nan
Btag b 400	0.0366 / 0.0366	-0.312 / -0.312	0.234 / 0.234	0.131 / 0.131	0.133 / 0.133	nan / nan
Btag b 500	-0.0162 / -0.0162	-0.0149 / -0.0149	-0.0347 / -0.0347	-0.0177 / -0.0177	-0.0181 / -0.0181	nan / nan
Btag b 600	-0.00677 / -0.00677	-0.00958 / -0.00958	-0.00465 / -0.00464	-0.00676 / -0.00676	-0.00412 / -0.00412	nan / nan
Btag c 100	-6.51 / -6.51	-22.9 / -22.9	-0.735 / -0.735	-0.499 / -0.499	-1.94 / -1.94	nan / nan
Btag c 200	-2.66 / -2.66	-11.6 / -11.6	-0.138 / -0.138	0.144 / 0.144	-0.619 / -0.619	nan / nan
Btag c 300	-0.726 / -0.726	-3.34 / -3.34	-0.0168 / -0.0168	-0.0955 / -0.0955	-0.138 / -0.138	nan / nan
Btag light 100	-2.16 / -2.16	-6.16 / -6.16	-0.705 / -0.705	-1.06 / -1.06	-0.224 / -0.224	nan / nan
Btag light 200	0.438 / 0.438	4.32 / 4.32	0.144 / 0.144	0.211 / 0.211	0.0262 / 0.0262	nan / nan
Btag light 300	2.52 / 2.52	5.91 / 5.91	0.00351 / 0.00351	0.398 / 0.398	-0.12 / -0.12	nan / nan
Btag light 400	-0.341 / -0.341	-0.388 / -0.388	-0.0521 / -0.0521	0.0111 / 0.0111	-0.00976 / -0.00976	nan / nan
Btag light 500	-0.219 / -0.219	-1.29 / -1.29	-0.0155 / -0.0155	-0.0203 / -0.0203	0.00886 / 0.00886	nan / nan
Btag light 600	-0.235 / -0.235	-1.57 / -1.57	-0.00981 / -0.00981	-0.0136 / -0.0136	0.0143 / 0.0143	nan / nan
Btag light 700	-0.023 / -0.023	1.57 / 1.57	0.0167 / 0.0167	-0.12 / -0.12	-0.00323 / -0.00323	nan / nan
Btag light 800	-0.165 / -0.165	-0.795 / -0.795	-0.00295 / -0.00295	-0.0495 / -0.0495	0.0108 / 0.0108	nan / nan
Btag light 900	0.173 / 0.173	-2.17 / -2.17	-0.0208 / -0.0208	0.229 / 0.229	0.006 / 0.006	nan / nan
Btag light 1000	0.0676 / 0.0676	-0.53 / -0.53	0.00127 / 0.00127	0.00108 / 0.00108	0.0117 / 0.0117	nan / nan
Btag light 1100	0.0378 / 0.0378	0.538 / 0.538	0.0072 / 0.0072	-0.00689 / -0.00689	-0.000716 / -0.000716	nan / nan
Btag light 1200	-0.0257 / -0.0257	0.291 / 0.291	0.00309 / 0.00309	0.0269 / 0.0269	-0.00393 / -0.00393	nan / nan
Btag light 1300	-0.0146 / -0.0146	-0.156 / -0.156	-0.00335 / -0.00335	-0.00559 / -0.00559	-0.00375 / -0.00375	nan / nan
Btag light 1400	0.0274 / 0.0274	-0.0515 / -0.0515	-0.00267 / -0.00267	-0.00502 / -0.00502	0.000901 / 0.000901	nan / nan
Btag light 1500	0.0128 / 0.0128	0.0106 / 0.0106	-0.000257 / -0.000254	0.000389 / 0.000391	-3.35e-05 / -3.35e-05	nan / nan
Btag light 1600	0.000103 / 0.000103	-0.0343 / -0.0344	-0.00102 / -0.00103	0.00094 / 0.000936	-0.00164 / -0.00164	nan / nan
Jet JVT eff.	0.32 / 0.32	0.45 / 0.45	0.188 / 0.188	0.27 / 0.27	0.0982 / 0.0982	nan / nan
EG Resolution	4.53e-05 / 4.53e-05	-2.14e-06 / -2.14e-06	-6.38e-05 / -6.24e-05	0 / 0	0.00429 / 0.00429	nan / nan
EG Scale	0 / 0	0 / 0	8.32e-06 / 8.32e-06	2.4e-05 / 2.4e-05	-0.00127 / -0.00127	nan / nan
Muon ID	-0.634 / -0.634	-13.4 / -13.4	0.0236 / 0.0236	0.522 / 0.522	-0.119 / -0.119	nan / nan
Muon ResBias	3.34e-05 / 3.34e-05	-9.43e-05 / -9.43e-05	-5.27e-05 / -5.13e-05	0 / 0	-2.79e-06 / -5.58e-06	nan / nan
Muo Rho	-1.19e-05 / -1.19e-05	-1.93e-05 / -2.25e-05	-5.13e-05 / -5.13e-05	-1.26e-05 / -1.26e-05	-2.79e-06 / -5.58e-06	nan / nan
Muon Scale	-0.382 / -0.382	-12 / -12	0.0017 / 0.0017	0.0833 / 0.0833	-0.0778 / -0.0778	nan / nan

Table 4.18: Systematic uncertainties (%) per sample in the $t\bar{t}$ CR region for muon channel (cont.).

	Z+jets	Diboson	$t\bar{t}$	Singletop	$t\bar{t} + V$	Signal (1 TeV)
JET Flavor Response	0.969 / 0.969	13.7 / 13.7	0.804 / 0.804	1.25 / 1.25	0.51 / 0.51	nan / nan
JET Effective NP1	2.97 / 2.97	11.2 / 11.2	2.43 / 2.43	0 / 0	1.83 / 1.83	nan / nan
JET Effective NP2	-0.51 / -0.51	12.2 / 12.2	-0.531 / -0.531	0 / 0	-0.195 / -0.195	nan / nan
JET Effective NP3	-0.161 / -0.161	-11.9 / -11.9	0.00253 / 0.00253	-0.269 / -0.269	-0.17 / -0.17	nan / nan
JET Effective NP4	0.362 / 0.362	11.9 / 11.9	0.161 / 0.161	0.269 / 0.269	0.163 / 0.163	nan / nan
JET Effective NP5	-0.137 / -0.137	-11.9 / -11.9	-0.0562 / -0.0562	-0.293 / -0.293	-0.067 / -0.067	nan / nan
JET Effective NP6	-0.0189 / -0.0189	11.9 / 11.9	-0.00907 / -0.00906	-0.0843 / -0.0843	-0.117 / -0.117	nan / nan
JET Effective NP7	-0.0838 / -0.0838	11.9 / 11.9	-0.107 / -0.107	0.224 / 0.224	0.0311 / 0.0311	nan / nan
JET NP8 RestTerm	0.236 / 0.236	11.9 / 11.9	0.052 / 0.052	0.0274 / 0.0274	0.0299 / 0.0299	nan / nan
JET EtaIntercalibration Modelling	0.912 / 0.912	11.8 / 11.8	0.941 / 0.941	0.978 / 0.978	0.367 / 0.367	nan / nan
JET EtaIntercalibration NonClosure	-0.159 / -0.159	-11.9 / -11.9	-0.401 / -0.401	0.0417 / 0.0417	-0.199 / -0.199	nan / nan
JET EtaIntercalibration TotalStat	0.405 / 0.405	11.7 / 11.7	0.498 / 0.498	1.13 / 1.13	0.324 / 0.324	nan / nan
JET Flavor Composition	3.89 / 3.89	8.09 / 8.09	3.93 / 3.93	2.41 / 2.41	2.06 / 2.06	nan / nan
JET PU Offset Mu	-0.481 / -0.481	12.1 / 12.1	-0.34 / -0.34	-1 / -1	-0.121 / -0.121	nan / nan
JET PU Offset NPV	0.579 / 0.579	13.4 / 13.4	0.518 / 0.518	-0.471 / -0.471	0.385 / 0.385	nan / nan
JET PU Pt Term	0.489 / 0.489	13.7 / 13.7	0.439 / 0.439	0.69 / 0.69	0.398 / 0.398	nan / nan
JET Punch Through	0.000285 / 0.000285	6.86e-05 / 6.86e-05	0.000554 / 0.000554	0.000678 / 0.000678	0.0284 / 0.0284	nan / nan
JET Single Particle High Pt	-4.41e-05 / -4.41e-05	3.64e-05 / 3.64e-05	3.61e-05 / 3.61e-05	2.4e-05 / 2.4e-05	2.37e-05 / 2.37e-05	nan / nan
JET JER SINGLE NP	3.52 / 3.52	16 / 16	0.199 / 0.199	0.286 / 0.286	-0.269 / -0.269	nan / nan
MET Reso Para	1.55e-05 / 1.55e-05	-1.55 / -1.55	0.057 / 0.057	-1.01e-05 / -1.01e-05	0.0482 / 0.0482	nan / nan
MET Reso Perp	1.07e-05 / 1.07e-05	-5.36e-05 / -5.68e-05	0.082 / 0.082	0 / 0	0.0507 / 0.0507	nan / nan
MET Scale	0.0145 / 0.0145	2.46e-05 / 2.46e-05	0.0473 / 0.0473	0 / 0	0.128 / 0.128	nan / nan
Z+jets cross section	5 / 5	0 / 0	0 / 0	0 / 0	0 / 0	nan / nan
Luminosity	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	2.2 / 2.2	nan / nan
Diboson cross section	0 / 0	6 / 6	0 / 0	0 / 0	0 / 0	nan / nan
$t\bar{t}$ scalevar	0 / 0	0 / 0	12.9 / 12.9	0 / 0	0 / 0	nan / nan
$t\bar{t}$ PDF	0 / 0	0 / 0	8.39 / 8.39	0 / 0	0 / 0	nan / nan
$t\bar{t}$ cross section	0 / 0	0 / 0	6 / 6	0 / 0	0 / 0	nan / nan
Singletop cross section	0 / 0	0 / 0	0 / 0	5 / 5	0 / 0	nan / nan
$t\bar{t}$ V cross section	0 / 0	0 / 0	0 / 0	0 / 0	12 / 12	nan / nan
SigXsecOverSM	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	inf / inf

4.5. Statistical Analysis and Expected Limits

We study four possible final discriminants for possible discovery or for setting limits: mass of the quark reconstructed from the Z boson, mass of the quark reconstructed from the Higgs boson, an average of these two masses and sum H_T . The sensitivity of the analysis was checked for these discriminants (see Appendix A.4 for details) and it was found that the VLQ mass averaged from Z and Higgs channels gives slightly better results as compared to other cases.

In the earlier version of our analysis, we have also considered three different scenarios regarding the use of b -tagging in the reconstruction of the H boson: not using the b -tag information at all (“un-btag”), requiring at least one (or both) jets used in the reconstruction of the H to be b -tagged (“1-btag” or “2-btag”). See Appendix A.6 for details.

The sensitivity of the analysis to the possible existence of the new quarks is validated with the so-called injection tests. In this tests, the pseudo-data obtained by summing the total SM background with a signal MC sample generated at a specific VLQ mass was analysed. Although the details can be found in Appendix A.3, it is shown that for the test case of 1TeV VLQ mass, the analysis is sensitive enough to discern it from the background even without using b -tag requirement to reduce the background.

In the event that no signal events are observed, it is planned to set 95% upper limits for the pair produced VLQ mass.

In order to take into account the systematic uncertainties, we choose to use the TReXStats/TReXFitter tool that is commonly used by various HQT exotics analyses. However, as an initial cross-check of this tool, we first obtain a few no-systematics results with it as a comparison to TLimit/MCLimit. The test yields essentially the same expected limits, so we confidently proceed with TReXFitter.

We have the most recent results of our analysis here, obtained with the 1-btag requirement that is applied as the last cut of the analysis. The final discriminant used is the average of the masses of the two reconstructed D quarks. The limits can be seen in Table 4.19 and in the Figures 4.54-4.56. Figures show results with statistical uncertainties only and with all the systematics included.

Table 4.19: The expected limits for the ee , $\mu\mu$ and combined channels.

b-tag case / Discriminant	ee channel (GeV)	$\mu\mu$ channel (GeV)	combined channel (GeV)
1-btag / Average D Mass	$1338^{+12.2}_{-14.8}$	$1306.1^{+14.5}_{-17.3}$	$1413.6^{+20.4}_{-17.3}$

The different NPs in the fit are included and those with an impact smaller than 1% are pruned from the fit. Figures A.1 and A.6 show the pruned NPs with different colours for different components pruned: shape, normalization or completely pruned for the 1 TeV signal reconstructed in the electron, muon and combined channels. Most of systematics are small and are pruned. Diboson sample has 2-3 % variation in the control regions, but it represents a tiny portion of the total background. Figures A.4, A.5 and A.9 show the correlation matrices of the nuisance parameters in the electron, muon and combined channels for 1 TeV signal, respectively. A variable is shown only if its correlation coefficient with at least one other variable is above 0.2. Of the over 100 systematics, most of these are found to be essentially uncorrelated; those very few which show significant correlation appear to have good physical motivation. The pre-fit and post-fit distributions of the final discriminant in the electron, muon and combined channels for the 1 TeV signal in the signal region and control region are shown in Figures A.10, A.11, A.12, A.13, A.14, A.15. The uncertainty bands include statistical and systematic uncertainties. Figures A.2 and A.7 show pull plots for the nuisance parameters for the fit to the Asimov data for the 1 TeV signal, for the electron and muon and combined channels. The behaviour seems generally normal. There are a couple of systematics that need careful attention. Those are plotted in Appendix (Figures A.16, A.17, A.18, A.19, A.20, A.21, A.22, A.23, A.24, A.25). We also observe that no significant correlation between signal and control regions results from NPs that are being considered over those multiple regions.

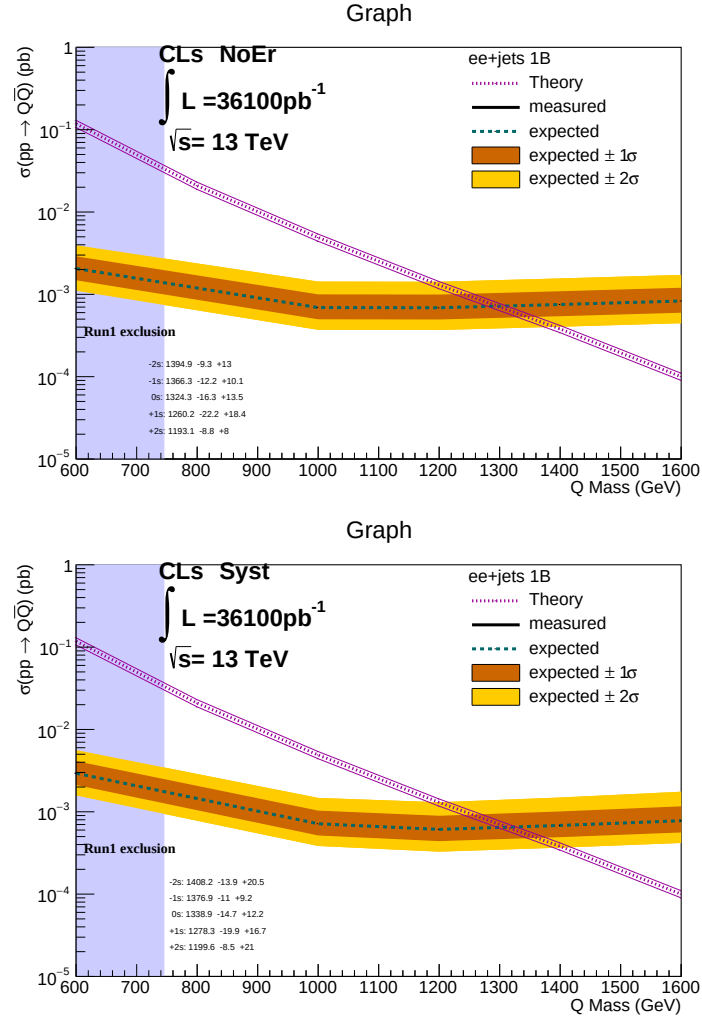


Figure 4.54: The expected limit with 95% CL for ee channel when none of the systematical uncertainties (up) and all of the systematical uncertainties (down) are included. The discriminant is the Average D mass for the 1-btagged case.

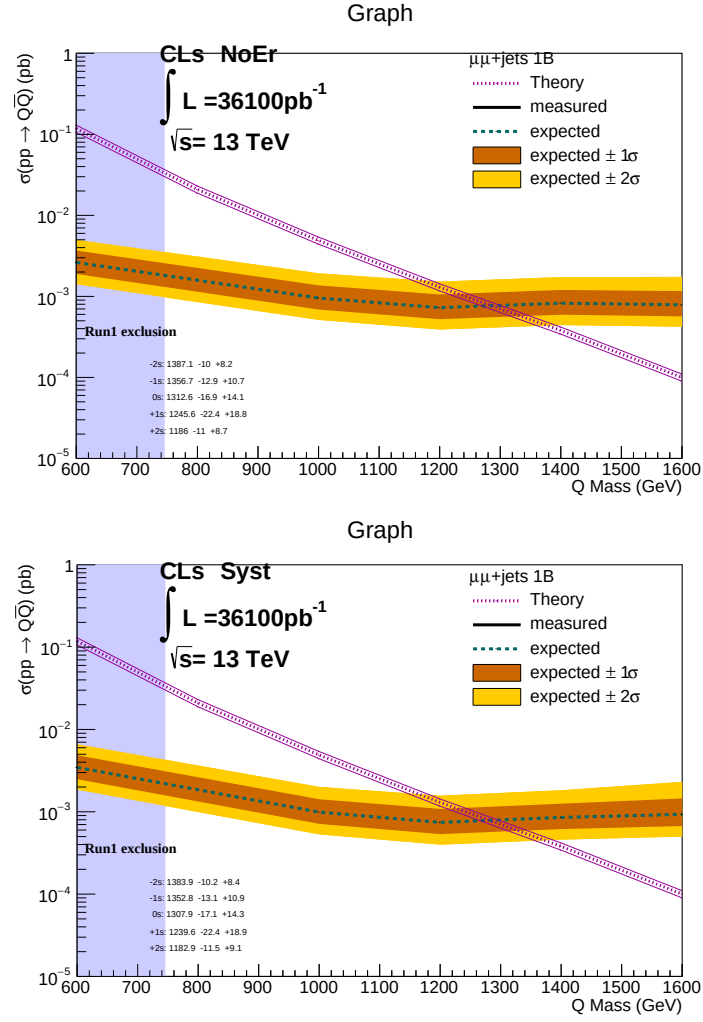


Figure 4.55: The expected limit with 95% CL for $\mu\mu$ channel when none of the systematical uncertainties (up) and all of the systematical uncertainties (down) are included. The discriminant is the Average D mass for the 1-btagged case.

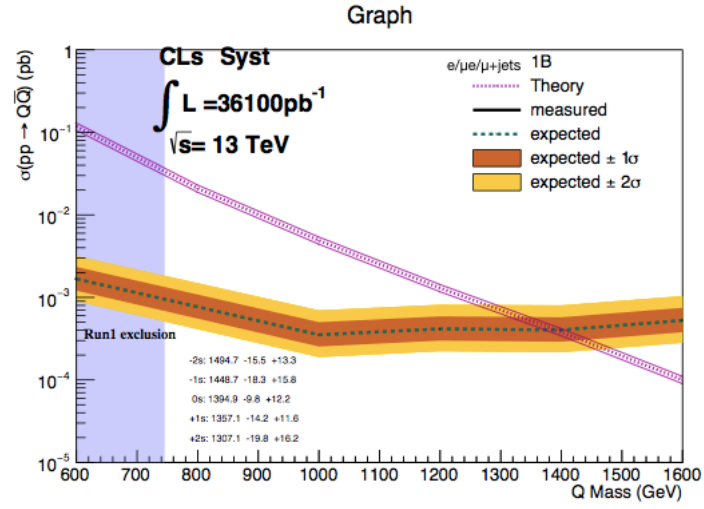


Figure 4.56: The expected limit with 95% CL for ee and $\mu\mu$ channels combined when all of the systematical uncertainties are included. The discriminant is the Average D mass for the 1-btagged case.

5. RESULTS

This analysis completely done blindly in the signal region as our analysis strategy. Meaning that: we didn't check distribution of data after our final cuts after the most decisive cut χ^2 in the signal region in order not to manipulate the cuts. Now that the all analysis done blindly and we saw that our data and Monte Carlo simulation agreement is good, we can move onto unblinding in our final discriminants.

5.1. Unblinding

First, the event yields are indicated without blinding the data in Tables 5.1 for ee channel and 5.2 for $\mu\mu$ channel.

Table 5.1: Expected signal and background yields for the electron channel in the signal region for the last four cuts.

	Total SM bkg	Signal + SM bkg	Data
$p_T^{LeadingJet} > 100 \text{ GeV}$	$(308 \pm 1) \times 10^2$	$(3093 \pm 11) \times 10^1$	$2.886 \times 10^4 \pm 169.9$
$p_T^{SubleadingJet} > 65 \text{ GeV}$	$(234 \pm 1) \times 10^2$	$(2358 \pm 8.7) \times 10^1$	$2.182 \times 10^4 \pm 147.7$
$\chi^2 < 15$	$(165 \pm 1) \times 10^2$	$(1663 \pm 6.6) \times 10^1$	$1.518\text{e}+04 \pm 123.2$
1 b -tagged jet	2371 ± 27	$(244.9 \pm 2.7) \times 10^1$	2224 ± 47.16

Table 5.2: Expected signal and background yields for the muon channel in the signal region for the last four cuts.

	Total SM bkg	Signal + SM bkg	Data
$p_T^{LeadingJet} \geq 100 \text{ GeV}$	$(46.4 \pm 0.32) \times 10^3$	$(464.4 \pm 1.6) \times 10^2$	$4.474\text{e}+04 \pm 211.5$
$p_T^{SubleadingJet} \geq 65 \text{ GeV}$	$(35.3 \pm 0.1) \times 10^3$	$(351.5 \pm 1.3) \times 10^2$	$(33.88 \pm 0.18) \times 10^3$
$\chi^2 < 15$	$(23.9 \pm 0.1) \times 10^3$	$(238.1 \pm 1.1) \times 10^2$	$2.283\text{e}+04 \pm 151.1$
1 b -tagged jet	2617 ± 57	3370 ± 115	3336 ± 57.76

The observed limits with the real data for ee , $\mu\mu$ and combined channels are

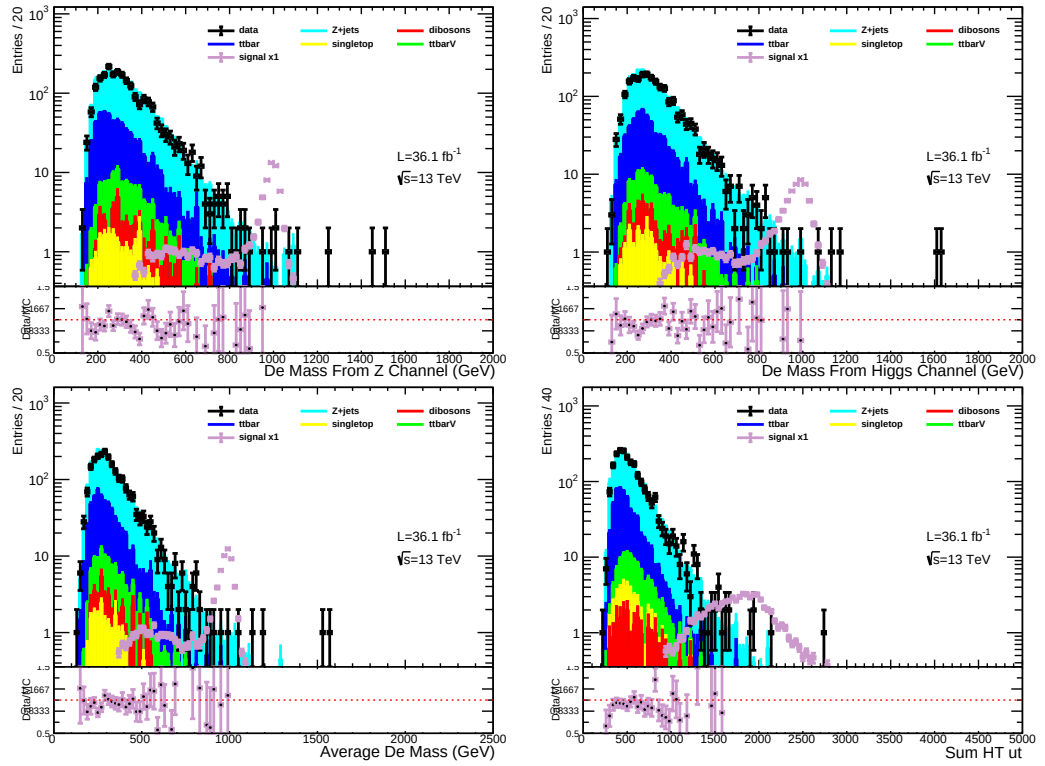


Figure 5.1: D quark mass reconstructed from a Z boson (*top-left*), D quark mass reconstructed from a H boson (*top-right*), average reconstructed D quark mass (*bottom-left*) and Sum H_T distributions (*bottom-right*) when one b-tagged jet is requested in Higgs-daughter jets in the ee channel in the signal region (after cut #11 in Table 4.2). Data is unblinded.

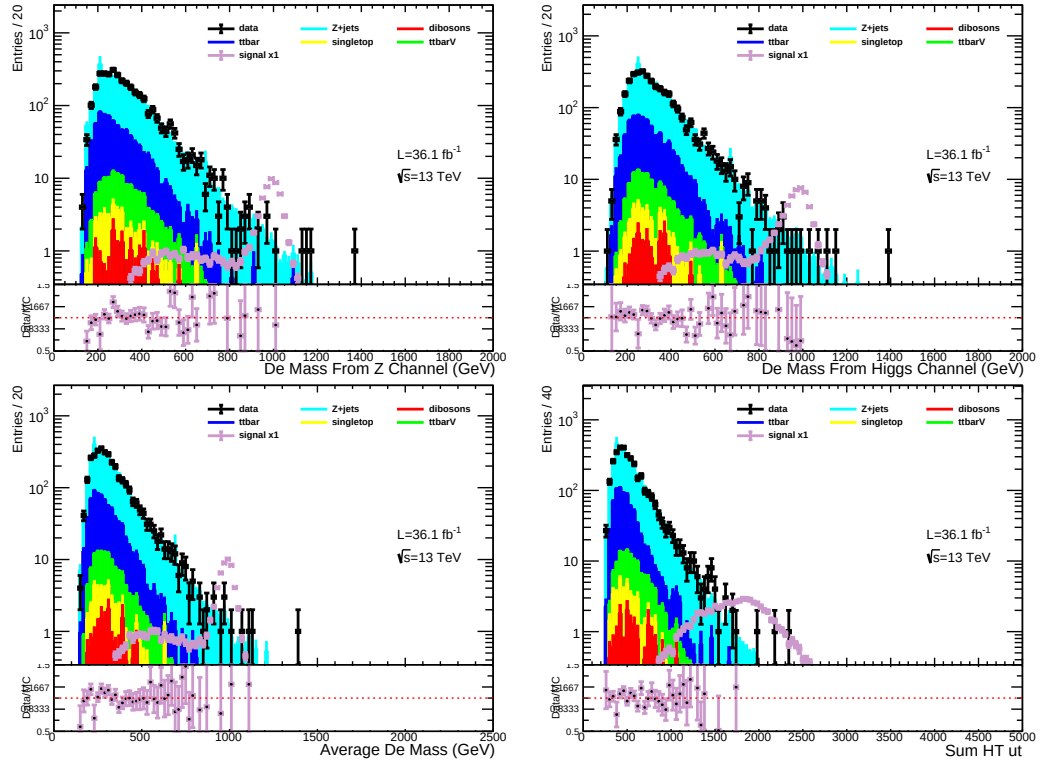


Figure 5.2: D quark mass reconstructed from a Z boson (*top-left*), D quark mass reconstructed from a H boson (*top-right*), average reconstructed D quark mass (*bottom-left*) and Sum H_T distributions (*bottom-right*) when one b-tagged jet is requested in Higgs-daughter jets in the $\mu\mu$ channel in the signal region (after cut #11 in Table 4.2). Data is unblinded.

shown in Table 5.3. The exclusion plots obtained with the real data for ee and $\mu\mu$

Table 5.3: The observed limits for the ee , $\mu\mu$ and combined channels.

b-tag case / Discriminant	ee channel (GeV)	$\mu\mu$ channel (GeV)	combined channel (GeV)
1-btag / Average D Mass	$1341.2^{+12}_{-14.5}$	$1359.1^{+10.4}_{-12.6}$	$1526.2^{+12.3}_{-14.6}$

channels separately and combined as shown in Figures 5.3, and 5.4.

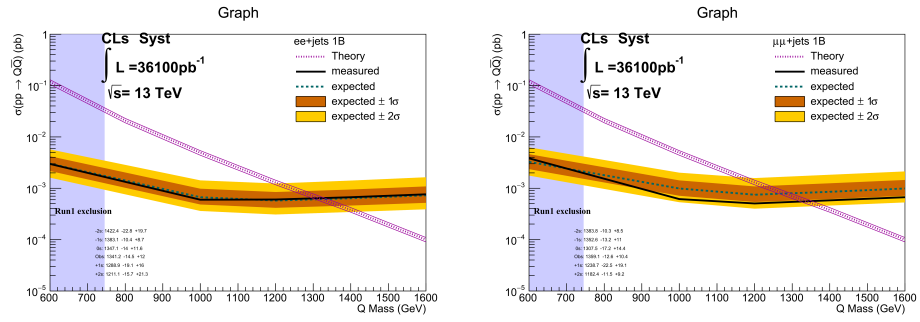


Figure 5.3: The expected limit with 95% CL for the ee channel (left) and $\mu\mu$ channel (right) with b-tagging requirement when Average D mass is used as the discriminant.

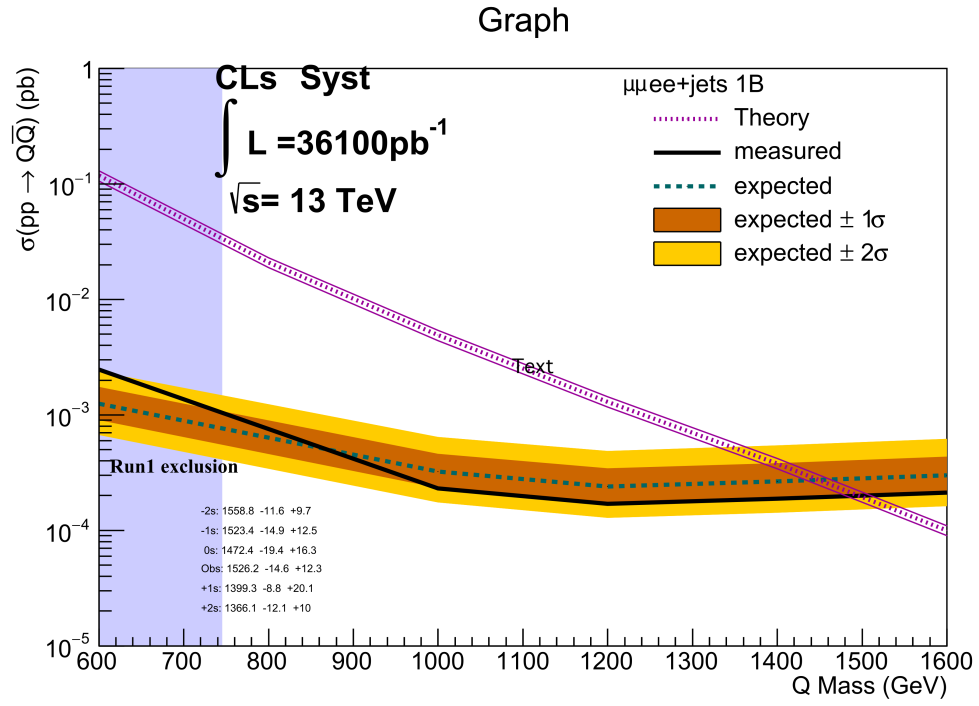


Figure 5.4: The expected limit with 95% CL for the ee channel and $\mu\mu$ channel combined with b-tagging requirement when Average D mass is used as the discriminant.

6. CONCLUSION

In this study, a search for pair produced E_6 iso-singlet quarks in pp collision data corresponding to an integrated luminosity of 36.1 fb^{-1} has been described. The iso-singlet quark analysed belongs to the first (up-down) family and is expected to be the lightest of the E_6 iso-singlet quarks. However no family specific requirements have been applied to the prompt jets, keeping the analysis sensitive to iso-singlet quarks of all the families.

A specific decay channel of the E_6 iso-singlet quark has been analyzed. The analysis examines the events where the quark pair decays via $pp \rightarrow DD \rightarrow H j Z j \rightarrow 4 j 2 \ell$ channel. The events that are reconstructed are expected to have four jets (at least one should be b -tagged) and a Z boson candidate that has been reconstructed from two charged leptons. A χ^2 algorithm is used in the reconstruction of the events. Under these prescriptions, no excess events have been observed beyond the Standard Model expectations. According to the iso-singlet quark decay branching ratios foreseen by the E_6 GUT theory, the expected limit based on MC studies is about $1526.2_{-14.6}^{+12.3} \text{ GeV}$, combining electron and muon decays of the Z boson.

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APPENDIX A: APPLICATION

A.1. Data, Signal and Background Monte Carlo Samples

A.1.1. Data Samples

We start with the ntuples generated for the VLQ OSML analysis, located at `/eos/atlas/atlascerngroupdisk/physics-exotics/hqt/OSML/data`.

Run numbers for data 15: 276262, 276329, 276336, 276416, 276511, 276689, 276778, 276790, 276952, 276954, 278880, 278912, 278968, 279169, 279259, 279279, 279284, 279345, 279515, 279598, 279685, 279813, 279867, 279928, 279932, 279984, 280231, 280273, 280319, 280368, 280423, 280464, 280500, 280520, 280614, 280673, 280753, 280853, 280862, 280950, 280977, 281070, 281074, 281075, 281317, 281385, 281411, 282625, 282631, 282712, 282784, 282992, 283074, 283155, 283270, 283429, 283608, 283780, 284006, 284154, 284213, 284285, 284420, 284427, 284484.

Run numbers for data 16: 297730, 298595, 298609, 298633, 298687, 298690, 298771, 298773, 298862, 298967, 299055, 299144, 299147, 299184, 299243, 299584, 300279, 300345, 300415, 300418, 300487, 300540, 300571, 300600, 300655, 300687, 300784, 300800, 300863, 300908, 301912, 301918, 301932, 301973, 302053, 302137, 302265, 302269, 302300, 302347, 302380, 302391, 302393, 302737, 302831, 302872, 302919, 302925, 302956, 303007, 303079, 303201, 303208, 303264, 303266, 303291, 303304, 303338, 311473, 303421, 303499, 303560, 303638, 303832, 303846, 303892, 303943, 304006, 304008, 304128, 304178, 304198, 304211, 304243, 304308, 304337, 304409, 304431, 304494, 305380, 305543, 305571, 305618, 305671, 305674, 305723, 305727, 305735, 305777, 305811, 305920, 306269, 306278, 306310, 306384, 306419, 306442, 306448, 306451, 307126, 307195, 307259, 307306, 307354, 307358, 307394, 307454, 307514, 307539, 307569, 307601, 307619, 307656, 307710, 307716, 307732,

307861, 307935, 308047, 308084, 309375, 309390, 309440, 309516, 309640, 309674, 309759, 310015, 310247, 310249, 310341, 310370, 310405, 310468, 310473, 310634, 310691, 310738, 310809, 310863, 310872, 310969, 311071, 311170, 311244, 311287, 311321, 311365, 311402, 311481.

A.1.2. Signal Monte Carlo

83k events, $m_D=1000$ GeV, full sim.:

```
mc15_13TeV.307510.CompHepPythia8EvtGen_A14_NNPDF23L0_HbbarZl1jj.
merge.DAOD_EX0T4.e5726_s2726_r7772_r7676_p2949
```

46544 events, $m_D=600$ GeV, fast sim.:

```
mc15_13TeV.308961.CompHepPythia8EvtGen_A14NNPDF23L0_HbbarZl1jj.
merge.DAOD_EX0T4.e6137_a766_a821_r7676_p2949
```

97277 events, $m_D=1200$ GeV, fast sim.:

```
mc15_13TeV.308963.CompHepPythia8EvtGen_A14NNPDF23L0_HbbarZl1jj.
merge.DAOD_EX0T4.e6253_a766_a821_r7676_p2949
```

49658 events, $m_D=1400$ GeV, fast sim.:

```
mc15_13TeV.308964.CompHepPythia8EvtGen_A14NNPDF23L0_HbbarZl1jj.
merge.DAOD_EX0T4.e6137_a766_a821_r7676_p2949
```

98242 events, $M_D=1600$ GeV, fast sim.:

```
mc15_13TeV.309073.CompHepPythia8EvtGen_A14NNPDF23L0_HbbarZl1jj.
merge.DAOD_EX0T4.e6253_a766_a821_r7676_p2949
```

A.1.3. Background Monte Carlo

We start with the ntuples generated for the VLQ OSML analysis, located at `/eos/atlas/atlascerngroupdisk/physics-exotics/hqt/OSML/`.

Z +jets, SHERPA 2.2.1: 364100, 364101, 364102, 364103, 364104, 364105, 364106, 364107, 364107, 364108, 364109, 364110, 364111, 364112, 364113, 364114, 364115, 364116, 364117, 364118, 364119, 364120, 364120, 364121, 364122, 364123, 364124, 364125, 364126, 364127, 364128, 364129, 364130, 364131, 364132, 364133, 364134, 364135, 364136, 364137, 364138, 364139, 364140, 364141

Dibosons: 364283, 364284, 364285, 364286, 364287

$t\bar{t}$: 410501

Single Top: 410011, 410012, 410025, 410026, 410050, 410064, 410065

$t\bar{t} + V$: 410080, 410081, 410155, 410156, 410157, 410218, 410219, 410220

A.2. Results from TRExFitter



Figure A.1: Summary of the nuisance parameters pruned in the fit, those with a variation below 1% are pruned either for shape, normalization or both. Plots are shown for the 1 TeV signal reconstructed in the electron (left) and muon (right) channels.

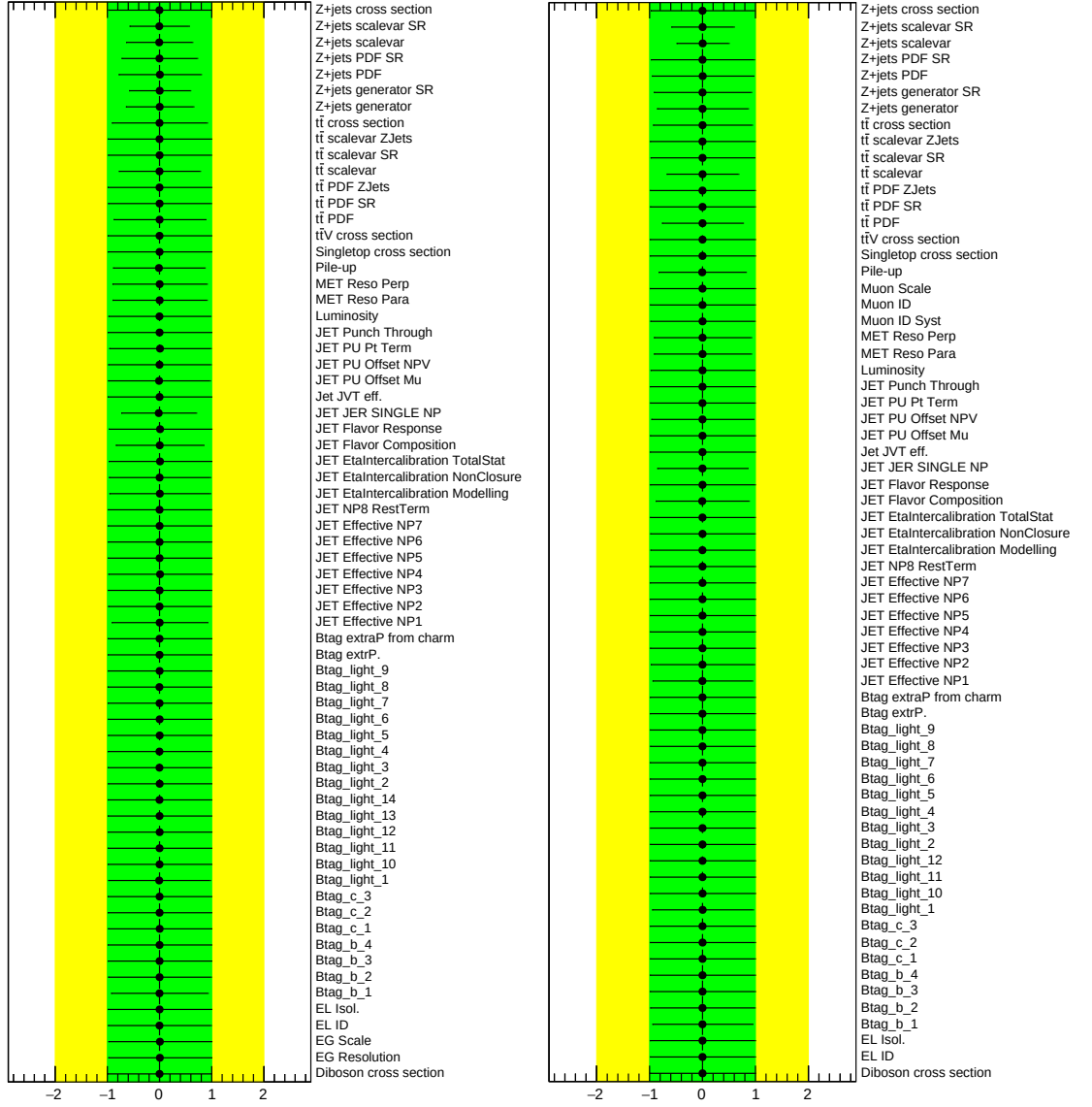


Figure A.2: Pull plot for the nuisance parameters for the fit to the Asimov data for the 1 TeV signal, for the electron (left) and muon (right) channels.

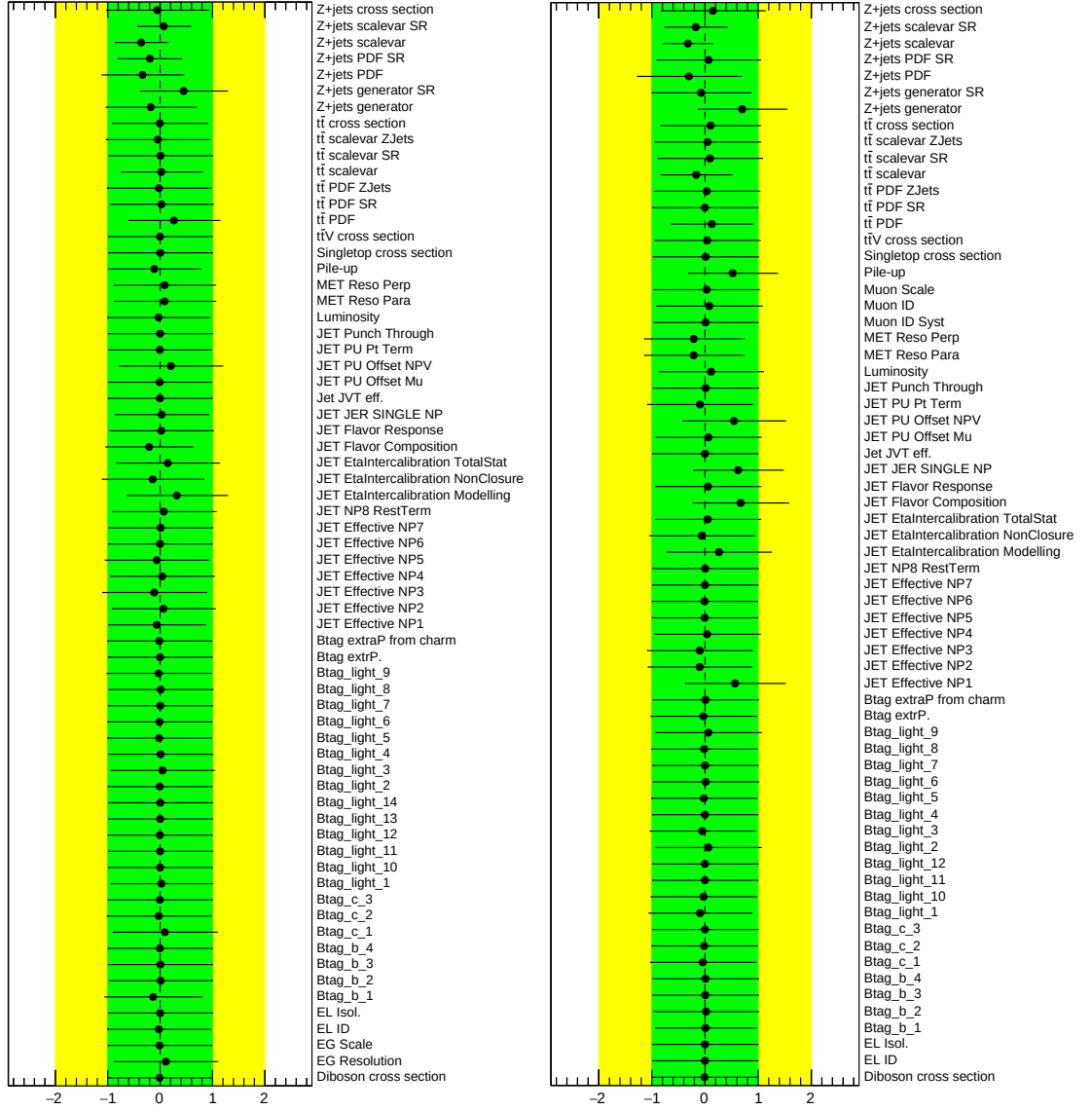


Figure A.3: Pull plot for the nuisance parameters for the fit to the real data for the 1 TeV signal, for the electron (left) and muon (right) channels.

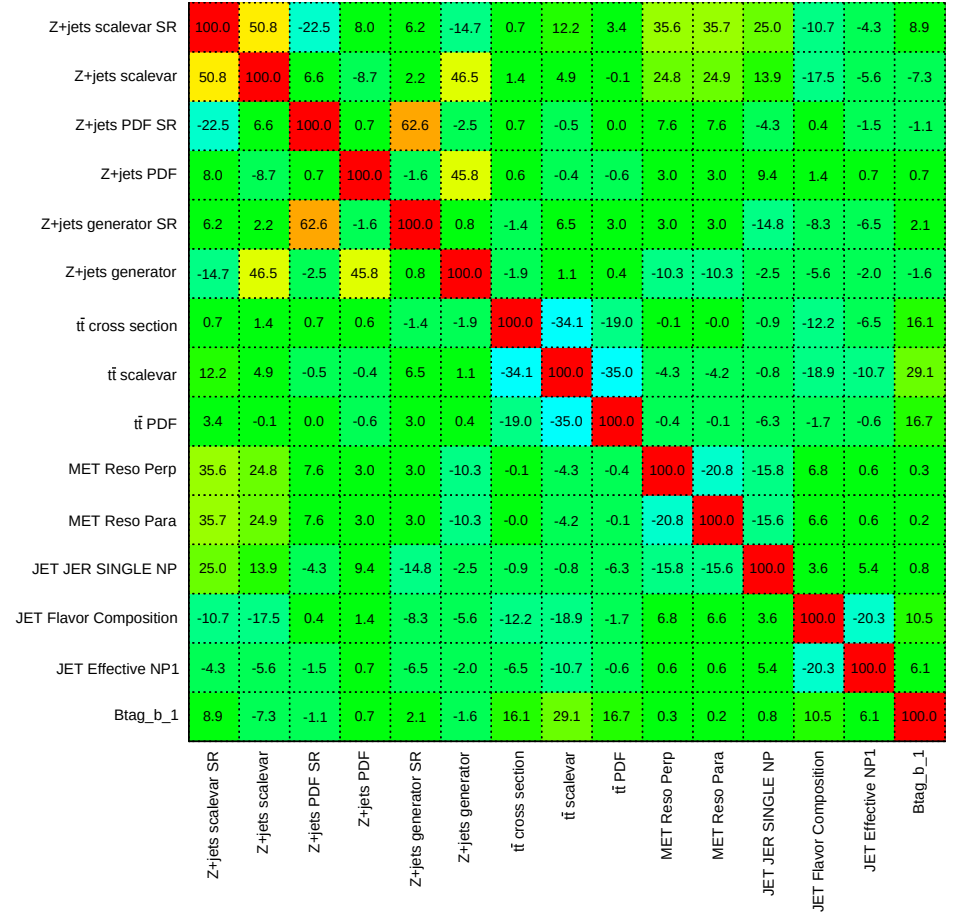


Figure A.4: Correlation matrix of the nuisance parameters in the electron channel for 1 TeV signal.

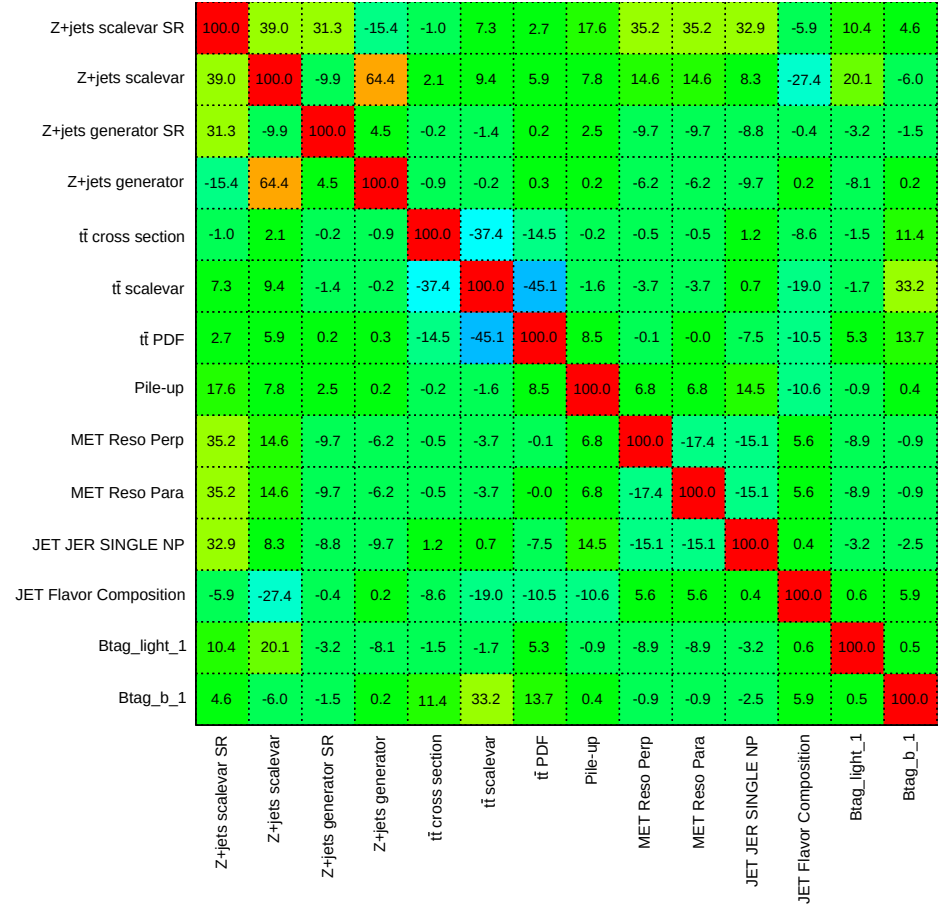


Figure A.5: Correlation matrix of the nuisance parameters in the muon channel for 1 TeV signal.

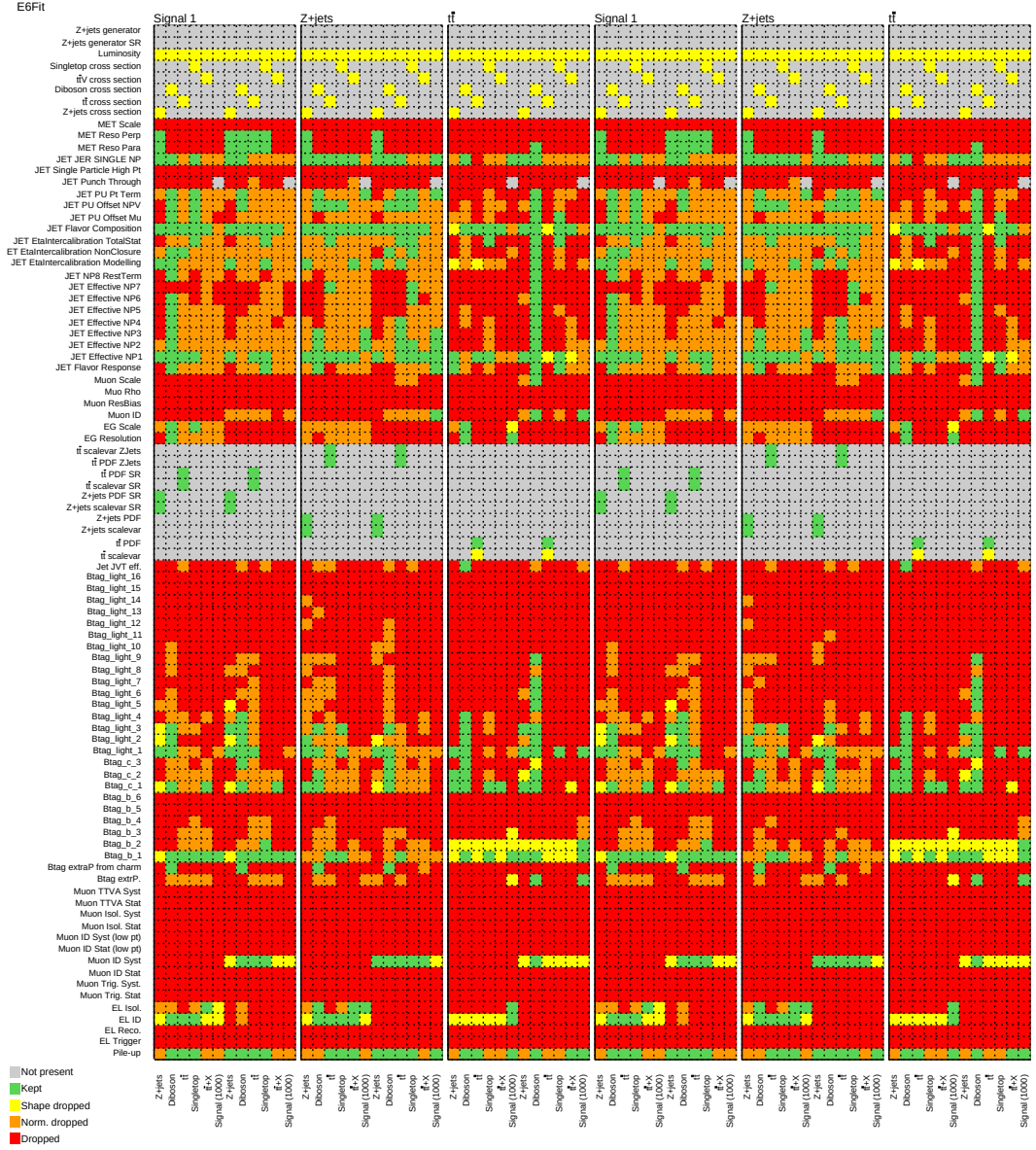


Figure A.6: Summary of the nuisance parameters pruned in the fit, those with a variation below 1% are pruned either for shape, normalization or both in the combined channel for the 1 TeV signal.

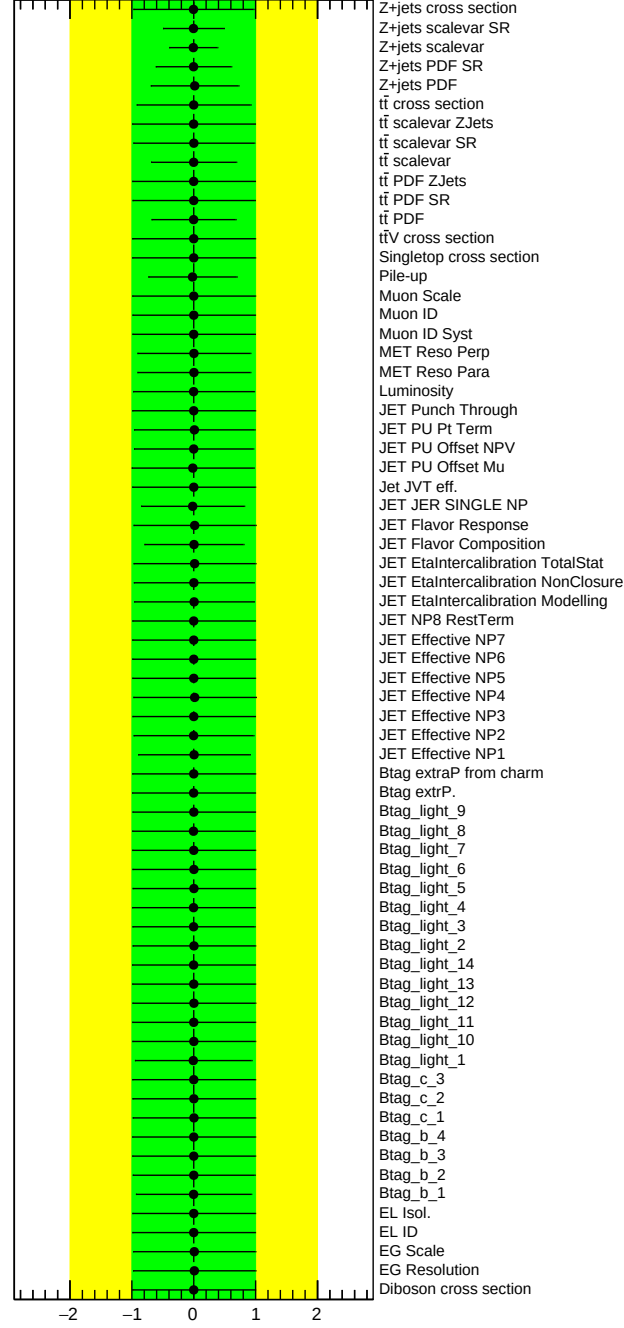


Figure A.7: Pull plot for the nuisance parameters in the electron and muon combined fit to the Asimov data for 1 TeV signal.

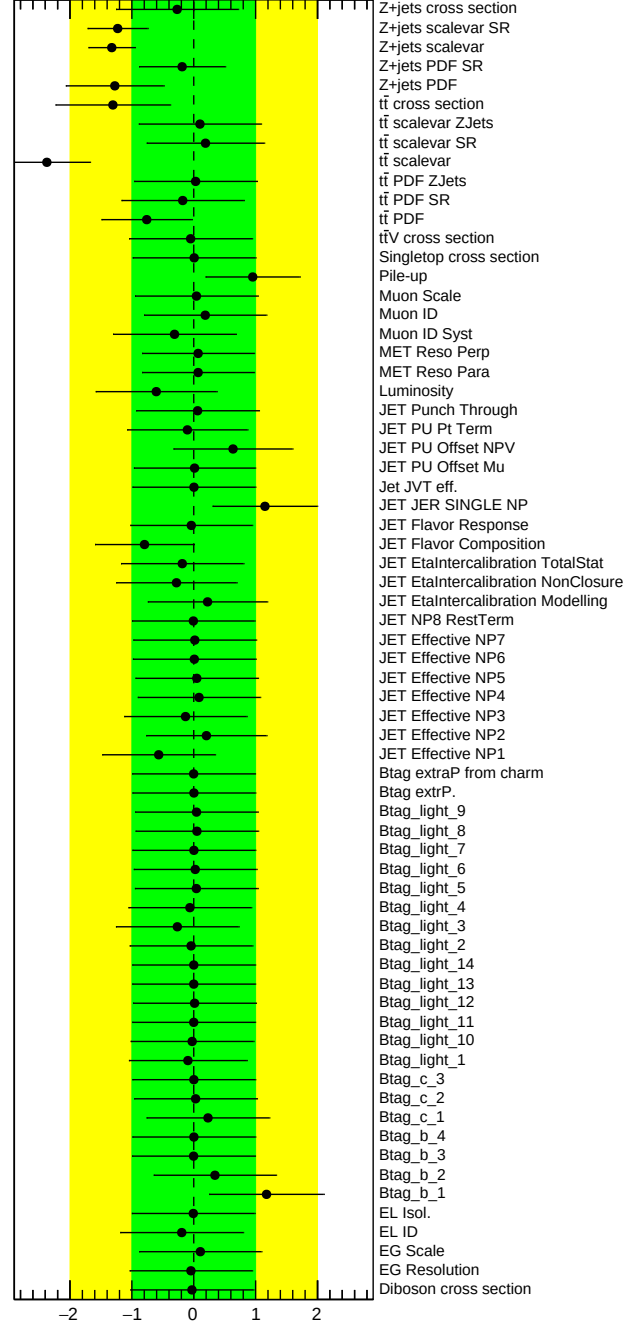


Figure A.8: Pull plot for the nuisance parameters in the electron and muon combined fit to the real data for 1 TeV signal.

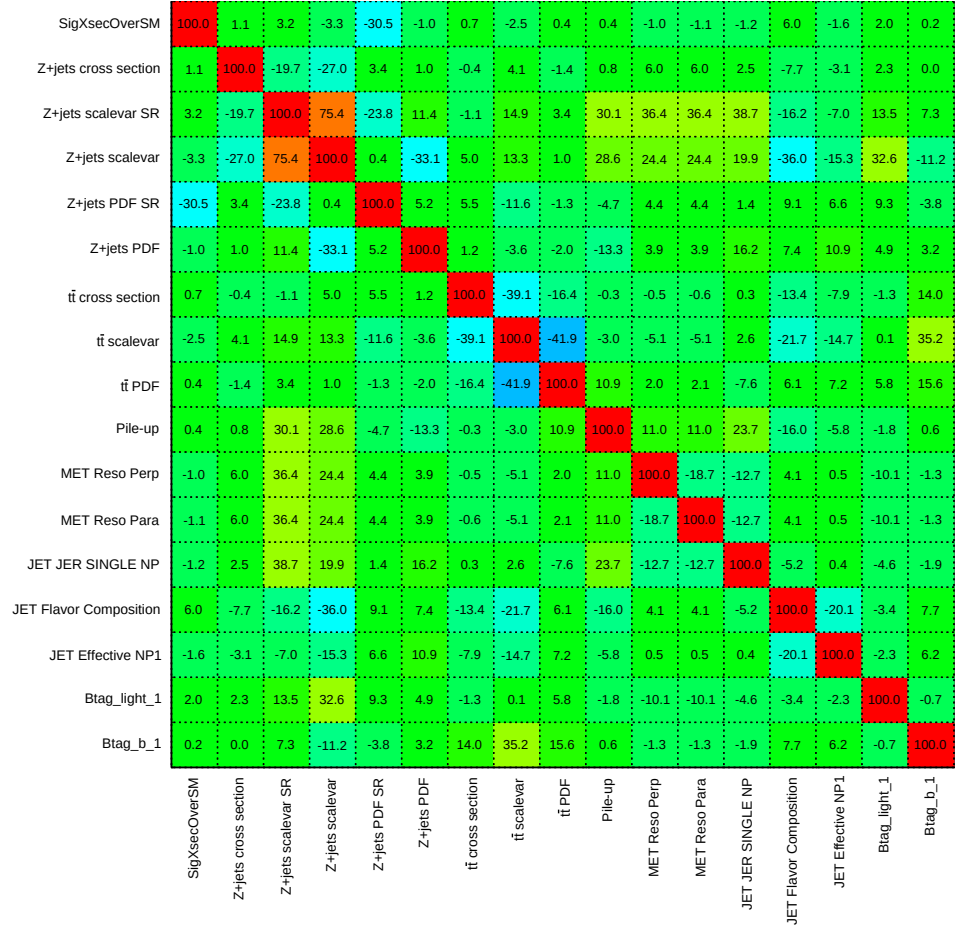


Figure A.9: Correlation matrix of the nuisance parameters in the combined fit to the Asimov data from electron and muon channels with 1 TeV signal.

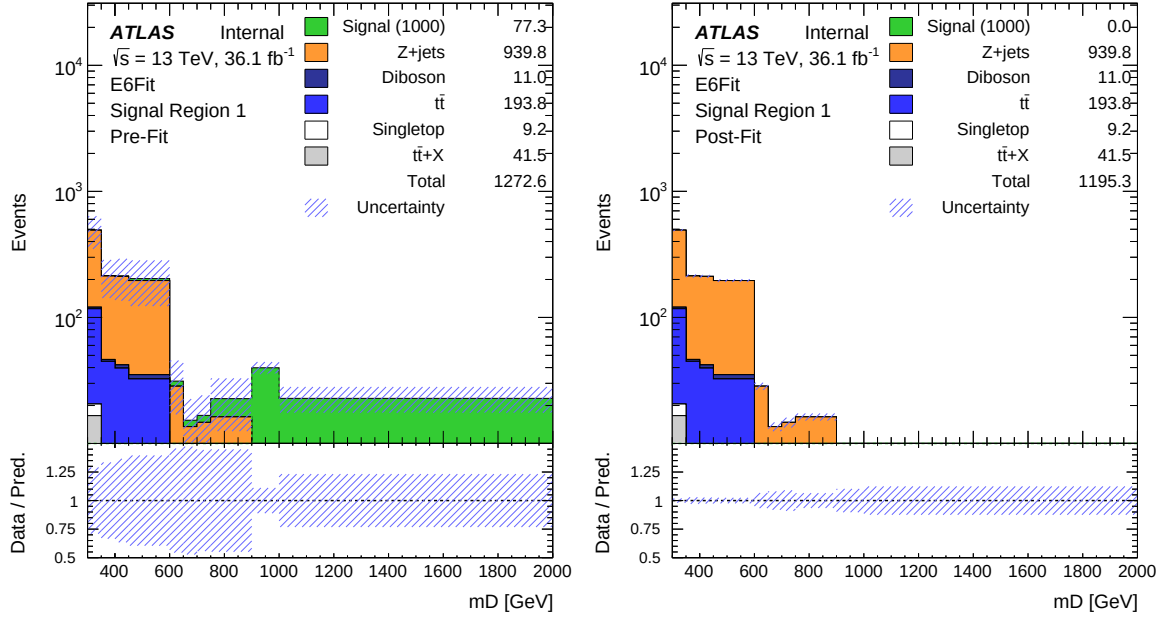


Figure A.10: The pre-fit (left) and post-fit (right) distribution of the final discriminant in the electron channel for the 1 TeV signal, in the signal region. The uncertainty bands include statistical and systematic uncertainties.

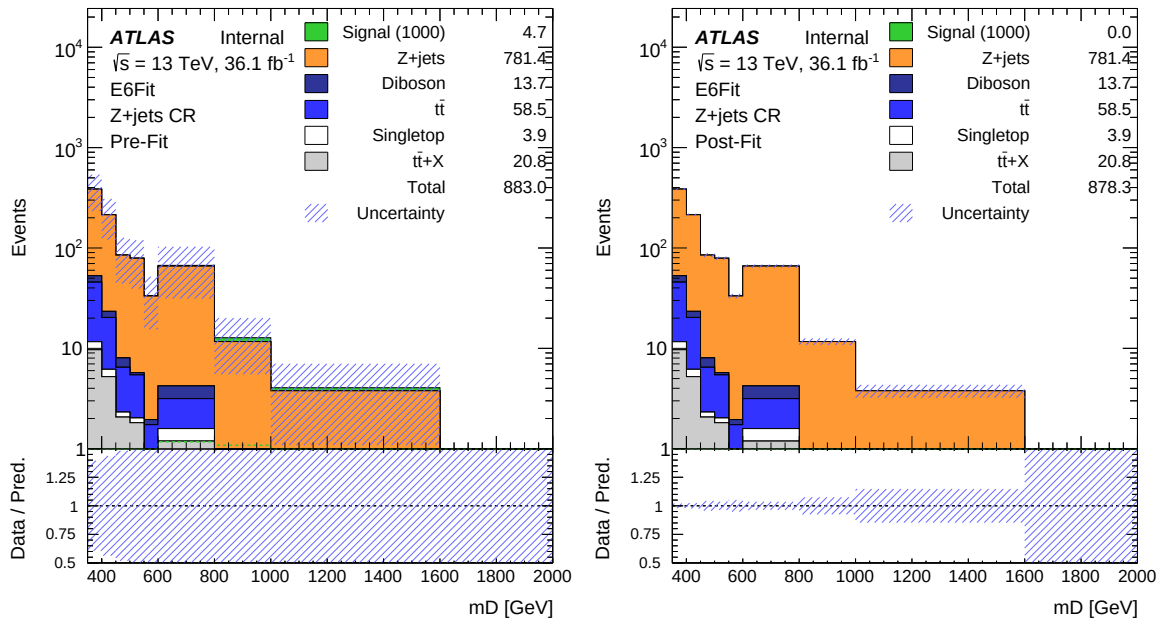


Figure A.11: The pre-fit (left) and post-fit (right) distribution of the final discriminant in the electron channel for the 1 TeV signal, in the Z+jets control region. The uncertainty bands include statistical and systematic uncertainties.

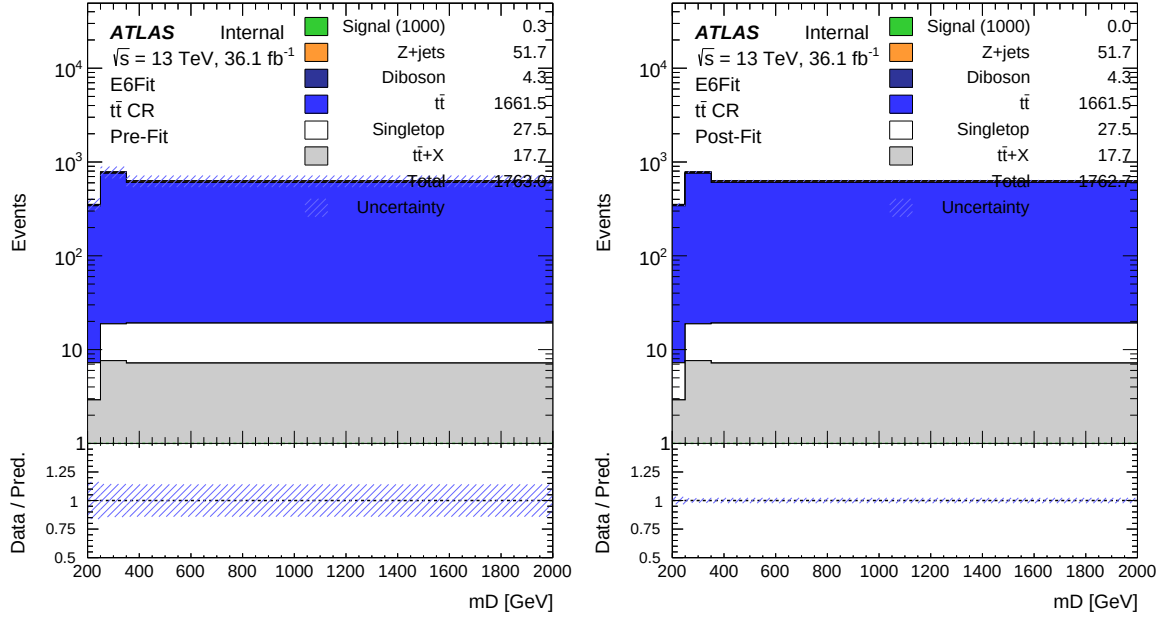


Figure A.12: The pre-fit (left) and post-fit (right) distribution of the final discriminant in the electron channel for the 1 TeV signal, in the $t\bar{t}$ control region. The uncertainty bands include statistical and systematic uncertainties.

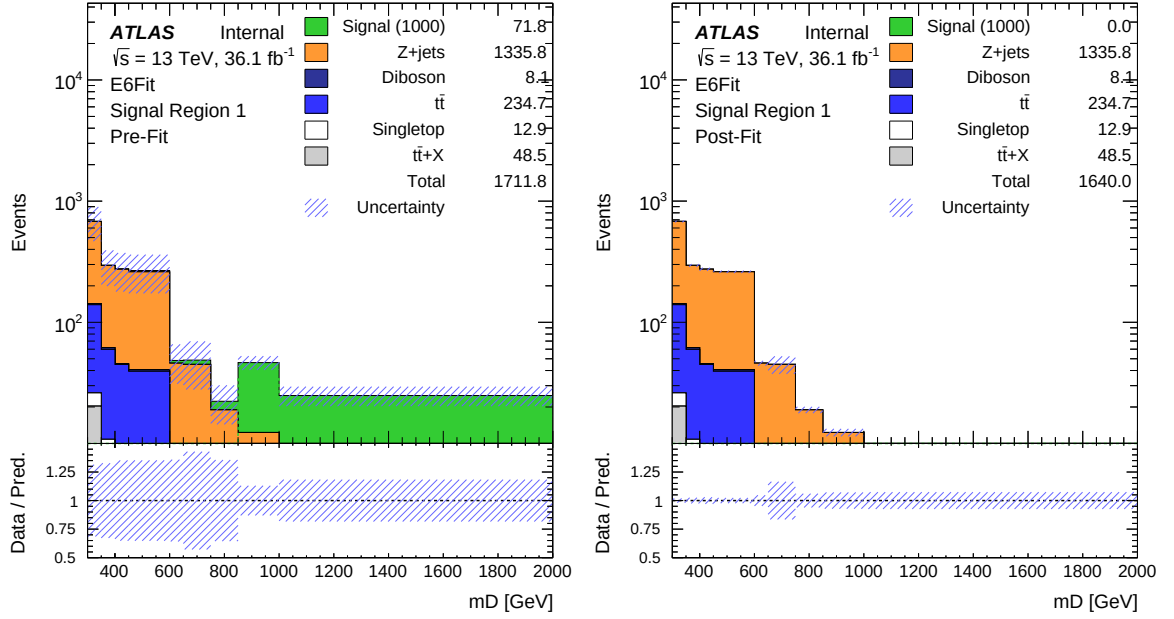


Figure A.13: The pre-fit (left) and post-fit (right) distribution of the final discriminant in the muon channel for the 1 TeV signal, in the signal region. The uncertainty bands include statistical and systematic uncertainties.

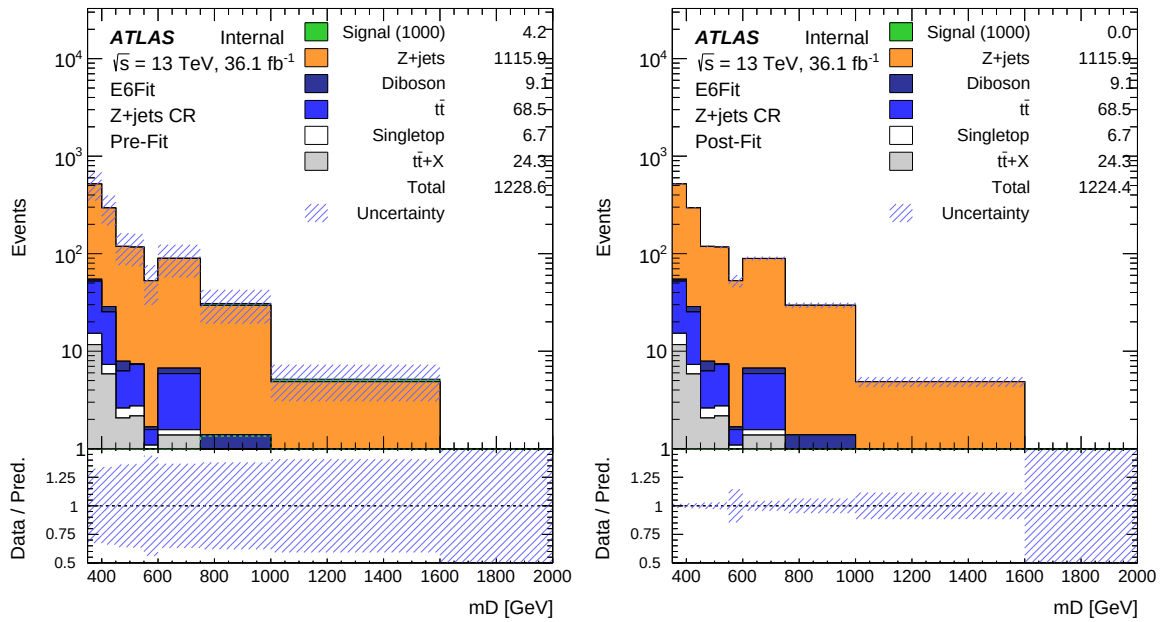


Figure A.14: The pre-fit (left) and post-fit (right) distribution of the final discriminant in the muon channel for the 1 TeV signal, in the Z+jets control region. The uncertainty bands include statistical and systematic uncertainties.

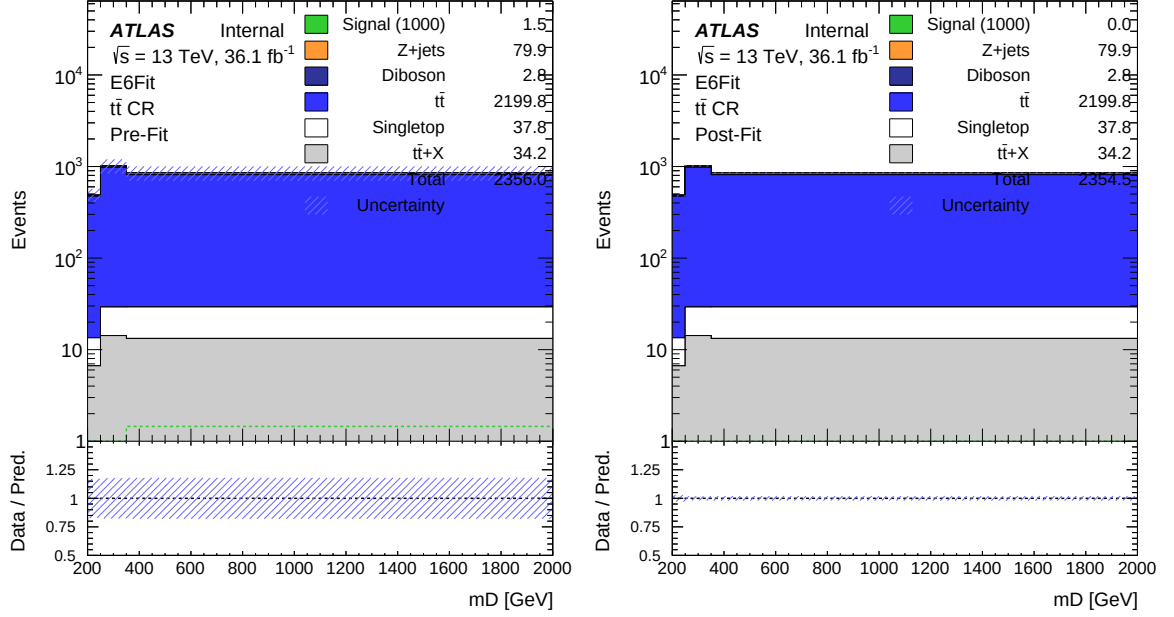


Figure A.15: The pre-fit (left) and post-fit (right) distribution of the final discriminant in the electron channel for the 1 TeV signal, in the $t\bar{t}$ control region. The uncertainty bands include statistical and systematic uncertainties.

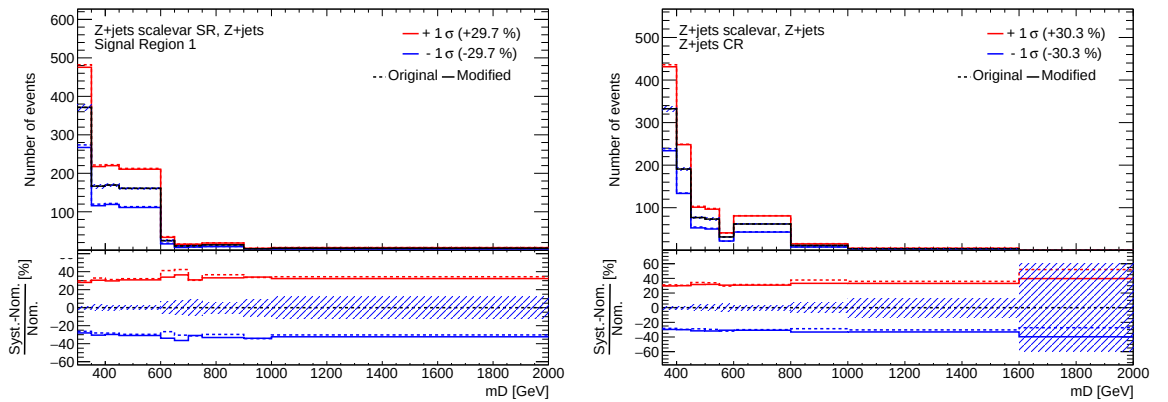


Figure A.16: Plots of the final discriminant showing the effects of the Z +jets scale variation systematic for the 1 TeV signal in the electron channel; signal region (left) and Z +jets CR (right).

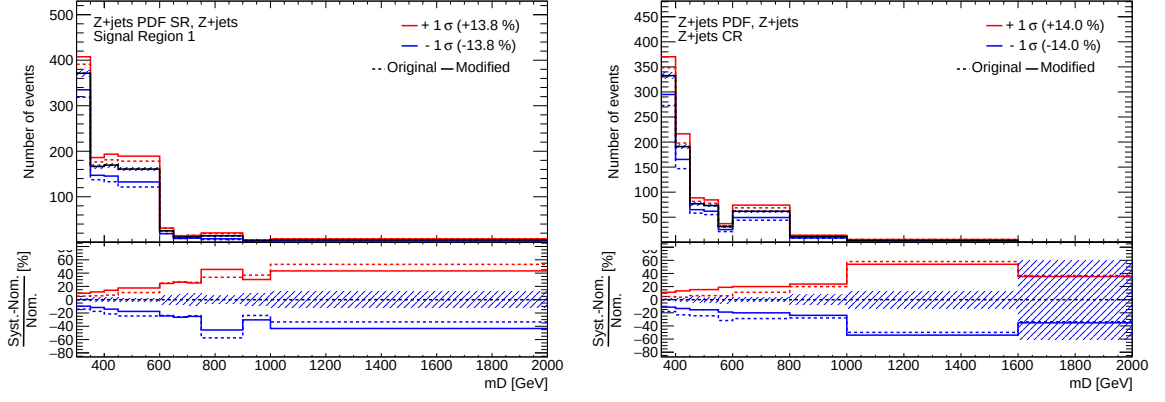


Figure A.17: Plots of the final discriminant showing the effects of the Z +jets PDF systematic for the 1 TeV signal in the electron channel; signal region (left) and Z +jets CR (right).

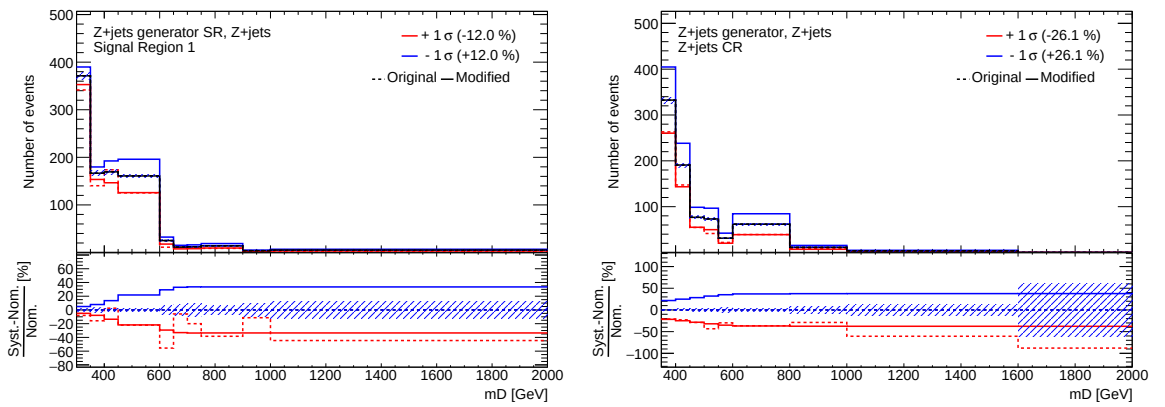


Figure A.18: Plots of the final discriminant showing the effects of the Z +jets generator systematic for the 1 TeV signal in the electron channel; signal region (left) and Z +jets CR (right).

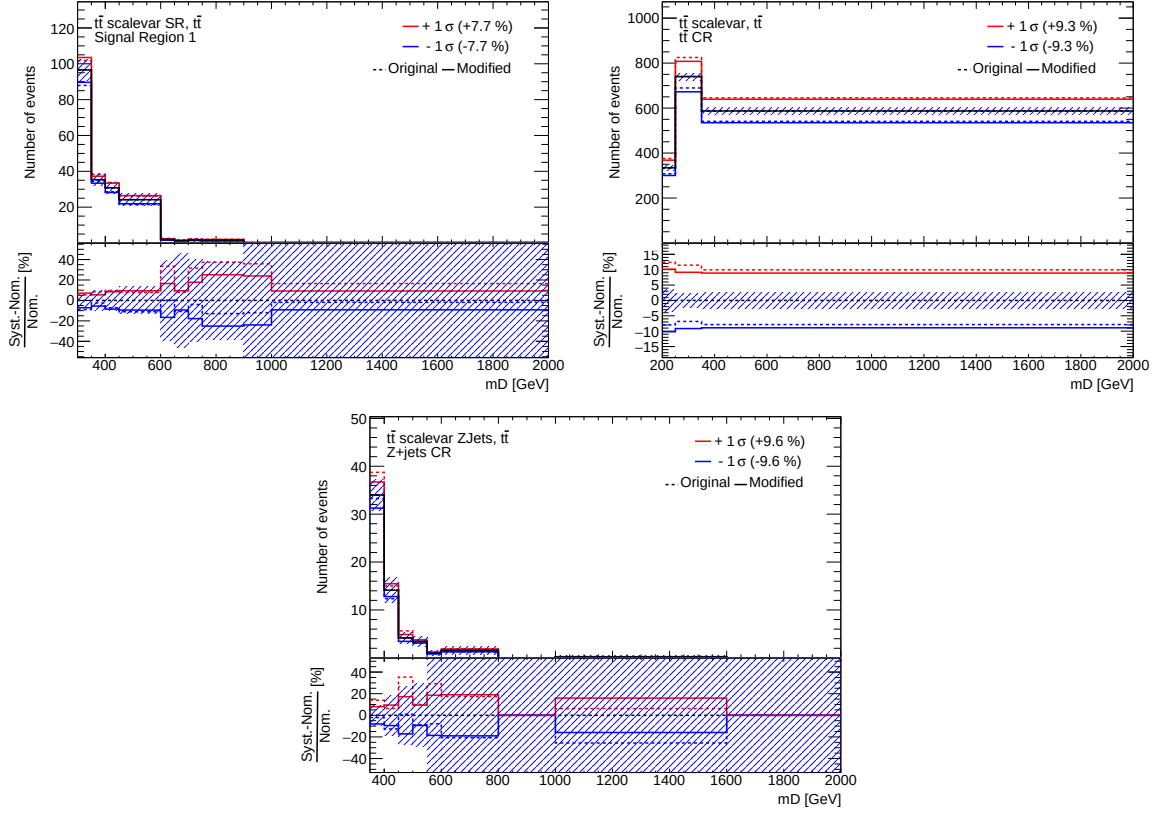


Figure A.19: Systematics shape plots in the electron channel for the $t\bar{t}$ scale variation systematic uncertainty for 1 TeV signal region (top-left), $t\bar{t}$ CR (top-right) and Z +jets CR (bottom).

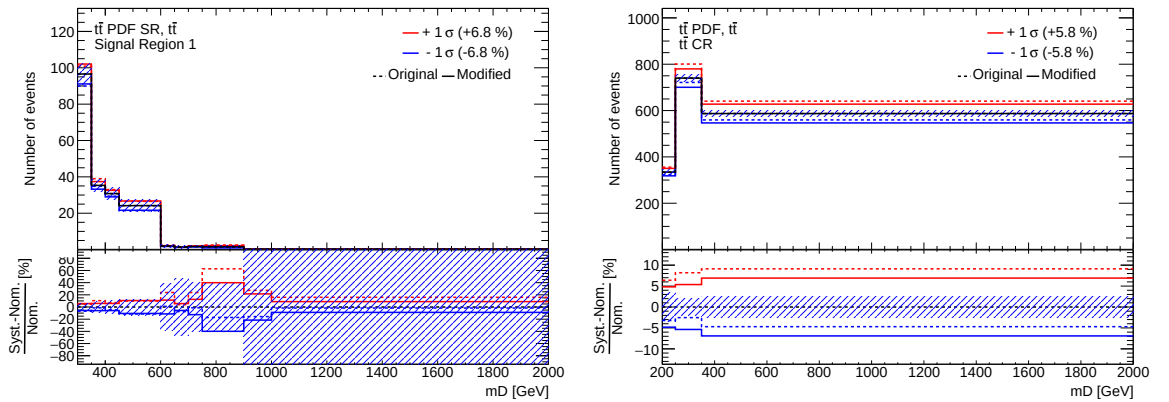


Figure A.20: Systematics shape plots in the electron channel for the $t\bar{t}$ PDF systematic uncertainty for 1 TeV signal region (left) and $t\bar{t}$ CR (right).

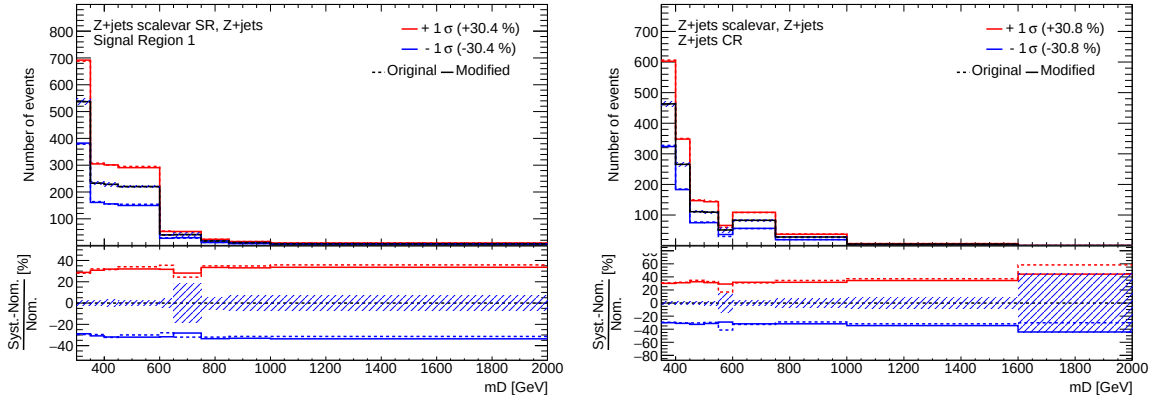


Figure A.21: Systematics shape plots in the muon channel for the Z +jets scale variation systematic uncertainty for 1 TeV signal region (left) and Z +jets CR (right).

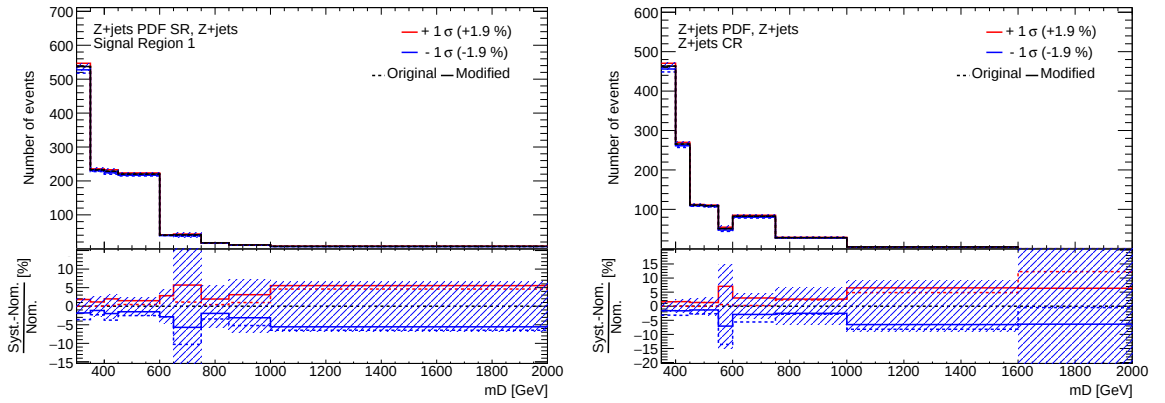


Figure A.22: Systematics shape plots in the muon channel for the Z +jets PDF systematic uncertainty for 1 TeV signal region (left) and Z +jets CR (right).

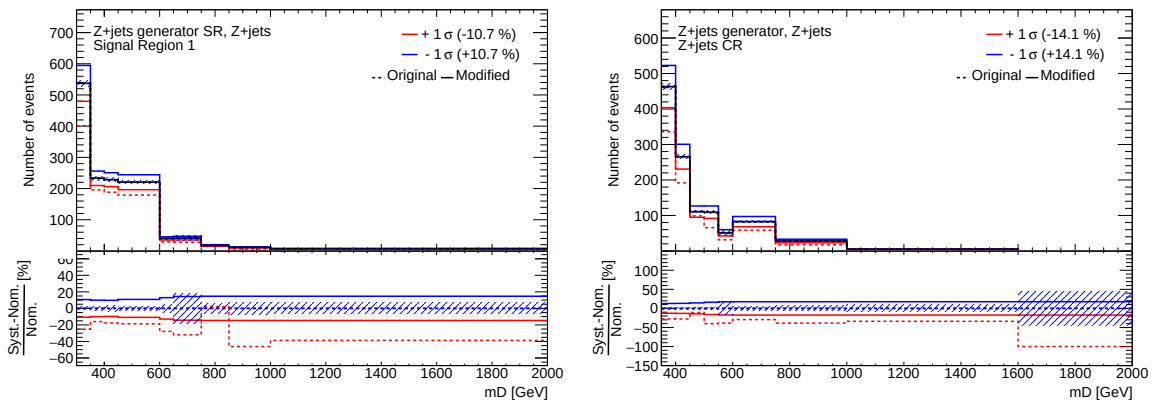


Figure A.23: Systematics shape plots in the muon channel for the Z +jets generator systematic uncertainty for 1 TeV signal region (left) and Z +jets CR (right).

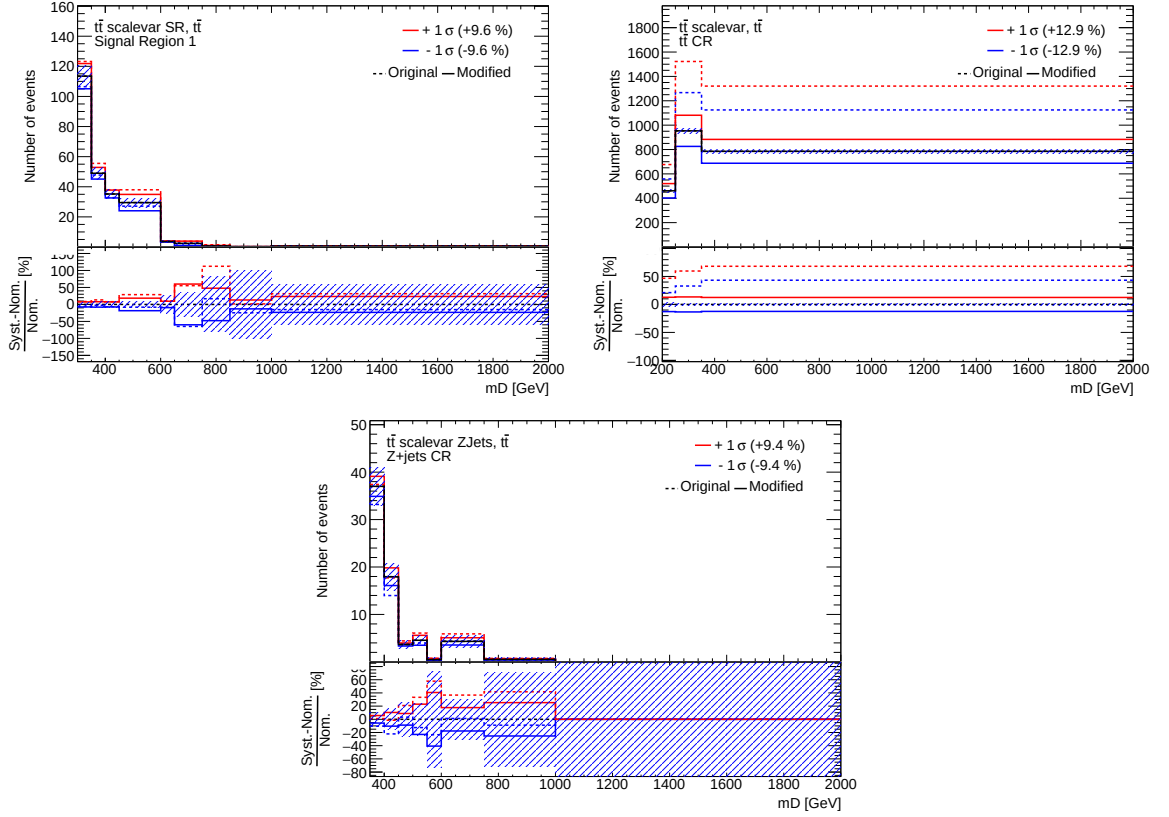


Figure A.24: Systematics shape plots in the muon channel for the $t\bar{t}$ scale variation systematic uncertainty for 1 TeV signal region (top-left), $t\bar{t}$ CR (top-right) and Z+jets CR (bottom).

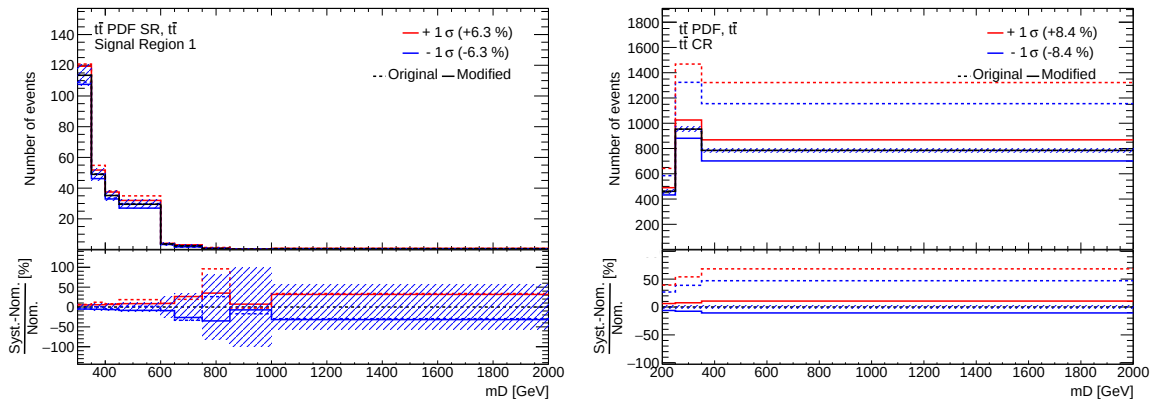


Figure A.25: Systematics shape plots in the muon channel for the $t\bar{t}$ PDF systematic uncertainty for 1 TeV signal region (left) and $t\bar{t}$ CR (right).

A.3. Injection Tests with TLimit

The so called “injection” tests were performed to investigate the discovery capabilities of the analysis algorithm. In this tests, the objective was to work with the pseudo-data obtained by summing the total SM background with a signal MC sample generated at a specific VLQ mass. After running the full analysis on all the MC samples, the final discriminant was investigated to determine whether it had any discovery potential. For these studies, the invariant mass of the BSM quark reconstructed using the Zj decay was selected for both the ee and $\mu\mu$ channels.

The Figure A.26 (A.27) contains such a study for electron (muon) channel in the un-tagged case. Here the injected signal (red histogram) was always at 1000 GeV whereas the MC signal mass (black histogram) was scanned between 600 and 1600 GeV. In all plots, the SM background histogram is shown in blue and the pseudo-data is shown in green.

The statistical analysis was performed with the simplest limit setter available in ROOT, namely the TLimit class, which is compatible with MCLIMIT when the systematic uncertainties are not considered. The results are shown in Figure A.28, where the “measured” limit line refers to a measurement with the pseudo-data. As one can see, in both electron and muon channels it is possible to distinguish a VLQ at the injected (1000 GeV) mass.

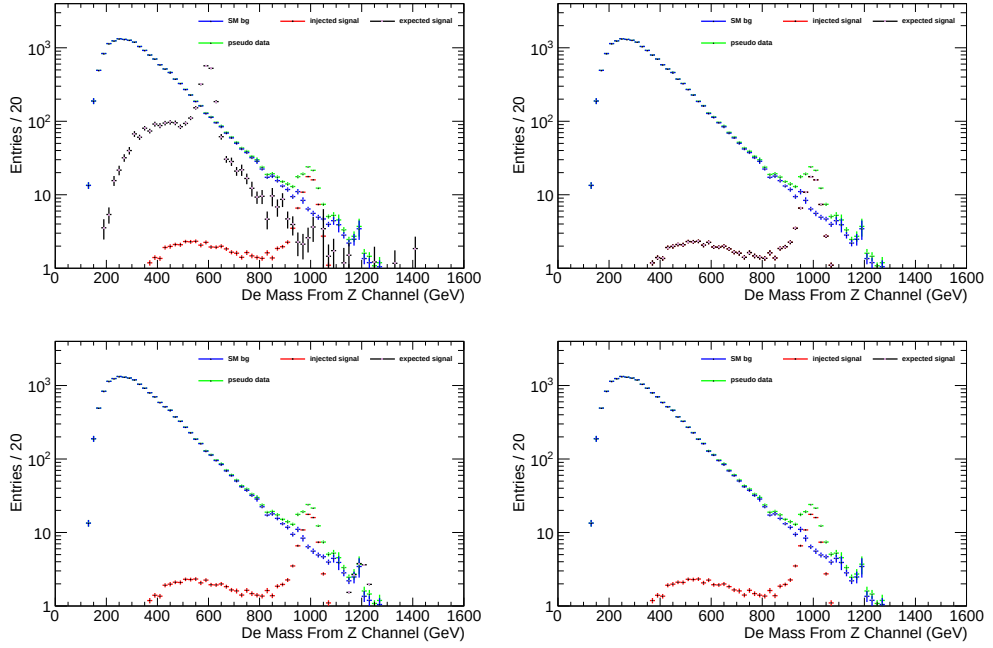


Figure A.26: $M_D = 600$ GeV (top left), $M_D = 1000$ GeV (top right), $M_D = 1200$ GeV (bottom left) and $M_D = 1400$ GeV (bottom right) injection for the ee channel. D mass from the Z channel used as discriminant.

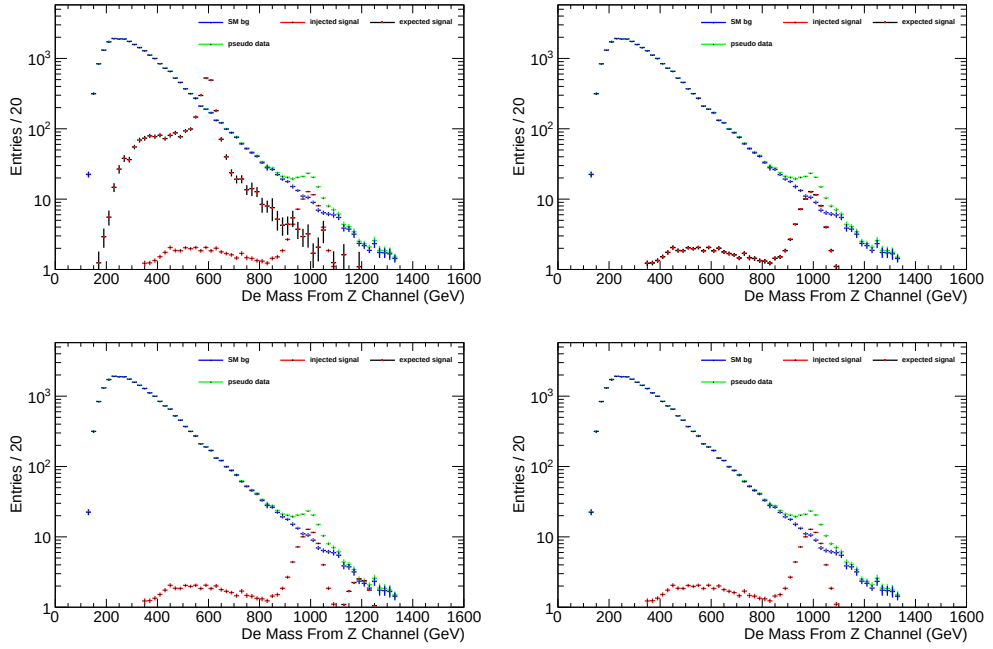


Figure A.27: $M_D = 600$ GeV (top left), $M_D = 1200$ GeV (top right), $M_D = 1400$ GeV (bottom left) and $M_D = 1600$ GeV (bottom right) injection for the $\mu\mu$ channel. D mass from Z channel used as discriminant.

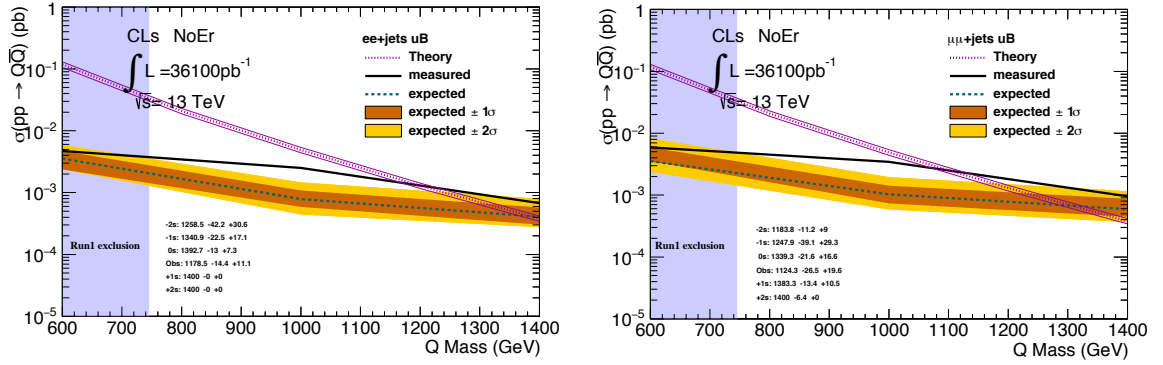


Figure A.28: Limit plots extracted with TLimit from pseudo-data composed of background and injected signal at 1000 GeV.

A.4. The Limit Studies with Various Discriminant Variables

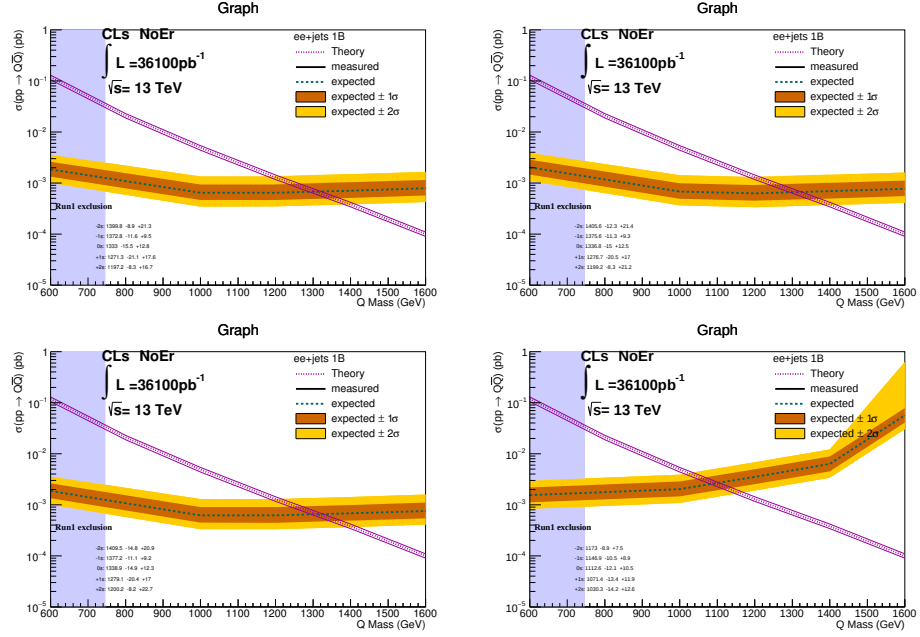


Figure A.29: The expected limit with 95% CL for the ee channel with b-tagging requirement when D mass from Z channel (top left), D mass from H channel (top right), Average D mass (bottom left) and Sum H_T (bottom right) are used as the discriminant. We apply leading jet $P_T > 100$ GeV and subleading jet $P_T > 65$ GeV.

A.5. Discriminant Histograms with Earlier Version of Cut Flow

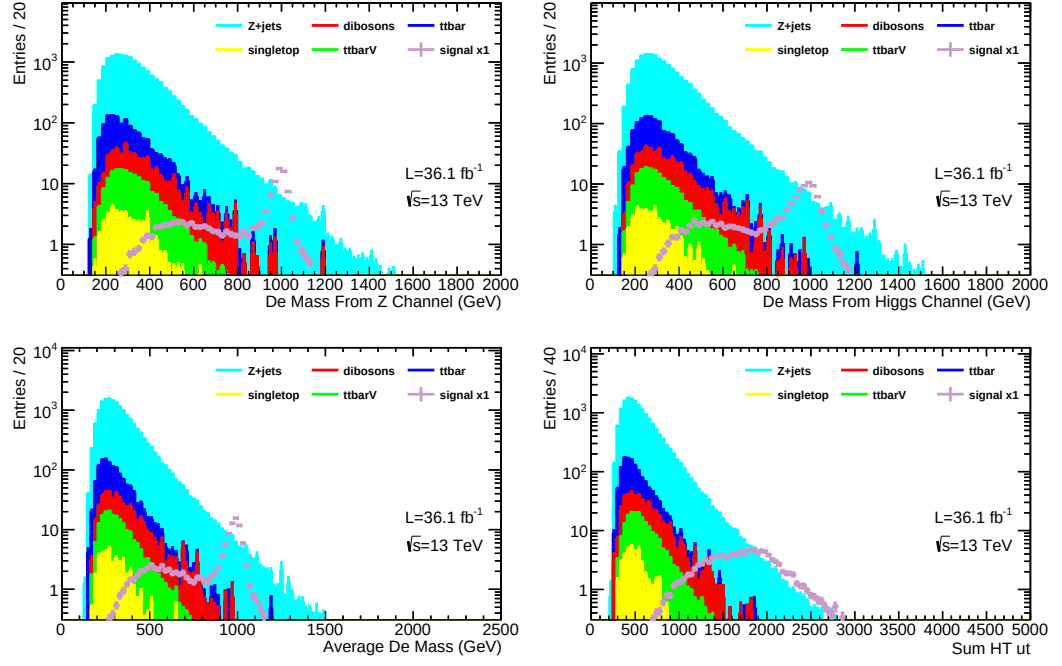


Figure A.30: D quark mass reconstructed from a Z boson, D quark mass reconstructed from a H boson, average reconstructed D quark mass and Sum H_T distributions in case of untagged for ee channel.

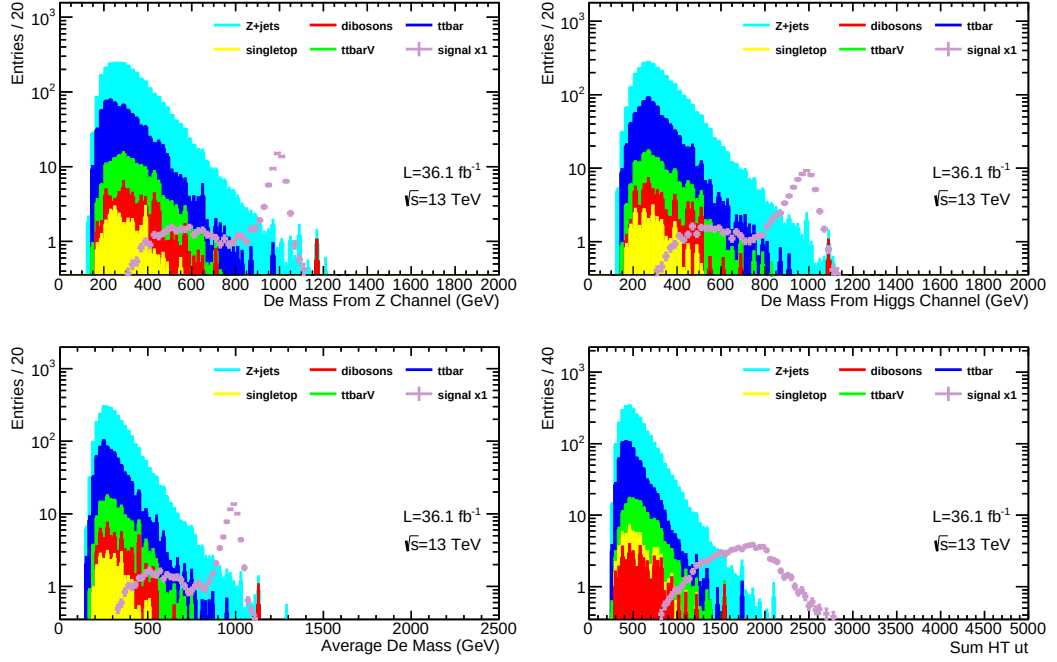


Figure A.31: D quark mass reconstructed from a Z boson, D quark mass reconstructed from a H boson, average reconstructed D quark mass and Sum H_T distributions in case of 1-btagged for ee channel.

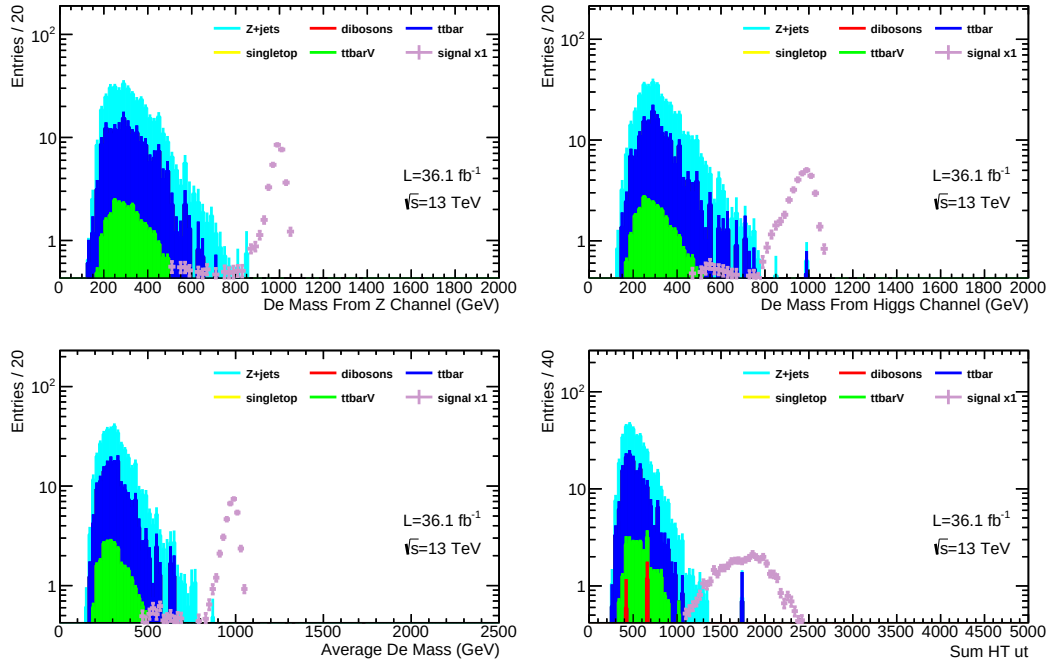


Figure A.32: D quark mass reconstructed from a Z boson, D quark mass reconstructed from a H boson, Average D emass and Sum H_T distributions in case of 2-btagged for ee channel.

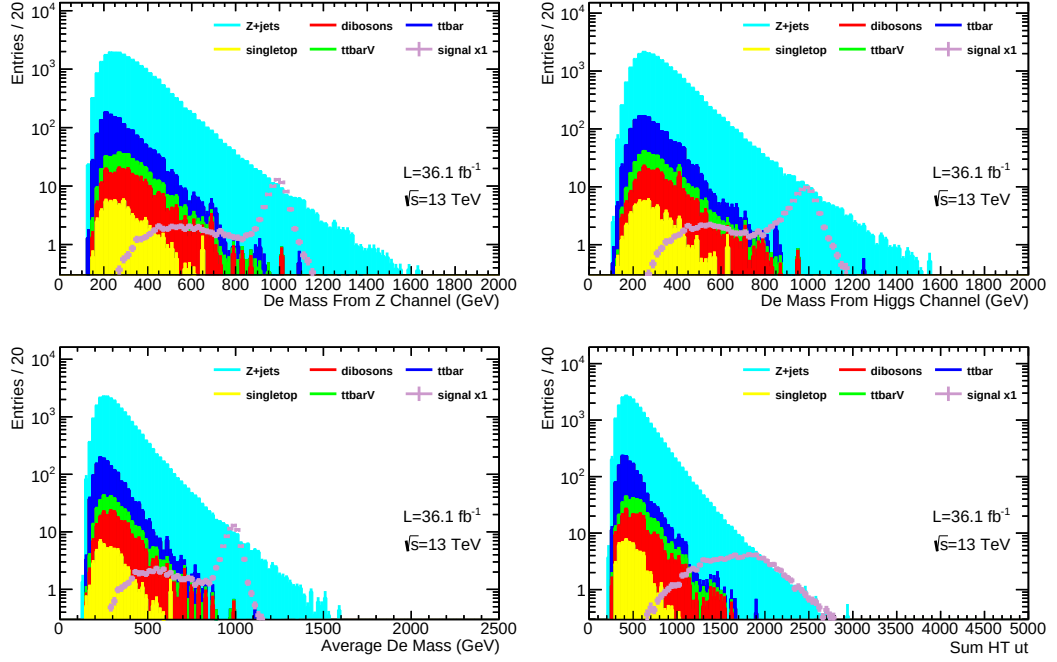


Figure A.33: D quark mass reconstructed from a Z boson, D quark mass reconstructed from a H boson, average reconstructed D quark mass and Sum H_T distributions in case of untagged for the $\mu\mu$ channel.

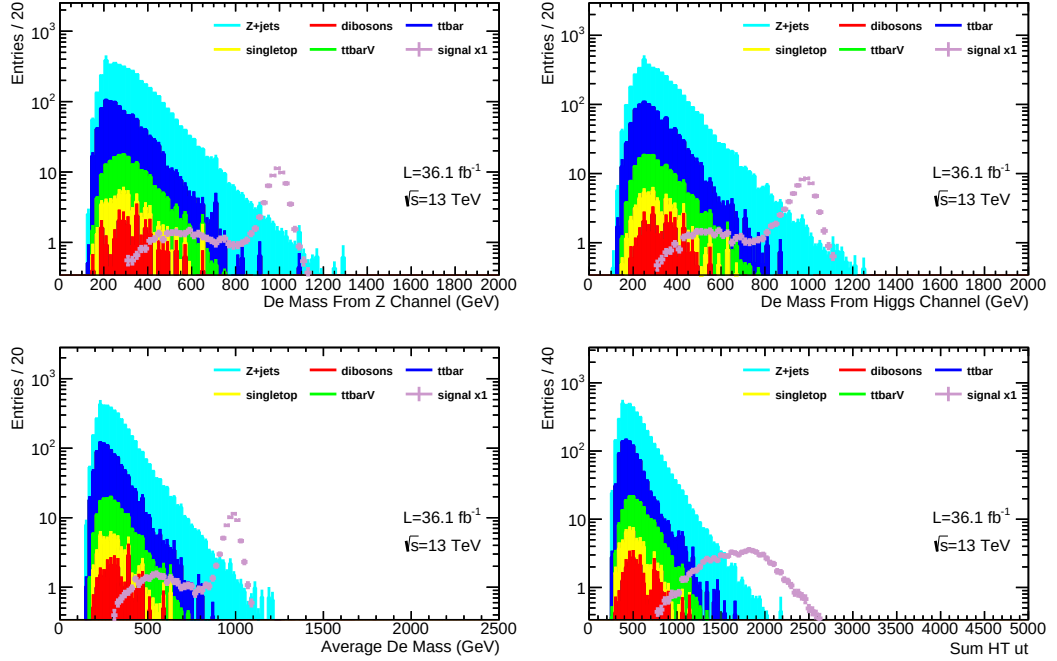


Figure A.34: D quark mass reconstructed from a Z boson, D quark mass reconstructed from a H boson, average reconstructed D quark mass and Sum H_T distributions in case of 1-btagged for the $\mu\mu$ channel.

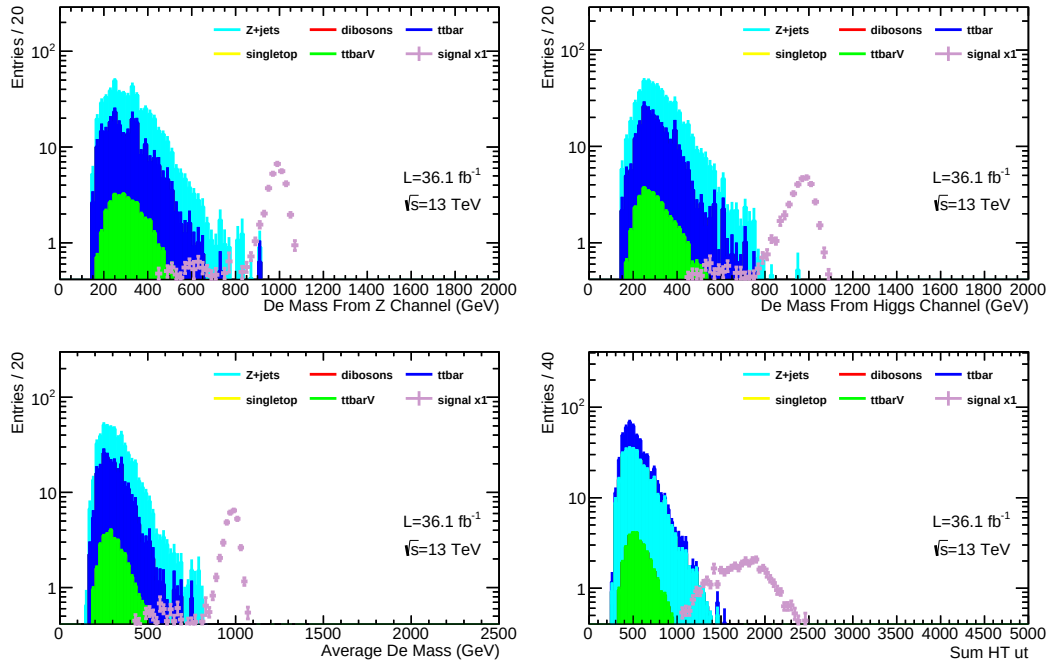


Figure A.35: D quark mass reconstructed from a Z boson, D quark mass reconstructed from a H boson, average reconstructed D quark mass and Sum H_T distributions in case of 2-btagged for the $\mu\mu$ channel.

A.6. Limit Results with Earlier Version of Cut Flow

The expected limit results for the earlier version of the analysis where we apply the b-tagging requirement on the Higgs-daughter jet candidates before the χ^2 cut can be found here. As the limit extraction is CPU intensive, we first obtain limits using the tools TLimit and MCLimit in the absence of systematic uncertainties. We show the expected limits on heavy iso-singlet quark as a function of M_D which reconstructed with various methods, compared to the theoretical prediction in Figures A.36 (untagged) A.37 (1 b-tagged) A.37 (2 b-tagged) and Figures A.39 (un-tagged) A.40 (1 b-tagged) A.41 (2 b-tagged) for the ee channel and $\mu\mu$ channels, respectively. The expected limits on the mass of the quarks are extracted from the previously referenced figures are summarized for the un-btag, 1-btag and 2-btag cases for both the ee and $\mu\mu$ channels in Table A.1. While the choice of final discriminant does not appear to have a huge impact on the extracted limit, the 1-btag analysis appear to yield more competitive results as compared to the un-btag and 2-btag analyses. The discriminant variable which yields the best results is average D mass from Z and Higgs channels.

Table A.1: Limits for the ee and $\mu\mu$ channels.

b-tag case / Discriminant	ee channel (GeV)	$\mu\mu$ channel (GeV)
untagged / D Mass from Z channel	$1371.7^{+12.5}_{-16.1}$	$1303.6^{+20.8}_{-27.0}$
untagged / D Mass from H channel	$1342.6^{+15.7}_{-20.2}$	$1270.8^{+27.2}_{-36.6}$
untagged / Average D Mass	$1371.0^{+12.0}_{-15.4}$	$1315.8^{+20.7}_{-27.4}$
untagged / Sum H_T	$1357.1^{+13.8}_{-17.7}$	$1307.1^{+20.9}_{-27.5}$
1-btag / D Mass from Z channel	$1429^{+19.9}_{-23.7}$	$1375.2^{+10}_{-12.4}$
1-btag / D Mass from H channel	$1408.1^{+24}_{-15.2}$	$1371.9^{+11.6}_{-14.6}$
1-btag / Average D Mass	$1426.9^{+16.3}_{-18.6}$	$1377.9^{+10.1}_{-12.5}$
1-btag / Sum H_T	$1408.5^{+25.1}_{-15.5}$	$1376.4^{+10.1}_{-12.6}$
2-btag / D Mass from Z channel	$1358.7^{+10.1}_{-12.1}$	$1357.1^{+10.6}_{-12.8}$
2-btag / D Mass from H channel	$1353.7^{+9.8}_{-11.6}$	$1356.5^{+10.8}_{-13}$
2-btag / Average D Mass	$1358.7^{+10.1}_{-12.1}$	$1348^{+10.8}_{-12.9}$
2-btag / Sum H_T	$1377.9^{+9.1}_{-11.1}$	$1367.3^{+9.9}_{-11.9}$

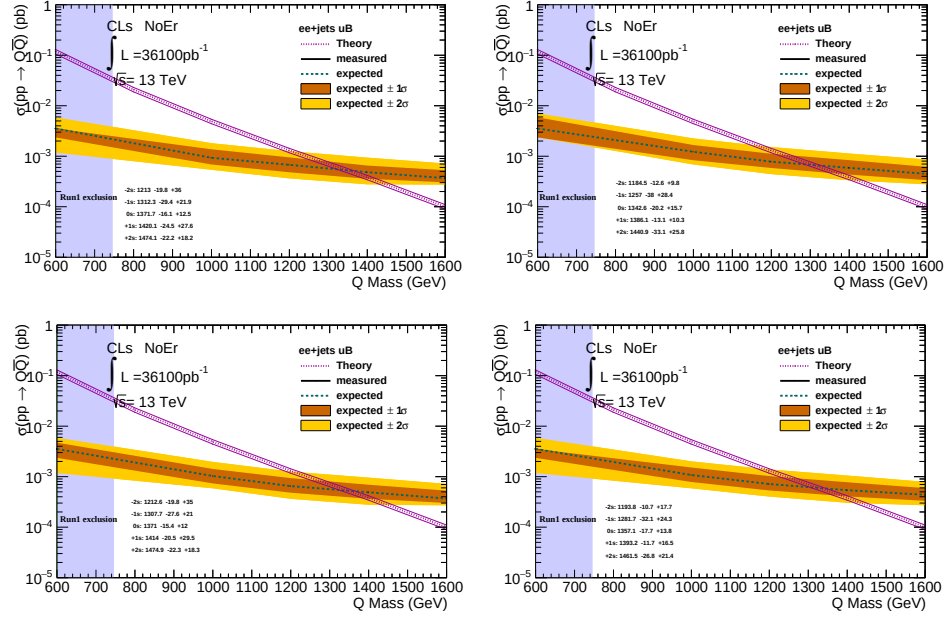


Figure A.36: The expected limit with 95% CL for the ee channel with untagged case, D mass from Z channel (top left), D mass from H channel (top right), Average D mass (bottom left) and Sum H_T (bottom right) are used as the discriminant. We apply leading jet $P_T > 100$ GeV and subleading jet $P_T > 65$ GeV.

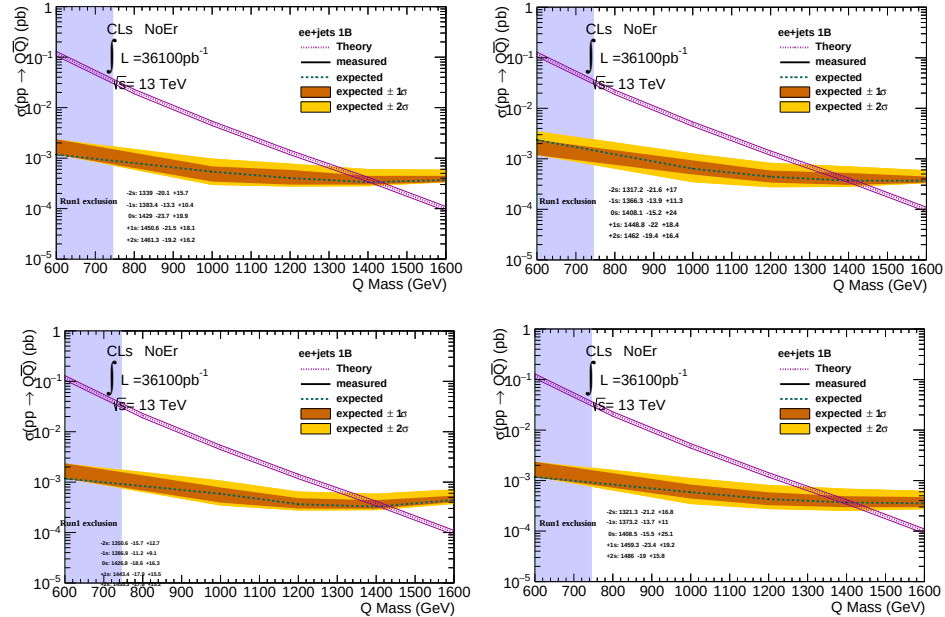


Figure A.37: The expected limit with 95% CL for the ee channel with 1 btag case, D mass from Z channel (top left), D Mass from H channel (top right), Average D mass (bottom left) and Sum H_T (bottom right) are used as the discriminant. We apply leading jet $P_T > 100$ GeV and subleading jet $P_T > 65$ GeV.

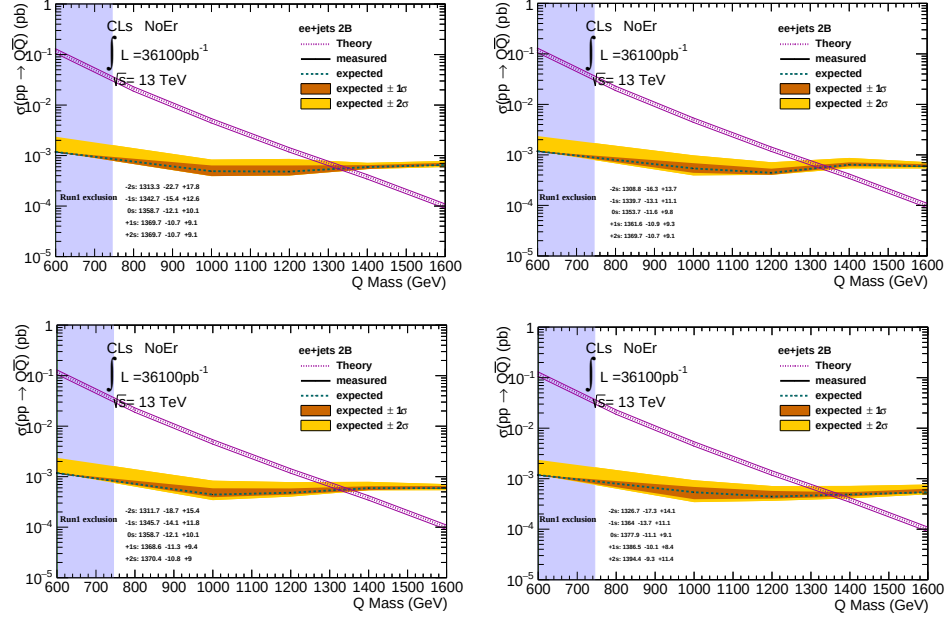


Figure A.38: The expected limit with 95% CL for the ee channel with 2 bt tag case, D mass from Z channel (top left), D mass from H channel (top right), Average D mass (bottom left) and Sum H_T (bottom right) are used as the discriminant. We apply leading jet $P_T > 100$ GeV and subleading jet $P_T > 65$ GeV.

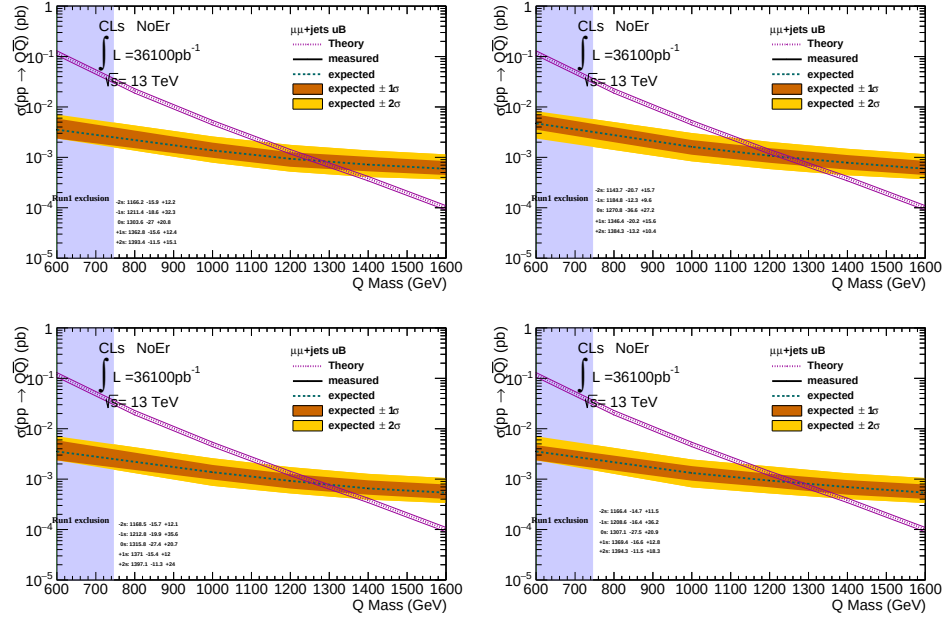


Figure A.39: The expected limit with 95% CL for $\mu\mu$ channel with untagged case, D mass from Z channel (top left), D mass from H channel (top right), Average D mass (bottom left) and Sum H_T (bottom right) are used as the discriminant. We apply leading jet $P_T > 100$ GeV and subleading jet $P_T > 65$ GeV.

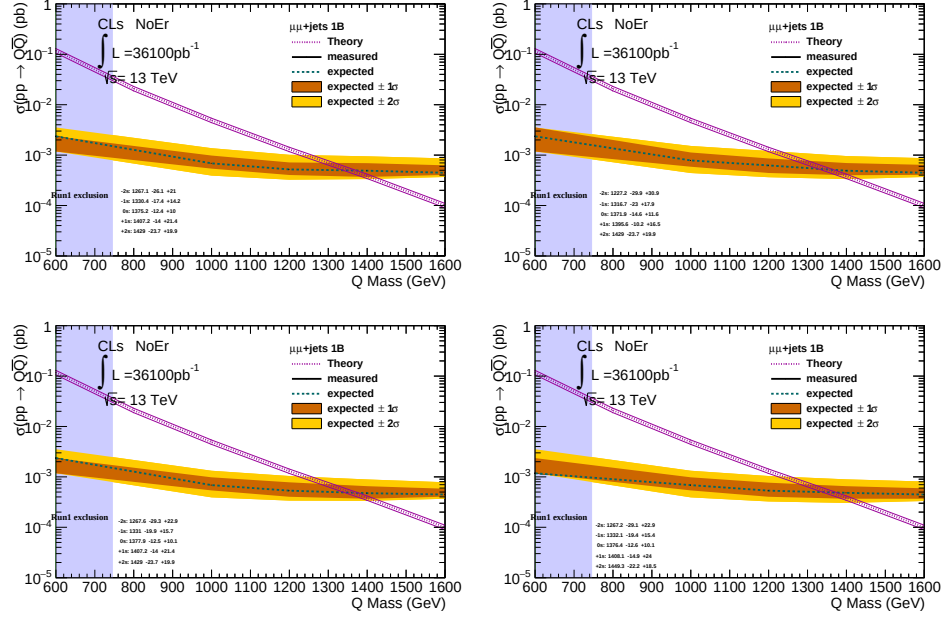


Figure A.40: The expected limit with 95% CL for $\mu\mu$ channel with 1 btag case, D mass from Z channel (top left), D mass from H channel (top right), Average D mass (bottom left) and Sum H_T (bottom right) are used as the discriminant. We apply leading jet $P_T > 100$ GeV and subleading jet $P_T > 65$ GeV.

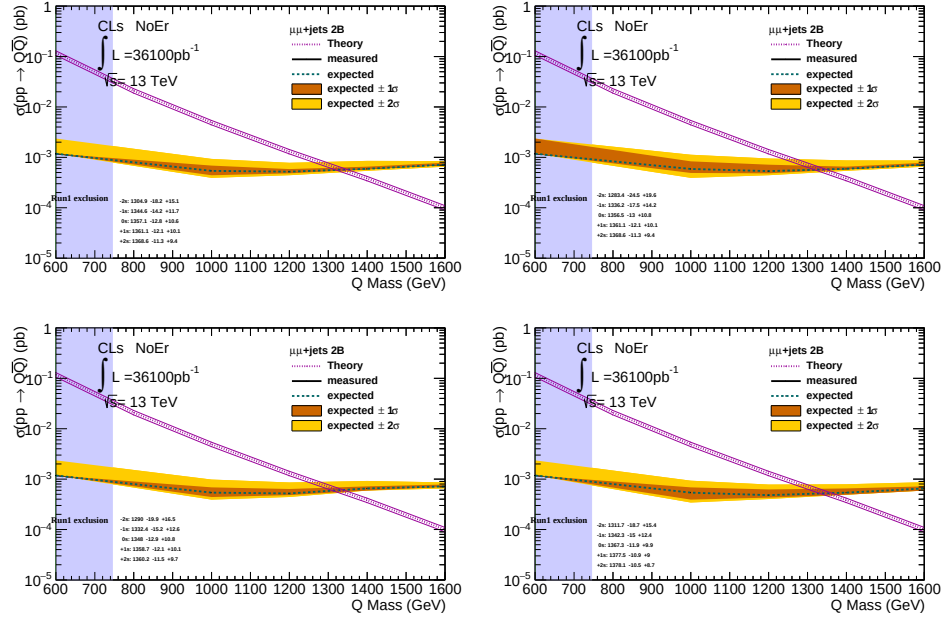


Figure A.41: The expected limit with 95% CL for $\mu\mu$ channel with 2 btag case, D mass from Z channel (top left), D mass from H channel (top right), Average D mass (bottom left) and Sum H_T (bottom right) are used as the discriminant. We apply leading jet $P_T > 100$ GeV and subleading jet $P_T > 65$ GeV.

Figures A.42 and A.43 and Figures A.44 and A.45 show the expected limits which is obtained with TRExFitter for the electron and muon channels respectively, and the mass of the D quark reconstructed from the Z boson is used as the final discriminant. We separately show the no-systematics limit, limits with only certain categories of systematic uncertainties included, and finally the limits with all systematical uncertainties. We have these figures for untagged version of the analysis. The limits have been obtained by fitting to the signal region and the two control regions simultaneously. Also, the expected limit result for both ee and $\mu\mu$ channels combined together with all systematics included is presented in the Figure A.46.

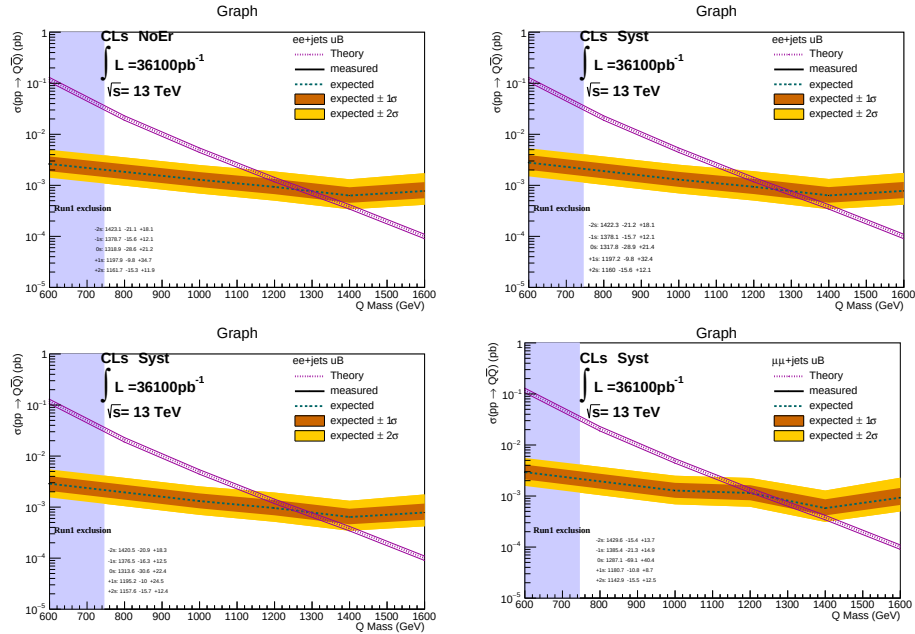


Figure A.42: The expected limit with 95% CL for ee channel with untagged case, D Mass from Z channel without any systematical uncertainties (top left), only scale factor systematics are added (top right), only object systematics are added (bottom left) only modelling uncertainties are added (bottom right).

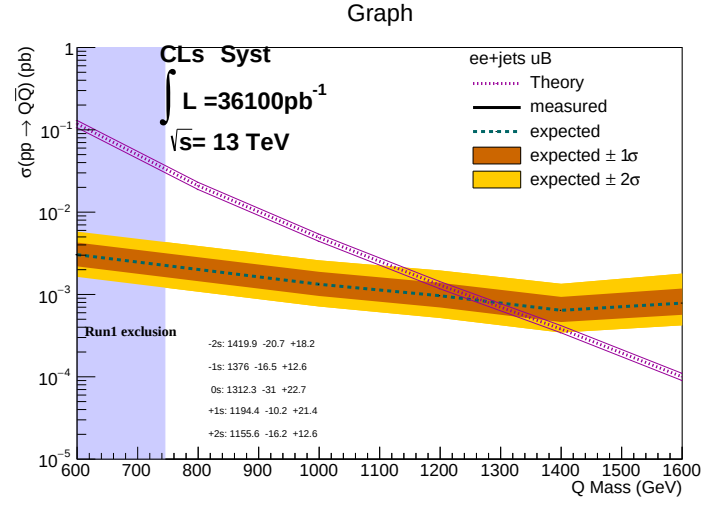


Figure A.43: The expected limit with 95% CL for ee channel when all of the systematical uncertainties are included. The discriminant is the D mass for Z channel for the untagged case.

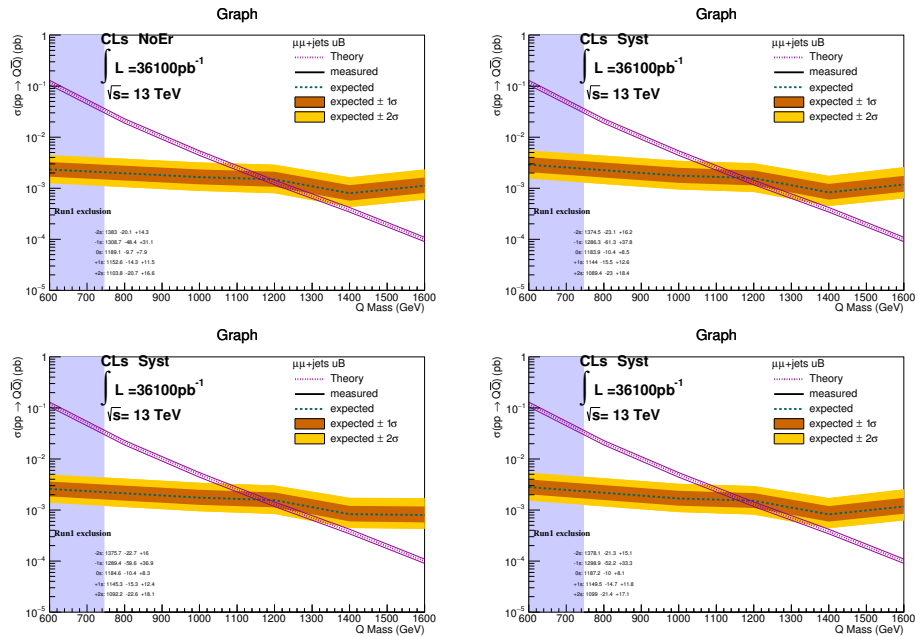


Figure A.44: The expected limit with 95% CL for $\mu\mu$ channel with untagged case, D mass from Z channel without any systematical uncertainties (top left), only scale factor systematics are added (top right), only object systematics are added (bottom left) only modelling uncertainties are added (bottom right).

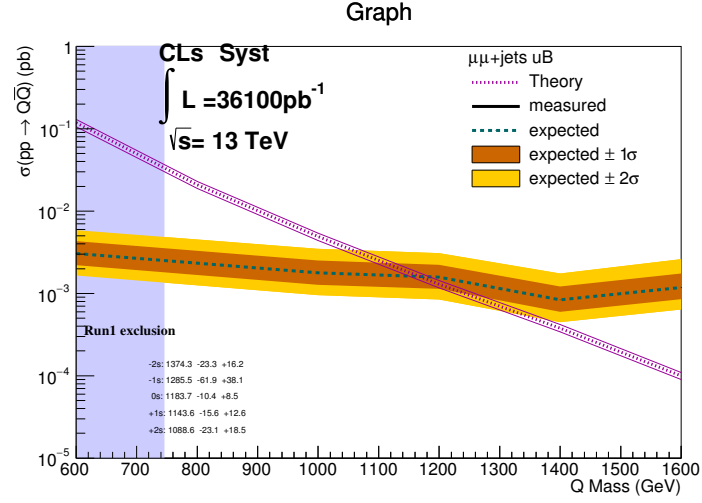


Figure A.45: The expected limit with 95% CL for $\mu\mu$ channel when all of the systematical uncertainties are included. The discriminant is the D mass for Z channel for the untagged case.

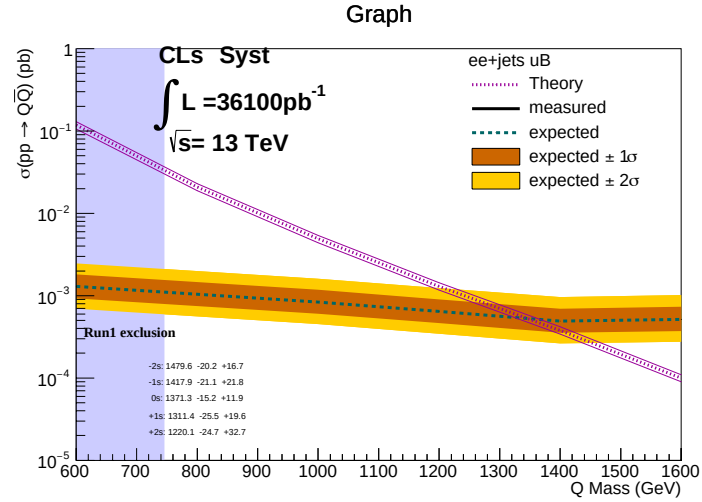


Figure A.46: The expected limit with 95% CL for ee and $\mu\mu$ channels combined when all of the systematical uncertainties are included. The discriminant is the D mass for Z channel for the untagged case.

A.7. Cut Optimization for P_T of the Leading and Subleading Jets

In the current version of the analysis, the cut on the P_T of the leading (subleading) jet is 100 (65) GeV. Before deciding to these values, we determined the expected the limit for the cases when cut on $P_T^{LeadingJet}$ is 200 GeV, 300 GeV, 400 GeV, 500 GeV, 600 GeV and 700 GeV while the cut on $P_T^{SubleadingJet}$ is 65 GeV. It was observed that up to $P_T^{LeadingJet} \geq 400$ GeV, the expected limit was improving, and it stayed at a plateau value until 600 GeV, and started to decrease afterwards. This sort of behaviour is not suprising as up to 400 GeV the cuts on P_T cause reduction of the background mainly. While after 400 GeV, we start to lose non-negligible chunks of events from the signal too. At $P_T^{LeadingJet} \geq 700$ GeV, the signal statistics become too limited for setting a better value on the limit.

In order to optimize the cut on $P_T^{SubleadingJet}$, the cut on $P_T^{LeadingJet}$ is set to 400 GeV, and the cut on $P_T^{SubleadingJet}$ is set to 200 GeV, 300 GeV and 400 GeV and not much of a difference is observed. The values can be found in Figure A.47.

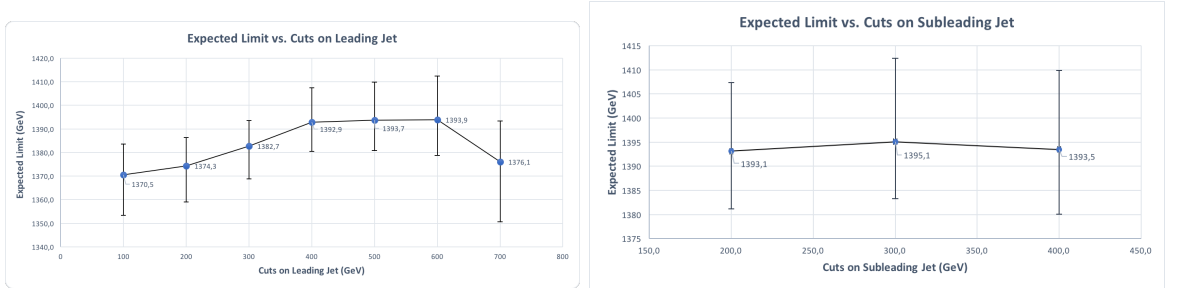


Figure A.47: The limit values which is obtained with varying leading and subleading jet criterias.

After this study, the highest expected limit is observed for the configuration $P_T^{LeadingJet} \geq 400$ GeV and $P_T^{SubleadingJet} \geq 300$ GeV. But, this study was for un-tagged case. For the 1 b-tagged case, it is observed that $P_T^{LeadingJet} \geq 100$ GeV and $P_T^{SubleadingJet} \geq 65$ GeV configuration has higher expected limit than all the various un-tagged cut combinations. Therefore, we have decided continue with the 1 b-tagged requirement in the Higgs-daughter jet candidates.