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Experimental research in particle physics: Characterization
of gas-avalanche THGEM particle detector and physics-
data analysis with the ATLAS experiment

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Declaration

I hereby declare that this thesis summarizes my independent research, except where explicit reference is made to the work of others. Chapters 1, 3, 5 and 7 describe original work related to this thesis. Furthermore, my specific contribution is described in the introduction to each chapter including a reference to the precise sections in the relevant publications, related to my work.

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List of Abbreviations

2DHM	2-Doublet Higgs Model	LEP	Large Electron-Positron collider
4(5)FS	four(five) Flavor Scheme	LF	Light Flavor
ATLAS	A Toroidal LHC ApparatuS	LHC	Large Hadron Collider
BDT	Boosted Decision Tree	LO	Leading Order
BR	Branching Ratio	MCA	Multi-Channel Analyser
BSM	Beyond the Standard Model	MC	Monte Carlo
CDF	Cumulative Distribution Function	MJ	Multi-Jet
CL	Confidence Level	MM	Matrix-Method
CMS	Compact Muon Spectrometer	MPGD	MicroPatern Gaseous Detectors
CR	Control Region	MS	Muon Spectrometer
DV	Discriminating Variable	MSSM	Minimal SuperSymmetric Model
ECAL	Electromagnetic CALorimeter	MVA	Multi Variable Analysis
ETE	Electron Transfer Efficiency	(N)NLO	(Next-to) Next to Leading Order
EW	Electro-Weak	OCS	Opposite Charge Sign
FCAL	Forward CALorimeter	OR	Overlap Removal
FEM	Finite-Element Method	PDF	Parton Distribution Function
FF	Fake-Factors	PSB	Proton Synchrotron Booster
GEM	Gas Electron Multiplier	PS	Proton Synchrotron
ggF	gluon-gluon Fusion	QCD	Quantum Chromo-Dynamics
HCAL	Hadronic CALorimeter	RPWELL	Resistive-Plate WELL
HEC	Hadronic End-Cap	SCS	Same Charge Sign
HF	Heavy Flavor	SCT	SemiConductor Tracker
IBL	Insertable B-Layer	SM	Standard Model
ID	IDentification	SPS	Super Proton Synchrotron
IP	Iteration Point	SR	Signal Region
JVF	Jet Vertex Fraction	THGEM	THick Gas Electron Multiplier
JVT	Jet Vertex Tagger	TRT	Transition radiation tracker
LAr	Liquid Argon	VBF	Vector Boson Fusion
LC	Locally Calibrated	WG	Working Group
LEM	Large Electron Multiplier	WP	Working Point

Abstract

Modern experimental research in particle physics incorporates a broad range of scientific fields, from the development of the experimental tools, experiment assembly and running - to the final analysis of the data. My thesis covers both ends; a systematic study of physical processes in a novel particle-detector for future particle-physics experiments and data analysis from the LHC-ATLAS experiment. The thesis is made of three parts. The first part of the thesis is devoted to an advanced study of charging up processes occurring in gas-avalanche detectors based on Thick Gas Electron Multipliers (THGEM). The second part is devoted to detector performance studies - that of photon identification efficiency in ATLAS. The third part is dedicated to ATLAS data analysis - in particular related to the search for rare processes or hypothetical particles.

Introduction

From the beginning of the recorded human history, the humankind strived to explain phenomena occurring in nature. The pathway to unlock the secrets of the universe is concealed in the examination of a broad range of its scales: from the basic research of the building blocks of all existing matter on the sub-atomic scale to the research of the dynamics of stars and galaxies on the universal scale. In my thesis work, I chose to dedicate my research to study the secrets of the universe from its basis – videlicet, to study the physics of elementary particles. Particle physics deals with matter in sub-atomic scales, covering the core of various fields in modern science.

Besides the ever-growing particle accelerators, of increasing energies and fluxes, the study of fundamental particles requires parallel advances in particle detectors capable of coping with new experimental needs. During my work, I was privileged to take part in research and development of novel gas-avalanche particle detectors. Gas-avalanche particle detectors are deployed in many physics experiments, collect and multiply particle-induced charges in an avalanche mode. The demand for mass-produced large-area detection tools, performing in a stable regime, triggered the development of a new family of MicroPatern Gaseous Detectors (MPGDs), replacing gradually current “wire chambers”. During my research, I took part in investigations of the novel Thick-Gaseous Electron Multiplier (THGEM) and detectors based on its concept. The main topic of my study has been the phenomenological modeling of the physical processes occurring in this type of detectors, which affect the detector’s stability [1]. The phenomenological model was verified in laboratory studies conducted by me [2]. During my research period in the Radiation Detection Physics laboratory, I also participated in the characterization of large-size THGEM-based detectors in a particle beam at the CERN Super Proton Synchrotron (SPS) [3, 4].

Detectors in large experiments, like the LHC-ATLAS, combine large assemblies of various detector kinds. Some of the characterizations of the ATLAS detector are performed “in-situ” during the experiment. During my research project, I participated in the performance studies of the ATLAS detector, in measuring the photon identification efficiency. The photon identification efficiency measurement is essential for deriving the precise physics results of the experiment. I measured the photon identification efficiency during 2012 data taking period [5]. In the same year, the Higgs Boson, the last missing ingredient of the Standard Model (SM) of Electro-weak interactions was discovered - with one of the discovery channels being the Higgs decay to a pair of photons. This was my first contribution to the measurement of the newly discovered particle.

With the Higgs boson discovery, I was privileged to participate in several measurements of the properties of the new particle. Predicted by the SM, the Higgs boson has the property of granting masses to most of the SM particles. This is reflected in both its production and decay. I took part in measuring the Higgs coupling to a pair of τ -leptons [6] via the gluon-gluon- and vector-boson-fusion production modes, and in particular my main contribution was to the study of the Higgs boson produced in association with a top-quark pair via its decay to a pair of τ -leptons [7]. Later, I took part in probing the width of the new resonance [8].

The SM is not a complete theory. There are already few pieces of evidence of physics beyond the Standard Model (BSM). For example, the elusive neutrinos change their flavor while propagating through space in contradiction to the SM postulates. One of the ways to search for the BSM physics is to search for a new particle, for example, a search for additional scalar fields (additional Higgs bosons). This approach is motivated by the fact that any additional fundamental non-scalar particle will lead to high dependence of the mass of the Higgs boson on quantum correction. The evidence

of the existence of an extended family of scalar particles can be achieved through the discovery of electrically-charged Higgs bosons. During my research study, I participate in a search for charged Higgs bosons in the decay to a $\tau\nu$ final state. In this search I was one of the analysis' leaders and later became one of the analysis' coordinators [9–11].

My contribution in the various aspects of experimental particle physics unveiled research in one of the most curious and fascinating fields, and enriched my knowledge comprehensively. The following thesis describes the main constituents of my work: part I (chapter 1) describes a Detector Physics project. My research efforts have been devoted to an advanced study of the processes occurring in gas-avalanche charge multipliers containing dielectric materials in contact with the gas medium where the multiplication occurs. Part II (chapters 2, 3) describes performance studies of the ATLAS detector. Here I worked on a data-driven method of measuring the photon identification efficiency. Part III (chapters 4–7) is a Data Analysis related to two front-edge topics: search for SM Higgs boson production in association with a pair of top-quarks in the $H \rightarrow \tau\tau$ decay mode, and a search for BSM physics – Charged Higgs bosons in the $H^\pm \rightarrow \tau^\pm\nu$ decay mode. The conclusions of this work are given in chapter 8.

Part I

R&D of Particle detectors

CHAPTER 1

Study of charging up processes affecting gain stability in THGEM gas-avalanche particle detectors

This chapter is based on reference [1]: "*Simulation of gain stability of THGEM gas-avalanche particle detectors*", and on reference [2]: "*Measurements of charging-up processes in THGEM-based particle detectors*".

My contribution: In the first paper, my contribution was in comprehensive phenomenological study with a recently developed simulation code [12], of the charging-up phenomena in THGEM detectors. The simulation package was developed in collaboration with P.P.M. Correia, at that time a Ph.D. student in Aveiro University. The phenomenological work was followed by additional extensive simulations and laboratory studies conducted by me, as described in the second paper.

1.1 Introduction

The time-evolution of the avalanche gain in Micro-Patterned Gaseous Detectors (MPGDs) has been a topic of major interest in the last years. Gain variations with time have been reported and are common in detectors containing dielectric materials in contact with the gas medium where multiplication occurs; the effects have been noticed particularly in detectors based on hole-type MPGDs with insulating surfaces in contact with active gases, e.g. Gas Electron Multipliers (GEMs) [13–15], Large Electron Multiplier (LEM) [16, 17] and Thick Gaseous Electron Multiplier (THGEM) - based detectors [18–23] and their recent derivative: the Resistive-Plate WELL (RPWELL) [24].

Gain variation over time in GEM and THGEM-based detectors can arise from different processes, e.g. polarization of the insulator's volume under applied voltage, and charging-up of the insulator's surfaces exposed to the free drifting charges (electrons and ions) in the gas volume (for example see

[18]). It has been also observed that detector's environmental conditions, such as gas impurities and moisture, can affect gain transients [20, 24].

In this work, we studied the effect of charging-up of the insulator surfaces. A quantitate study about the mobility of the charges inside the dielectric material has not been performed yet; we assume that these effects are negligible here. Previous studies suggest that the mobility of charges on top of the insulator surface is the main factor responsible for the long-term evolution (from hours to days) of the gain in THGEMs [23]. I suggest here that both long-term and short-term THGEM gain evolutions are rather associated with the charging-up of the dielectric material.

A simulation program has been developed for phenomenological studies of charging-up effects in GEM detectors [25, 26]. The tool is based on the superposition principle according to which the field inside the holes is the sum of the field prior to any charge accumulating on the insulating surface and the field due to the charge accumulated on the insulators. This simulation tool predicted the time dependence of the gain in the GEM detectors with double-conical holes.

In this work, the simulation tools were extended to charging-up studies in THGEM-based detectors [1]. A typical scheme of the THGEM detector configuration and a simulated avalanche process are shown in figure 1.1.1. The operation mechanism is the following: electrons originating from radiation-induced gas ionization (primary cloud of electrons) are focused into the holes, where they undergo avalanche multiplication under high electric field. The avalanche electrons are collected either by the THGEMs bottom-electrode or by a readout anode located under the THGEM. The moving charges of the avalanche (both electrons and ions) induce current on the conductive planes; it can be measured, using a readout chain, on each of the electrodes.

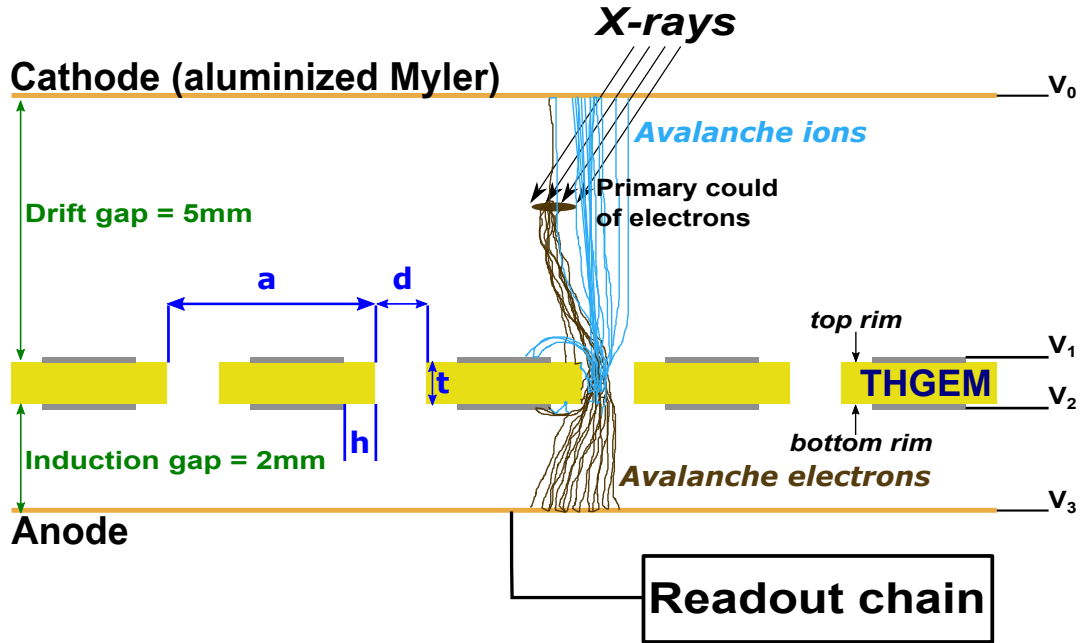


Figure 1.1.1: Scheme of the THGEM detector irradiated by an external ^{55}Fe x-ray source (not to scale); the aluminized-Mylar window, serving as a drift electrode (cathode); multiplied charges are collected through the induction gap between the THGEM bottom-electrode and the readout anode. The detector parameters are: t , thickness; d , hole diameter; a , hole pitch; h , rim size at the hole circumference.

In this work, we explore the effect of charging-up of the detector's dielectric material on its gain stability, both phenomenologically and experimentally as summarized in [1, 2].

1.2 The simulation toolkit for phenomenological studies

1.2.1 Electric field calculations

The total field $\vec{E}_{\text{tot}}$ can be estimated using the superposition principle

$$\vec{E}_{\text{tot}} = \vec{E}_{\text{uncharged}} + \vec{E}_{\text{charges}} \quad (1.2.1)$$

Here $\vec{E}_{\text{uncharged}}$ is the electric field resulting from the voltage applied to the THGEM electrodes prior to any charging-up, $\vec{E}_{\text{charges}}$ is the field due to the charges accumulating in the insulator surfaces (electrons and ions). While $\vec{E}_{\text{uncharged}}$ remains constant, $\vec{E}_{\text{charges}}$ varies due to the continuous accumulation of charges. Hence, the total field at equilibrium can be obtained in an iterative process, where in each iteration $\vec{E}_{\text{charges}}$ is modified according to the cumulative surface charge.

During the first iteration, that corresponds to the simulation of the multiplication process in a THGEM before irradiation, i.e., prior to charge accumulation on the insulator surfaces, a set of primary avalanches is simulated. A fraction of the free charges (drifting electrons and ions) end up accumulating on the insulator, as depicted in figures 1.2.1c and 1.2.1a in case of electrode with and without hole-rims respectively. These charges will modify the electric field by some amount, resulting in a new field map, $\vec{E}_{\text{tot}}$; it can be obtained from the superposition of $\vec{E}_{\text{uncharged}}$ and $\vec{E}_{\text{charges}}$, as depicted in figures 1.2.1d and 1.2.1b for electrode with and without hole-rims respectively.

1.2.2 Simulations steps

The finite-element method (FEM), as implemented in **ANSYS®**¹, is used to calculate the electric potential in the gas volume, which then is used to infer the electric field at a given point of all the avalanche electrons' path [27]. Avalanche-size calculations and transport properties of the charges (electrons and ions) are calculated in Garfield++ [28] (which interfaces with Magboltz [29]), that simulates collisions of electrons in a given gas mixture and detector geometry.

It is an iterative method in which the first iteration corresponds to the simulation of the multiplication process in a THGEM before irradiation, i.e., prior to charge accumulation on the insulator surfaces. In the first iteration, $\vec{E}_{\text{uncharged}}$ is calculated from the electric-field value derived from the voltages applied to the detector's electrodes. During the first iteration, a set of primary avalanches is simulated. In the simulation, the free charges (drifting electrons and ions) may end up accumulating on the insulator. These charges will modify the electric field by some amount – resulting in a new field-map – $\vec{E}_{\text{charges}}$. The $\vec{E}_{\text{tot}}$ can be obtained from the superposition principle by adding the original $\vec{E}_{\text{uncharged}}$ to the $\vec{E}_{\text{charges}}$, as represented in figures 1.2.1b and 1.2.1d.

The second iteration and subsequent ones take into consideration the updated $\vec{E}_{\text{tot}}$ values of the previous iterations. The different electric-field values during next iterations are changing the avalanche process, which will influence the measured gain. Assuming a certain irradiation rate, a time-evolution of the gain can be simulated. A flowchart of the superposition algorithm is depicted in figure 1.2.2.

For a THGEM, the following procedure is applied for computing the field maps of interest:

- The THGEM insulator surface is divided into 20 slices as shown in left hand size of figure 1.2.3.
- The $\vec{E}_{\text{uncharged}}$ is calculated from the voltages applied;
- For each slice, a field map, considering only the electric field due to an unitary charge distributed uniformly over the exposed surface of the slice, is calculated - defined here as $\vec{E}_{\text{slices}}$.
- For a THGEM electrode with hole rims, the insulator surface is divided into 20 slices and two additional surfaces, as shown in right hand size of figure 1.2.3.

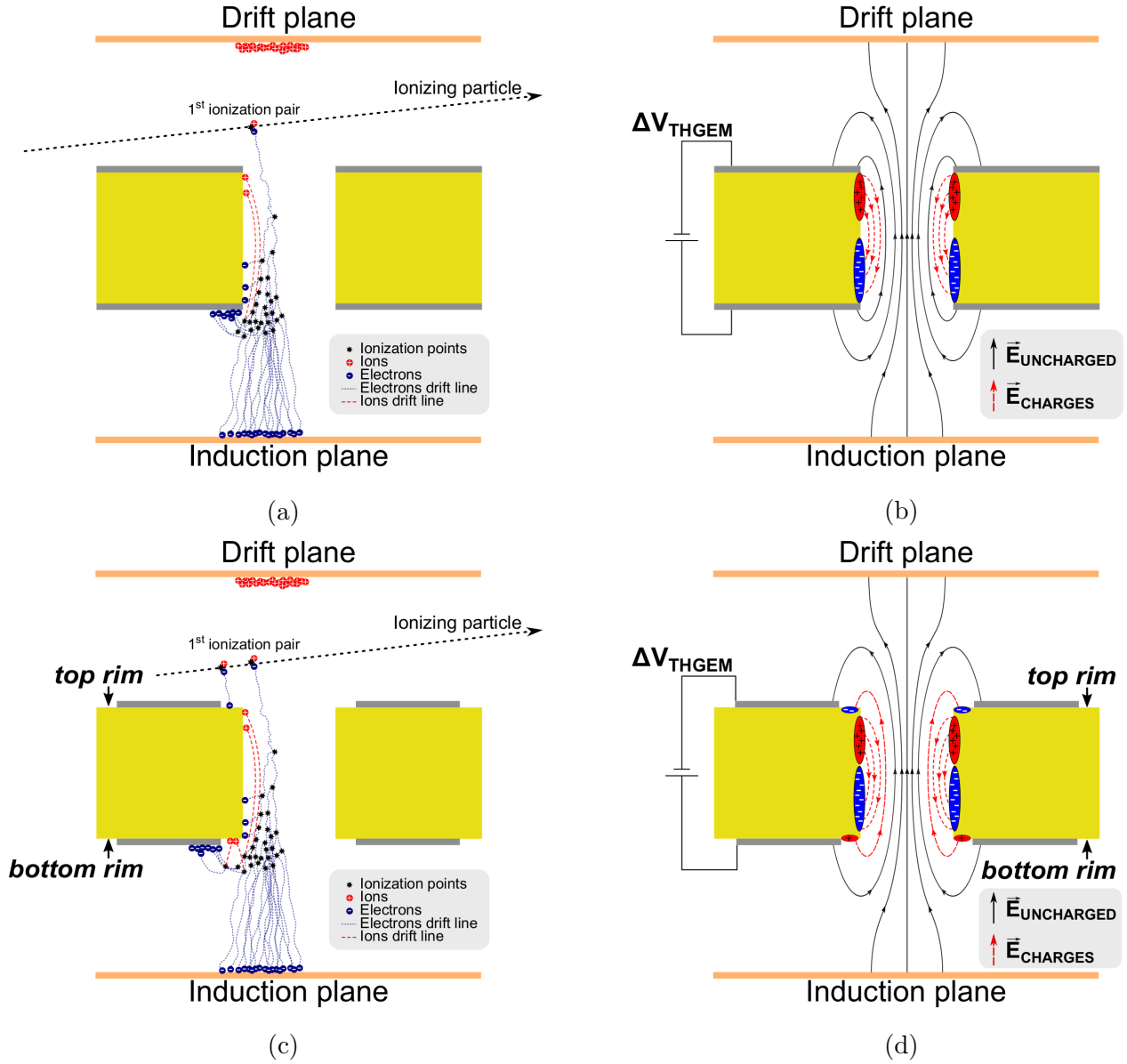


Figure 1.2.1: Left: Schematic drawing of the charging-up process during an avalanche. Right: Charging-up superposition algorithm of the THGEM. The total electric field is a sum of $\vec{E}_{\text{uncharged}}$, calculated when voltages are applied on the electrodes and the detector was not exposed to ionizing radiation yet, superimposed with the electric field induced by accumulated charges on the insulator's surface of the detector $\vec{E}_{\text{charges}}$. The bottom and top figures show THGEM-electrode geometry with and without hole-rims respectively.

Once these field maps are available, the Garfield++ simulation can start. To perform the simulation, Garfield++ imports the coordinates of the nodes and the associated electric potential as a list. In order to calculate $\vec{E}_{\text{charges}}$, an avalanche is calculated, and the position of all the electrons or ions deposited on an insulating surface is stored. The total number of accumulated charges $N = N_{\text{electrons}} - N_{\text{ions}}$ (the number of accumulated electrons minus that of accumulated ions) is assigned to the corresponding slice. Since the expected variation of the field from N charges on a given slice for a single avalanche is very small, for fast algorithm convergence, the total number of accumulated charges attached to a single slice is usually multiplied by a constant value s (*step-size*). Therefore, in the case where N charges have stopped on the surface of a slice j (without other extra

¹www.ansys.com

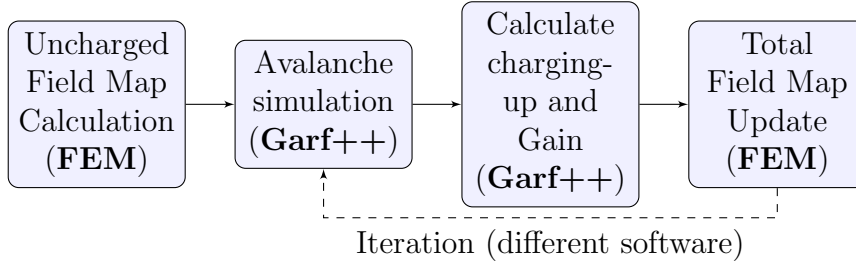


Figure 1.2.2: Flowchart of the superposition method.

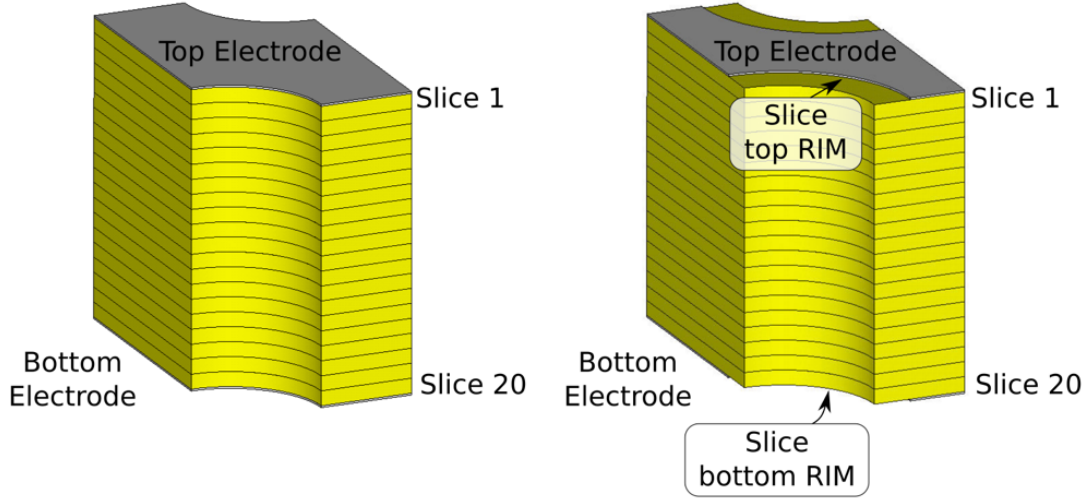


Figure 1.2.3: The THGEM cell employed in the simulations. Left: THGEM holes with no rim; the insulator surface is divided into 20 slices along the hole. Right: THGEM with hole rims; the insulator surface is divided into 20 slices + 2 rim surfaces.

charges accumulated in the remaining surfaces), we need to calculate, for each node i , the electric potential V for that node which is given by Equation 1.2.2:

$$V(charges, i) = V(uncharged, i) + N \times s \times V(j, i) \quad (1.2.2)$$

where $V(j, i)$ is the electric potential on node i due to the presence of a unitary positive charge in the surface of slice j , calculated from the $\vec{E}_{slices}$ described previously. Depending on the accumulated charges, N can either be positive (more ions) or negative (more electrons).

Once $\vec{E}_{charges}$ is calculated, the next iteration is launched, where the total electric field is given as a sum of $\vec{E}_{charges}$ and $\vec{E}_{uncharged}$ (Equation 1.2.1). In the following iteration, a new $\vec{E}_{charges}$ is calculated according to a new amount of accumulated charges; this procedure is repeated until the total amount of accumulated charges N , after a given number of iterations, is equal to zero – $\vec{E}_{tot}$ remaining constant with the increasing number of iterations.

1.3 Application of the method to THGEMs

1.3.1 Simulation setup

The THGEM-detector geometry simulated in this work has an electrode with an hexagonal pattern of $d = 0.5$ mm diameter holes, a hole-pitch of $a = 1$ mm and FR4 electrode substrate having thickness of $t = 0.4$ mm, 0.8 mm and 1.2 mm; hole geometries were selected without rims and with rims of a width $h = 0.1$ mm. The different parameters were selected for evaluating their influence on the

charging-up process. Respective electric fields of 0.2 and 0.5 kV cm⁻¹ were set across the drift and induction gaps respectively (figure 1.1.1).

Different potential values, ΔV_{THGEM} , were applied across the THGEM electrode. Several gas mixtures were used in the simulations; in most of the cases Ne and Ne/CH₄(5%). To obtain similar electron multiplication values over a broad range of applied voltages, the simulation work was extended to Ar-based gas mixtures: Ar, Ar/CH₄(5%) and Ar/CO₂(5,7%). Since some of these are believed to be Penning-mixtures [30], Penning factors of 0.4 for Ne/CH₄(5%), 0.18 for Ar/CH₄ (5%), 0.35 for Ar/CO₂(5%) and 0.4 for Ar/CO₂(7%) [31–33] were used.

Standard room-temperature conditions were considered ($T=293\text{ K}$ and $P=1\text{ bar}$). A constant irradiation rate of 10 Hz mm⁻², 8 keV x-rays, was assumed. In the simulations, a random location for primary charges originated by the incoming x-rays is assumed and the charges are drifted towards the THGEM holes from different positions.

At each iteration, the gain for a single-electron avalanche multiplication was calculated. Electron multiplication is a stochastic process, and the gain is determined as the average number of electrons generated during the electron avalanche process. At each iteration a given number of avalanches between 100 and 1000 was simulated (denoted in the text as n_{AV}). In all simulations, the statistical error on the mean gain of the detector was taken as

$$\sigma(\text{Gain}) = \sqrt{\frac{\text{Gain}}{n_{\text{AV}}}} \quad (1.3.1)$$

In each avalanche, the position of all the electrons or ions deposited on an insulating surface is stored, and assigned to the corresponding slice. Electrons that do not end up on the insulator are either collected on the THGEM bottom electrode, on the induction plane, while non-trapped ions end up on the top THGEM electrode or on the drift plane. Some of the electrons are attached to the gas molecules (CO₂ or CH₄) and are not taken into account in the gain calculation.

1.3.2 Physical interpretation

The number of simulated iterations (n_{iter}) can be translated to a physical irradiation time (t) as follows: given the number of primary charges induced in the gas by the ionizing event² (n_{p}), the irradiation rate (R) and the *step-size* (s) can be related to a physical irradiation time:

$$t[\text{sec}] = \frac{s}{n_{\text{p}} \times R [\text{Hz}]} \times n_{\text{iter}} \quad (1.3.2)$$

A short-term gain evolution curve over time, in the simulation, was fitted using:

$$G(t) = G_F + \Delta G \cdot e^{-t/\tau} \quad (1.3.3)$$

where $G(t)$ is the gain at a given instant, $G_F = G(+\infty)$ is the final gain, τ is the relaxation time constant (or *characteristic time*), and ΔG is the gain variation. The initial gain, G_0 , can be calculated in terms of G_F and ΔG :

$$G_0 = G_F + \Delta G \quad (1.3.4)$$

In case when in the simulation, the gain-stabilization exhibits a long-term component (As it will be discussed later is a result of charge accumulation on a detector's "top rim"), then the fitted function is extended to a double exponential curve:

$$G(t) = G_F + \Delta G \cdot e^{-t/\tau} - \Delta G_{\text{UP}} \cdot e^{-t/\tau_{\text{UP}}} \quad (1.3.5)$$

²8 keV X-rays produce ~ 220 or ~ 310 primary electrons on average in Ne-based or Ar-based gas mixtures, respectively [34].

where the ΔG_{UP} is the long-term gain increase, and τ_{UP} is the characteristic time of the long-term component.

An example of a simulation result of the gain evolution in a THGEM detector, in Ne/CH₄(5%) gas mixture with the parameters: $t=0.8$ mm, $a=1$ mm, $d=0.5$ mm, and $h=0$ (no-rim), is shown in figure 1.3.1. The quality of the fit to Equation 1.3.3 indicates upon a good agreement ($\chi^2/\text{n.d.f.} = 0.73$)

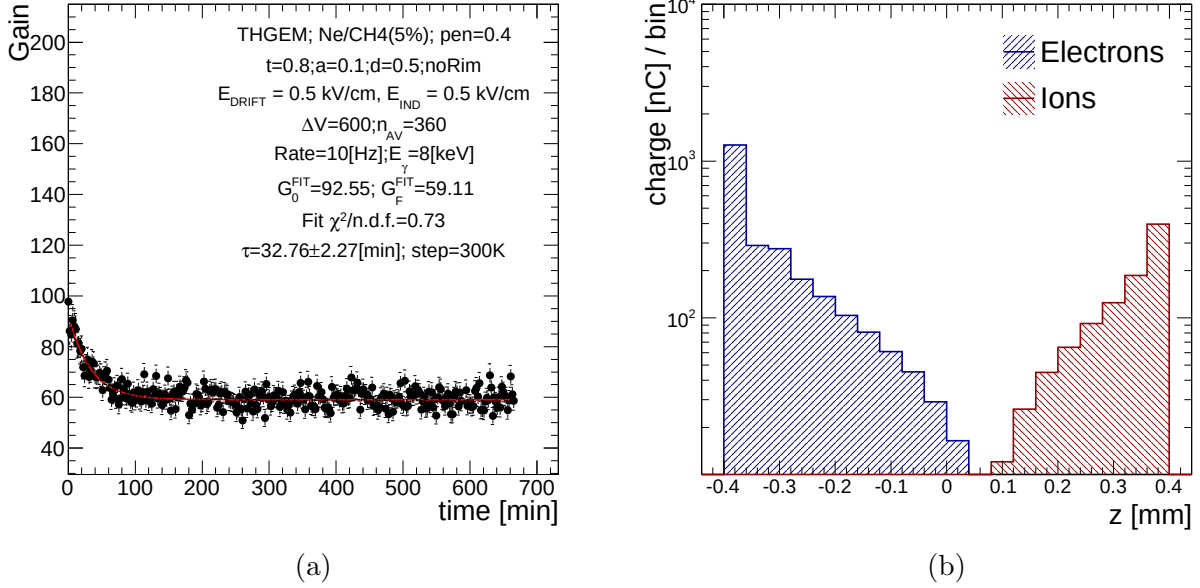


Figure 1.3.1: Simulated gain evolution in the THGEM as function of time (a) and the distribution of the accumulated charges onto the insulating hole's walls, along the hole's z -axis (b), in Ne/CH₄(5%). The exponential fit in the left figure relies on Equation 1.3.3. The fitted parameters are shown in the inner caption.

to the simulation (n.d.f., number of degrees of freedom, being the number of iterations). The exponential model is driven by the assumption that the amount of the accumulated charges is proportionally decreasing with the amount of charges attached to the insulating surfaces. In figure 1.3.1, after about ~ 100 min, the gain reaches a plateau, indicating that the ongoing charge accumulation is no longer capable of modifying the electric field in a way that could affect the gain because the electric fields due to new incoming electrons and ions cancel each other.

Using the formalism above, one can define a *characteristic charge*, Q_{tot} - the total charge, which pass through the THGEM holes during the relaxation period (τ):

$$Q_{\text{tot}} = q_e \times n_p \times R \times \int_0^\tau G(t)dt = q_e \times n_p \times R \times \tau \times \left(G_0 - \frac{\Delta G}{e}\right) \quad (1.3.6)$$

where q_e is the electron charge. Replacing the *characteristic time* by *characteristic number of iteration* (τ_{iter}), using Equation 1.3.3, one can rewrite Equation 1.3.6 in terms of the *step-size* and τ_{iter} :

$$Q_{\text{tot}} = q_e \times s \times \tau_{\text{iter}} \times \left(G_0 - \frac{\Delta G}{e}\right) \quad (1.3.7)$$

The choice of the *step-size* s is an important parameter for simulation convergence. An example of simulation results of THGEM detector, in Ne/CH₄(5%) gas mixture with the parameters: $t=0.4$ mm, $a=1$ mm, $d=0.5$ mm, and no-rim, with different *step-size* values (from 0.5×10^6 to 40×10^6) is shown in figure 1.3.2. The behaviour of the gain $G(t)$ should remain unchanged, regardless the *step-size*. In figures 1.3.2a and 1.3.2b the fitted τ is similar, while in figures 1.3.2b and 1.3.2c clearly show that higher *step-size* lead to different trends.

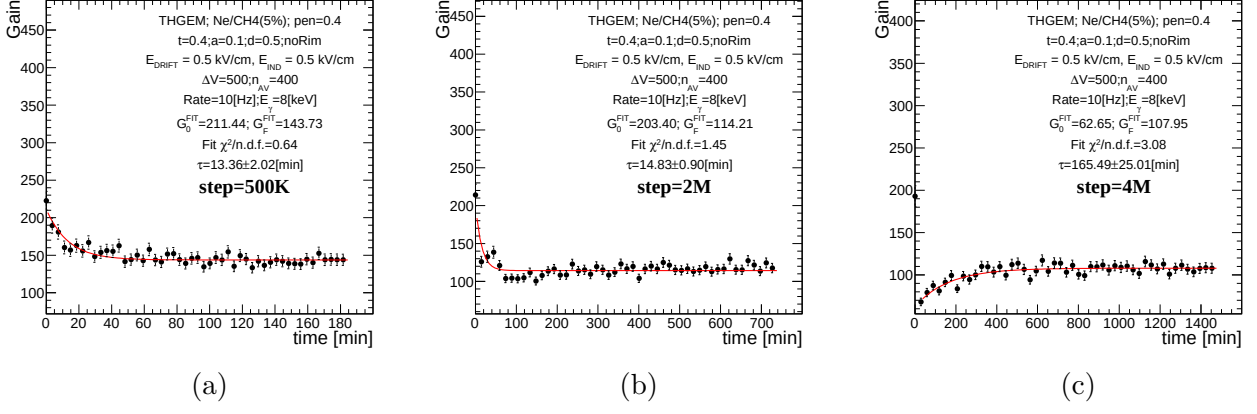


Figure 1.3.2: Simulation results of gain stabilization for different step-size values. (a) Gradual decrease of gain due to moderate step-size, (b) the electrode fully charges up after the first iteration, (c) too large step-size.

1.3.3 Convergence rules

Since the step-size should not affect the gain over time, a plot of the gain stabilization over time, simulated for different s -values from 0.1×10^6 to 0.5×10^6 , for the same detector geometry, is shown in the figure 1.3.3a, only for those step-size values that do not vary the gain trend. According to the results obtained in figure 1.3.2a, for a step size of 0.5×10^6 the gain stabilizes after about 3-4 iterations, therefore the step-size was reduced by a factor of five to inspect the gain stabilization over 50 simulated iterations. From these curves, the average fitted τ is 13(2) min. The plot of $1/\tau_{\text{iter}}$ as a function of $q_e \times s \times (G_0 - \frac{\Delta G}{e})$, depicted in the figure 1.3.3b, allows to calculate the value of $Q_{\text{tot}} \approx 58 \text{ pC}$.

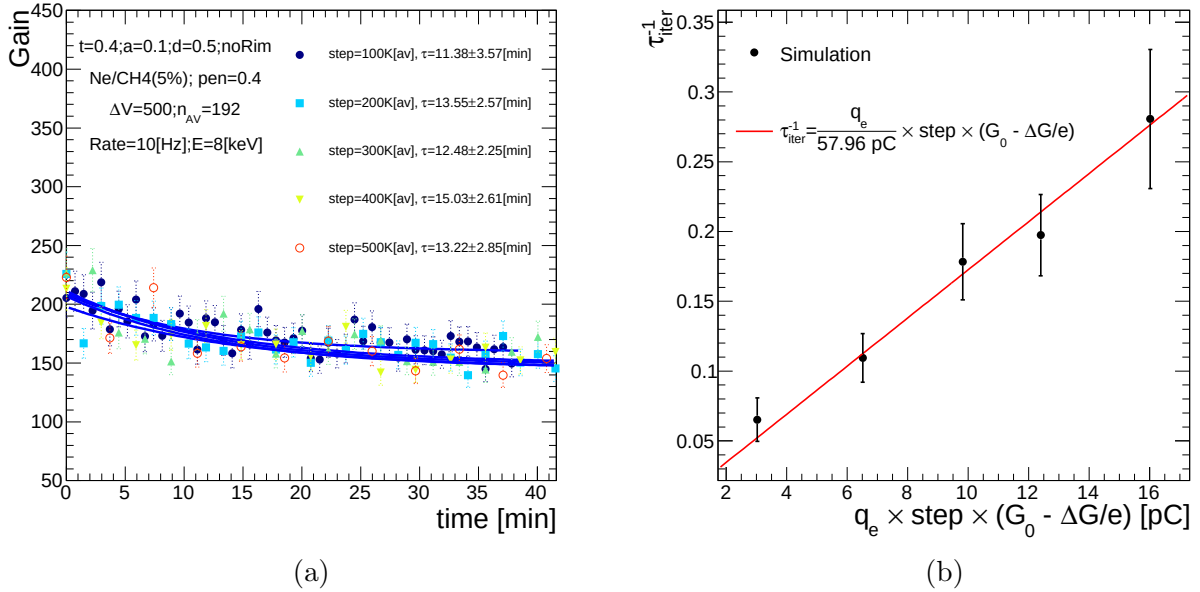


Figure 1.3.3: (a) Simulated gain stabilization in the THGEM detector, calculated in the time domain, the solid blue lines are the fitted exponential curves (from Equation 1.3.3). (b) The linear relation between the characteristic times in iteration domain vs the step-size s .

1.4 Simulation results

1.4.1 Effect of the hole-rim on gain stabilization

Previous studies showed that etching a small area around the holes (a rim; typically 0.05 – 0.1mm) reduces the discharge probability [19]. Other works indicated that the presence of a rim affects gain stability [23]. Rims were included in the simulations by introducing two additional slices “*top rim*” and “*bottom rim*”, as shown in right hand side of figure 1.2.3. As discussed in section 1.2.1, in THGEM detectors, charges originating from the avalanche that are attached to the hole’s wall, reduce the electric field within the hole, resulting in a decrease of the gain over time. In contrary, charges that are attached to the rim surface, expect increase the electric field in the detector holes since they have opposite charge to the charges attached to the hole’s wall, resulting in an increase of the detector gain. To test the effect of the charging up along the hole’s insulator surface, only a single slice was allowed to charge up, while all others remained un-charged. After being fully charged (with no more electrons or ions attached to the given slice), the final gain was estimated. figure 1.4.1 shows the charge distribution on the insulating walls of a THGEM electrode geometry with a 0.1mm rim, after gain stabilization. The black points show the simulated gain after stabilization, while the blue lines show the total charge accumulated on the insulator surface. As it is seen in the simulation result, the upper part of the hole is positively charged (due to drifting ions from the avalanche process), and the lower half part of the hole is negatively charged (avalanche electrons). These electrons and positive ions reduce the total gain, by creating an electric field in an opposite direction to that of the initial one. This charge distribution is that within the hole’s walls of an electrode without a rim.

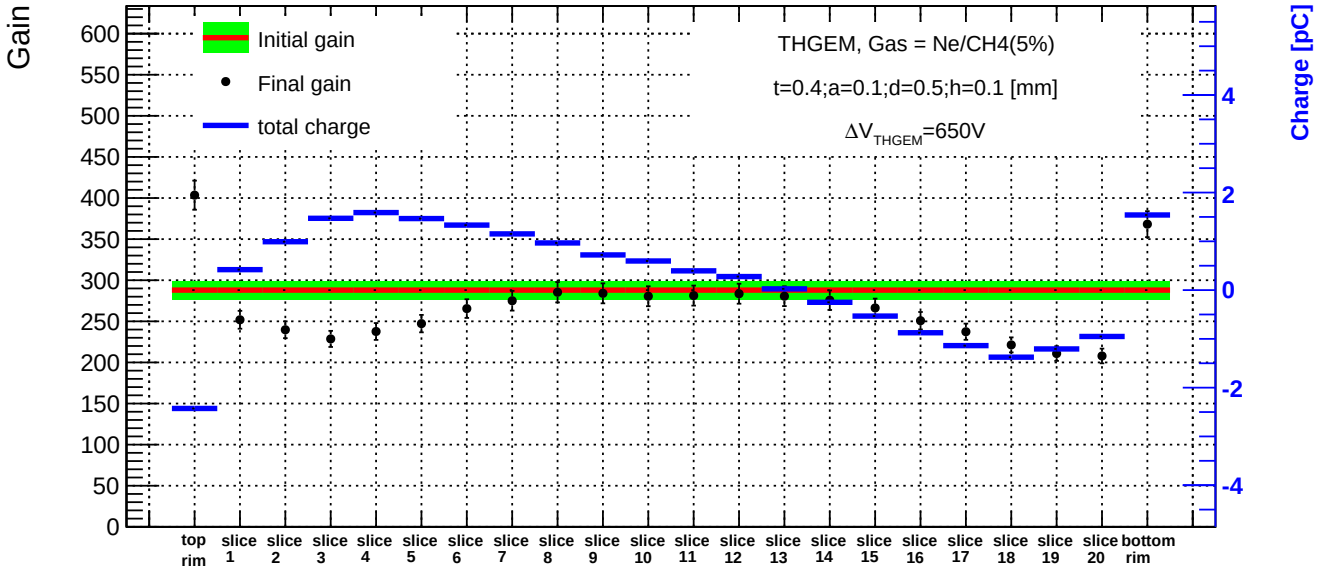


Figure 1.4.1: Simulated effect on the gain, resulting from each slice (THGEM with hole-rims; figure 1.2.3), and the distribution of accumulated charge along the detector hole. Shown are the initial detector gain (green band), the gain per slice when only one slice is charged-up (black) and the total charge accumulated on a single slice when detector gain reached stability (blue).

In the contrary to the effect of the attached charges inside detector’s holes, the charges that accumulate on the detector rim have an opposite effect on the detector gain. The “*bottom rim*” is charged positively; drifting ions created in an avalanche close to the bottom rim have a non-zero probability to deviate from the field lines that are focusing them into the holes, and positively charge the rim. The “*top rim*” is charged negatively due to primary charges that were not focused to the

detector holes. The characteristic charging-up time of the top rim is therefore proportional to the initial number of charges (number of primary electrons induced by incoming ionizing event), while the characteristic charging-up time for the holes and the bottom rim is proportional to the final number of charges created during the multiplication process. figure 1.4.2 shows the simulation results in pure Ne, for a THGEM with a rim of 0.1mm, for three cases Left: charges are not allowed to accumulate on the top and bottom rims, Middle: charges are not allowed to accumulate on the top rim, Right: charges are accumulated on all slices. Since the effective time to charge up the bottom electrode, is similar to that for charging up the detector hole walls, the result of adding a bottom rim is a smaller gain drop. Charging up also the top rim results in a long-term gain variation, since the difference between short-term and long-term variations are proportional to the total gain, and the electron transfer efficiency (ETE).

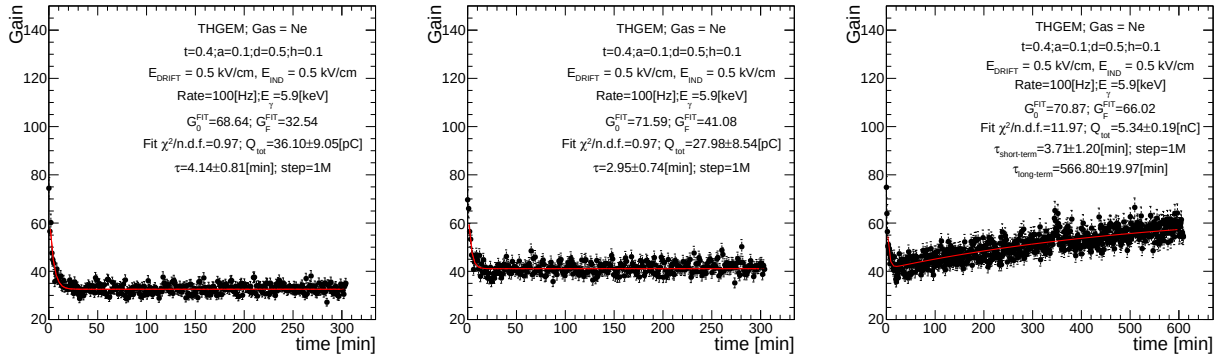


Figure 1.4.2: Simulated gain stability (in Ne) for an electrode with a rim of 0.1 mm, for three different cases – Left: none of the rims was charged up. Middle: top rim was not charged up. Right: all slices were charged up. The red lines are fit results of the simulation to an exponential function (equation 1.3.3), for long-term component a double-exponential function is fitted (equation 1.3.5).

1.4.2 Voltage effect on gain stabilization

Simulations were performed at different THGEM operation voltages, in the range $\Delta V_{\text{THGEM}} = 500 - 1100 \text{ V}$, aiming at investigating their influence on gain evolution. To compare the gain evolution for a broader range of ΔV_{THGEM} values, the simulation was performed for different gas mixtures (with the highest operation voltages in Ar mixtures).

In figure 1.4.3, the calculated Q_{tot} value (obtained from Equation 1.3.7) increases with voltage, indicating that the higher the voltage, the higher the irradiation rate (or time) is needed to reach gain stabilization.

1.4.3 Electrode-thickness effect on the gain stabilization

Gain stabilization was simulated for THGEM electrodes of different thickness, in Ne/CH₄(5%) and Ar/CO₂(5%) (Ar-based mixtures have about two-fold higher operational voltages, and lower transverse electron diffusion for electric fields below 10 kV cm^{-1} [35]). The Q_{tot} value calculated from the charging-up of THGEM hole walls and the fraction of the avalanche charges attached to the THGEM walls for an uncharged electrode are shown in Table 1.1.

An increase of the Q_{tot} is observed with the decrease of the electrode thickness; it is found to be more pronounced than the dependence on the THGEM voltages or electron transport parameters, e.g. for thicker structures, and higher applied voltages, a lower total-charge value would be needed for modifying the gain. For thicker electrodes, the fraction of accumulated charges on the THGEM holes is larger, due to a broader transverse expansion of the avalanche.

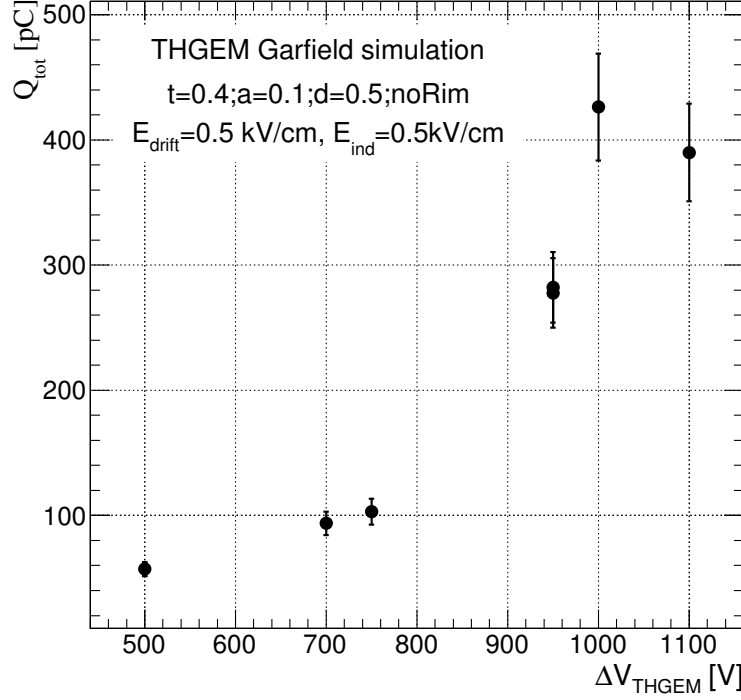


Figure 1.4.3: Simulated Q_{tot} for different applied voltages across the THGEM. The Q_{tot} is calculated according to Equation 1.3.7. The error bars indicate the spread of calculated Q_{tot} values among few tens of simulations with varying step-size s .

Gas	Thickness	ΔV_{THGEM}	G_0	$Q_{\text{tot}} [\text{pC}]$	Fraction [%]
Ne/CH ₄ (5%)	0.4	450	80	48.11	23.4±1.8
Ne/CH ₄ (5%)	0.4	500	220	57.14	23.1±1.8
Ne/CH ₄ (5%)	0.8	600	110	34.25	31.9±0.8
Ne/CH ₄ (5%)	1.2	750	130	30.43	38.0±0.7
Ar/CO ₂ (5%)	0.4	950	120	277.75	18.3±0.3
Ar/CO ₂ (5%)	0.8	1300	130	130.61	22.9±1.4

Table 1.1: The simulated Q_{tot} for different electrode thickness and operation voltages and the fraction (in %) of the avalanche charge for uncharged THGEM electrode that accumulates on the THGEM-hole walls.

1.5 Experimental studies

1.5.1 Introduction

The phenomenological model of the charging-up process in THGEM-like detectors reveals several features related to short-term and long-term gain stability; it explains its dependence on detector geometry, and applied voltages. To verify this phenomenological model in various aspects, an experimental study was carried out in different THGEM geometries and gases. The following sections describe the methodological approach for systematic studies of the charging-up process in THGEM-based detectors; it examines the different consequences of detector's operation parameters and geometries on the charging up of the detector electrodes in various aspects. In section 1.5.2, we introduce a systematic method of detector initialization, in section 1.5.3 we discuss the gain of

the THGEM-based electrodes in various gas mixtures and geometries, section 1.5.4 describes the measurements and characterization of the charging-up process. In section 1.5.5, we show gain stabilization as function of gain and irradiation rates. In section 1.5.6, we discuss the effect of the hole-rim on detector gain stabilization, under different operational conditions, such as induction- or drift-field strength.

1.5.2 Experimental setup and methodology

1.5.2.1 Experimental setup

Small (30 mm × 30 mm) 0.4 mm thick FR4 THGEM electrodes, copper clad on both sides, were used in this work. The electrode holes of 0.5 mm diameter, were arranged in an hexagonal lattice with a pitch of 1 mm. The operation with dual-face THGEM electrodes with holes having 0.1 mm wide etched rims was compared with that of holes without rim. An induction gap of 2 mm was maintained between the bottom THGEM electrode and the readout anode (figure 1.1.1). A drift gap of 5 mm was maintained between the top electrode and the cathode. The investigated detectors were placed in a small aluminum vessel. They were flushed with gas at a constant flow of 20 sccm. The detector's design that was used in this study is shown in figure 1.5.1. Noble gases (Ar, Ne) were used in most

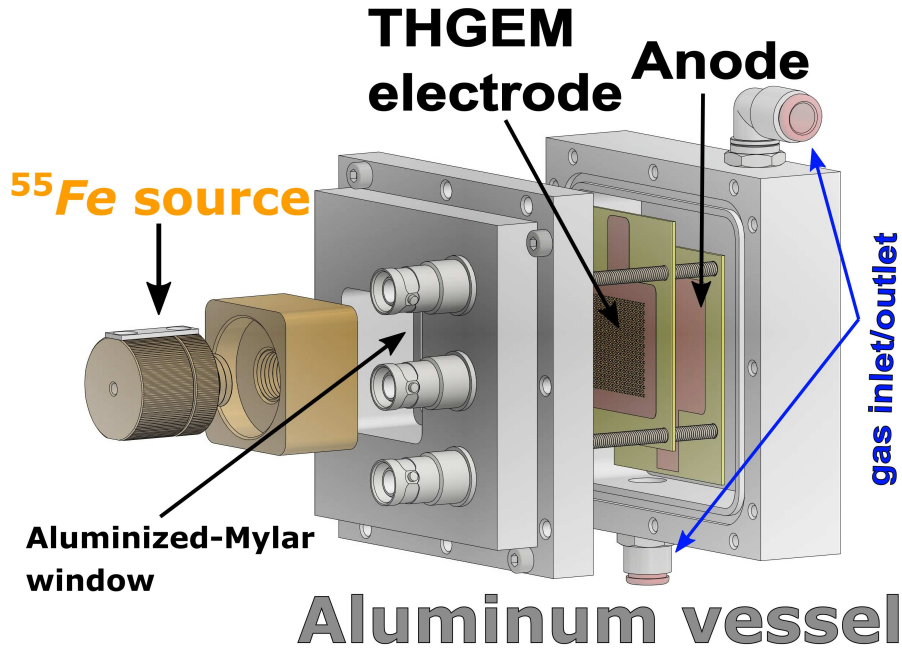


Figure 1.5.1: A design of the detector: THGEM electrode and anode are placed in small aluminum vessel. The gap between the aluminized-Mylar window and the THGEM electrode serves as a drift gap, and the gap between the THGEM-electrode and the anode serves as an induction gap. The ^{55}Fe source is placed on top of the window.

of the measurements, since they are not electro-negative; electro-negative gas mixtures can partially attach charges accumulating on the THGEM insulating surfaces, introducing additional dependency of the gain-stabilization process. The detectors were irradiated through a 20 μm thick aluminized Mylar window, with 5.9 keV photons emitted from ^{55}Fe source. The detector electrodes (except the grounded drift cathode) were positively biased through low-pass filters, using CAEN N471A power supply units. The signals were recorded from the anode using an amplification chain comprising a Canberra2006 charge-sensitive preamplifier, Ortec572A linear amplifier and an Ampek 8000a Multi-Channel Analyzer (MCA). The amplification chain was calibrated prior to each measurement using a pulse generator through the preamplifier test input.

1.5.2.2 Detector initialization

As described in [24], measurements of charging up effects are strongly affected by the charge history of the electrode. Thus, the electrodes must undergo an initialization procedure prior to each measurement. To clean up the electrode's history (i.e. to remove all previously-accumulated charges from the insulator), two approaches have been tested: rinsing with solvents, or flushing for ~ 1 minute with a jet of ionized nitrogen. Solvent-based cleaning was done by immersing the electrode in the solvent for ~ 1 minute and drying it at 100°C for ~ 30 min. Ionized-nitrogen jet cleaning was performed with an anti-static gun (Electrostatics Inc. model 190M). Results using these approaches are shown in figure 1.5.2, compared with that of a new electrode with no previous history. In addition, the gain

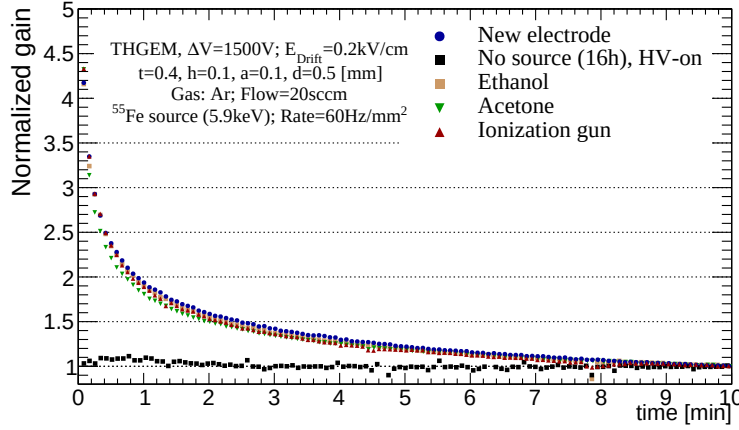


Figure 1.5.2: Measured relative gain variation in Ar due to charging up of a new THGEM electrode, electrodes cleaned by different solvents or by ionized nitrogen; data are compared to an electrode having previous history, 16 h after gain stabilization, with no irradiation but under applied voltage. The gain in each experiment was normalized to its value after 10 minutes of irradiation.

stabilization was measured for an electrode that was irradiated until the gain was stabilized, followed by switching off the source for 16 h while keeping the High-Voltage on; the gain was observed to remain constant, indicating that the accumulated charge remained on the insulator surfaces even under applied voltage. The measurements were performed in Ar, to ensure no charge losses from detector's insulator by electro-negative gas molecules, and to avoid possible neutralization of the charged electrodes by the gas molecules.

It was found that by rinsing with solvents or flushing with ionized nitrogen, the electrode was fully initialized, cleaned from all previously-attached charges. It should be noted though, that cleaning the electrode with solvents leaves some residuals (mostly moisture), causing spontaneous discharges during the first few hours of operation.

1.5.3 Gain measurements

Gain measurements were performed in a THGEM configuration of figure 1.1.1. The detectors were operated at one bar, at room temperature, with a nominal flow of 20 sccm. They were irradiated, with ^{55}Fe 5.9 keV X-rays at a rate of 60 Hz mm^{-2} , through a 5 mm in diameter aperture. The gain curves shown in figure 1.5.3 ended at voltage values where a discharge occurred within the first five minutes of measurement. The detector was irradiated until reaching gain stabilization. At the highest achievable gain, when a first discharge occurs after a few minutes of irradiation, highly conductive plasma within the electrode hole absorbs some of the attached charges to the electrode-hole walls; such discharges, causing gain increase, should be avoided. The different gases permitted investigating the detector operation over a broad voltage range. It was observed, that above the highest achievable gain, an

eventual discharge causes the gain to increase. This observation can be explained by neutralization of accumulated charges by highly-conductive plasma within the electrode hole, that removes some of the attached charges to the electrode-hole walls. The effect of the discharge on the measured gain was not studied here. Therefore, to avoid potential discharge-induced effects, all measured gain values were recorded below the discharge limit. The different gases permitted investigating the detector operation over a broad voltage range. The lower gain for Ar, in figure 1.5.3, could result from photon-feedback limits and from instabilities at the higher applied voltage. The presence of the 0.1 mm rim permitted reaching slightly higher gain values in Ne/CH₄(5%), as reported in [19]; however, the presence of the rim requires higher detector voltages for an equal gain, due to a different field configuration within the hole. The presence of a quencher increased the maximum achievable gain due to suppression of UV-photon induced secondary avalanches (photon feedback).

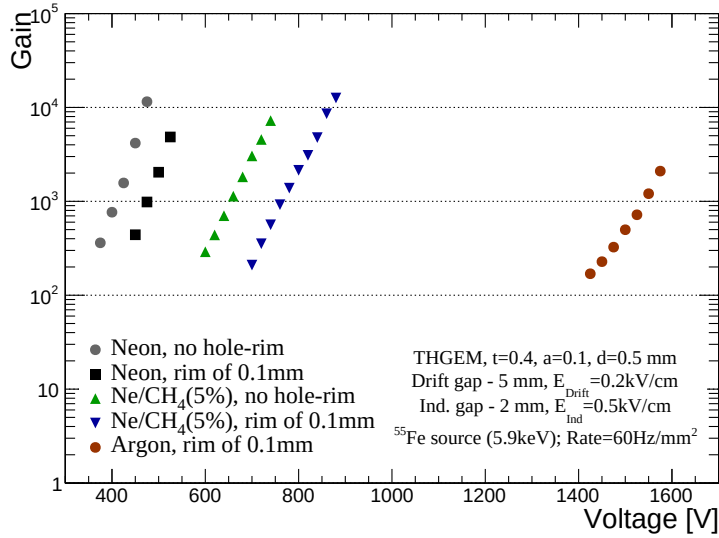


Figure 1.5.3: Measured gain curves in different gases, in the THGEM detector, with 5.9 keV X-rays, at a rate of 60 Hz mm⁻² over a 5 mm in diameter spot size.

1.5.4 Characterization of the charging-up process

In all measurements, the detector electrode was initialized as described in section 1.5.2, using the anti-static gun. The chamber was flushed for at least one hour with a flow of 20 sccm. The voltages were set an hour preceding irradiation, to ensure insulator is fully polarization. The gain variation over time was recorded with the MCA, in steps of 5 or 30 sec depending on the irradiation rates. At each step, the measured pulse-height spectra were fitted to a Gaussian and the mean value was recorded.

During the first minutes of irradiation, the detector gain dropped due to accumulation of charges on the surface of the insulator walls. The characteristic stabilization time (τ) is defined to be:

$$\tau = \tau_{0.5} / \log(2) \quad (1.5.1)$$

where $\tau_{0.5}$ is the time when the gain decreased to half of the total gain variation. Such definition is made in order to relate the measured characteristic time to the one extracted from the simulation.

1.5.4.1 Empirical fit model

The exponential curve described in section 1.3.2 (equation 1.3.3) is a first approximation for the selected parameters in the simulation (drift and induction field). The actual gain stabilization curve

is affected by the rate of the charge accumulation on the detector's walls, which might be different for different points along the hole's walls. As it will be shown later, drift and the induction fields affects detector's gain evolution. It was also observed that rates of accumulating charges on the surface of the hole's walls vary with the position of the charge accumulation (or slice in case of simulation), and the gain evolution in some cases might not match a single exponential function. It was observed, that in order to achieve a proper modeling of the short-term gain evolution the exponential curve must be extended. The short-term evolution of the measured gain over time was fitted to empirical fit function given by:

$$G_{\text{SHORT}}(t) = G_F + \Delta G_1 \exp(-t/\tau_1) + \Delta G_2 \exp(-t/\tau_2) \quad (1.5.2)$$

where G_F is the final gain, ΔG_i is a gain drop value for characteristic time of τ_i ($i = 1, 2$), and the initial gain being $G_0 = G_F + \Delta G_1 + \Delta G_2$ (i.e. the gain at $t = 0$). This function was found to better model the gain evolution than single exponential curve, or other empirical functions provided elsewhere [16, 17].

The long-term gain evolution as it discussed in section 1.4.1, is a result of charge accumulation on a detector's "top rim" (figure 1.2.1d), such process will typically have a single characteristic time, and it is expected to be fitted to exponential curve. The long-term evolution of the measured gain over time is fitted to an exponential function given by:

$$G_{\text{LONG}}(t) = \Delta G_{\text{UP}} \exp(-t/\tau_{\text{UP}}) \quad (1.5.3)$$

Therefore, when the long-term component is present, the gain evolution curve is fitted to a linear combination of short- and long-term components:

$$G(t) = G_{\text{SHORT}} + G_{\text{LONG}} \quad (1.5.4)$$

In both simulation and measurements, gain stabilization is characterized in terms of the total amount of charge (in units of q_e) passing through the THGEM holes during relaxation period:

$$Q_{\text{tot}} = q_e \times n_p \times R \int_0^{\tau} G(t) dt \quad (1.5.5)$$

1.5.5 Evolution of the gain stabilization over short-term periods

1.5.5.1 Comparison to simulation

A comparison of gain stabilization between the simulation outcome and the measured data was made for Ne/CH₄(5%). This mixture, of a known Penning transfer rate [31], permits good comparison with the simulation results for a short-term gain stabilization time. figure 1.5.4 shows a comparison between the simulated and measured gain evolution, over the first 8 minutes. In the measurements, the applied voltages were chosen such that the initial gain from simulation (G_0) will match the data within the 10%. The stabilization time in both, simulation (black squares) and the measured data (blue circles) was found to be similar within the first 2 minutes. The "characteristic charge" of the measured gain stabilization was calculated from the empirical fit and was found to be in a good agreement with the simulation result. To first approximation, the shape of the measured gain evolution with time was found to be consistent with simulations, and hence with the assumption that charging up of the THGEM hole dominates the gain-stabilization processes over this time. The difference in the shape between the data and the simulation results (different fit functions) could have several origins. In the measured data, some systematic variations in the experimental conditions may cause changes in the stabilization curve; different position of the x-ray spot over the area above the detector electrode, inhomogeneity in the electrode's geometry or small amounts of gas impurities can

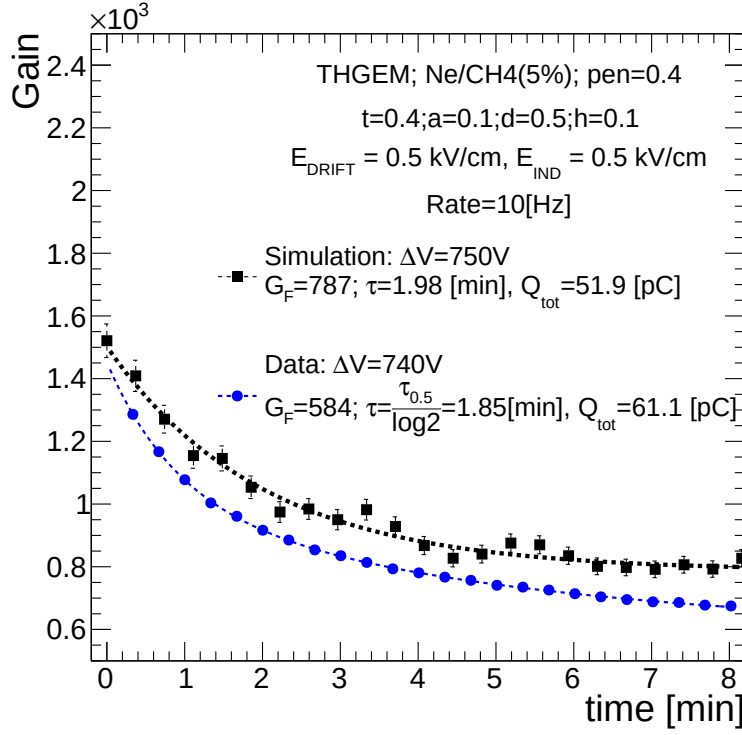


Figure 1.5.4: Gain evolution for an initial gain of ~ 1500 vs. time in a THGEM operated in Ne/CH4(5%). Simulation results (black) and measurements (blue). The measurements were performed for an electrode of clean history. The measured gain variation was fitted to an empirical function (equation 1.5.2), while the simulated one was fitted to a single-exponential function (equation 1.3.3). The parameters are shown in the figure.

also affect the gain stabilization. In the simulation, selected conditions as the number of slices or position of the initial charge deposition can also be a source of systematic variations of the results. In this work, we will examine qualitatively the charging up phenomena, pointing out at the major sources affecting the detector's stability.

1.5.5.2 Irradiation-rate effects

To validate the argument that the source of gain variations is due to charging up of the insulator, measurements were carried out at different rates. figure 1.5.5 shows gain variation over time for

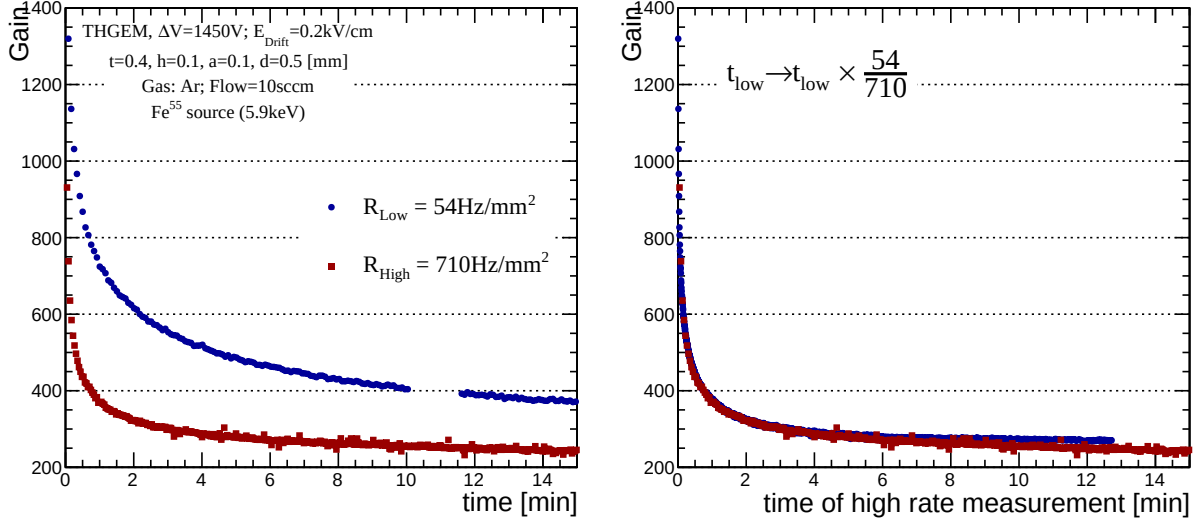


Figure 1.5.5: Measured gain stabilization (in Ar) for two different rates. In the left plot, gain stabilization is shown as a function of time, while in the right one, the time was scaled by the ratio of rates to compare the trends ($t \rightarrow t \times \frac{R_{low}}{R_{high}}$).

different rates, measured in Ar. In the left plot of figure 1.5.5 the gain stabilization is shown as a function of time. Since the stabilization time is expected to be linear with the inverse of the irradiation rate (see equation 1.3.2), when the rate increases by constant value X, the characteristic time should decrease by a factor of X. To show this effect for the two curves in the left plot of figure 1.5.5, the x-axis (time) for the low-rate gain stabilization measurement was scaled by the ratio between the different rates, i.e. instead of $G_{low-rate}(t)$ we show $G_{low-rate}(t \times \frac{R_{low}}{R_{high}})$, and the two stabilization curves are compared on the right plot of figure 1.5.5.

1.5.5.3 Charging up at different gains

The short-term stabilization time at different gas gains was simulated and compared to measurements. The characteristic charge - the total number of charges that pass through the THGEM holes until the gain stabilizes - is proportional to the detector's gain, irradiation rate and the relaxation time (1.5.5). At higher detector gain, the charge that flows through the THGEM holes is higher; thus, the gain stabilization time is expected to occur faster. According to this model, the characteristic time is proportional to the inverse function of detector's gain. Evolution of the detector's gain and the fitted characteristic time (τ) for different applied voltages across a $t = 0.8$ mm thick THGEM electrode, in Ne/CH₄(5%) gas mixture is shown in figure 1.5.6. From the fitted characteristic time and the initial gain, using equation 1.3.6, one can obtain the Q_{tot} . figure 1.5.6 also shows linear relation between the inverse of the characteristic time and the product of irradiation rate and the gain. The difference in the applied voltages on the detector electrodes has negligible effect on the fitted Q_{tot} value.

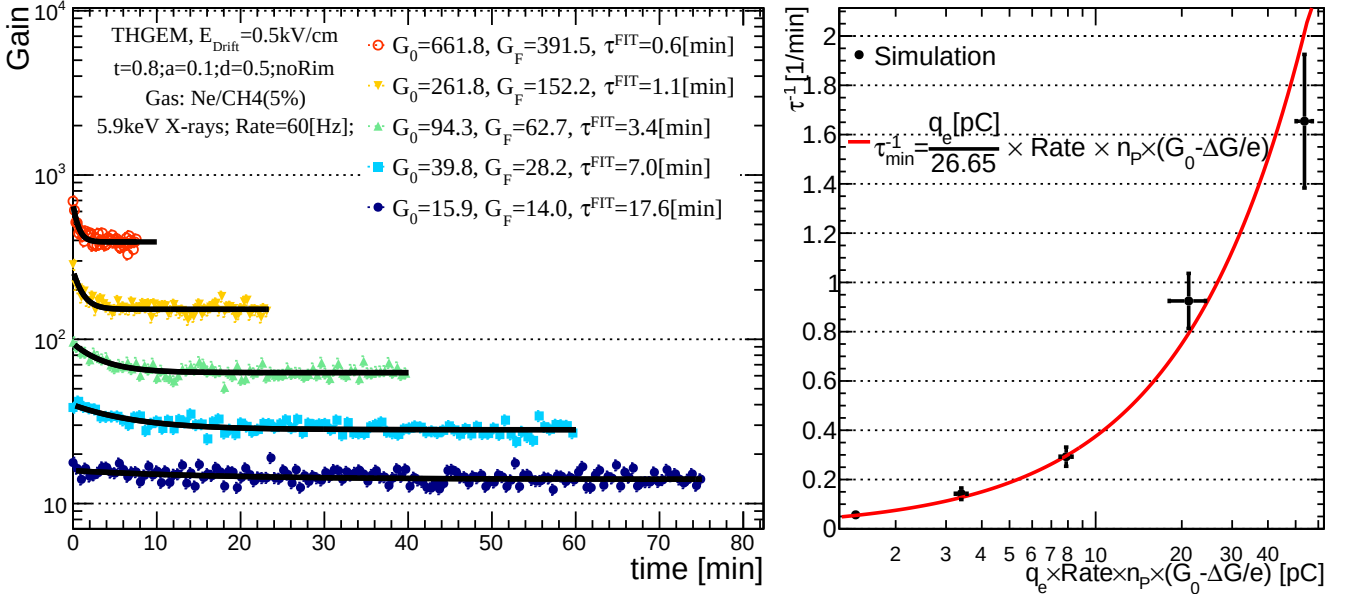


Figure 1.5.6: Left: Simulated gain stabilization for different initial voltages (initial gains) as a function of time. The gain evolution is fitted by an exponential function; the fitted “characteristic time” values are shown in the legend. Right: Linear dependence (linear fit) of the inverse of the characteristic time as a function of the product of the gain and the irradiation rate.

The stabilization time at different gains was measured in pure Ar (due to its larger “characteristic time” value than in Ne – see Table 1.1). The electrode was irradiated with 5.9 keV X-rays at a rate of 60 Hz mm⁻². Gain stabilization over time, for different gains, is shown in figure 1.5.7. The characteristic time shows linear dependence with the initial gain - as suggested by the simulations. In both simulation and the measurement, the characteristic time is proportional to the inverse of the detector’s gain. The “characteristic charge” estimated from the measured “characteristic time” vs the detector’s gain, is also found consistent with that simulated for Ar-based mixtures (of order of hundreds of pC, Table 1.1).

The linear dependence between the initial gain and the inverse of the characteristic time suggests a safe extrapolation of the results between low and high gains.

1.5.6 Long-term time evolution of the gain - the effect of hole rims

As mentioned in section 1.4.1, the presence of hole-rims introduced long-term gain-stabilization characteristic times, attributed to the long time scale of charging up the top rim with primary electrons. The effect of the rim was investigated (in Ne) with a THGEM electrode; the result of gain stabilization over time is shown in figure 1.5.8. The gain variation over time, in case of an electrode with a hole-rim, was fitted to a triple-exponential curve (equation 1.5.4).

In the THGEM configuration without hole-rim, the gain monotonically decreases with time, until it reaches a stable value after about few ten of minutes. In the THGEM configuration with a hole-rim, we observe two characteristic timescales: a short one (minutes) and a long one (about few hours). The short timescale is related to a decrease of the detector’s gain; the total gain drop measured for an electrode with a hole-rim is considerably smaller than without a hole-rim, since an additional charging-up of the bottom rim increases the gain. The rate of the charging-up of the bottom-rim and the THGEM holes is proportional to detector’s gain. With an induction field of 0.5 kV cm⁻¹, the rate of charging-up of the bottom rim is lower compared to the charge accumulation rate on the electrode’s walls; therefore the sum of both components results in a decrease of a gain on the short timescale.

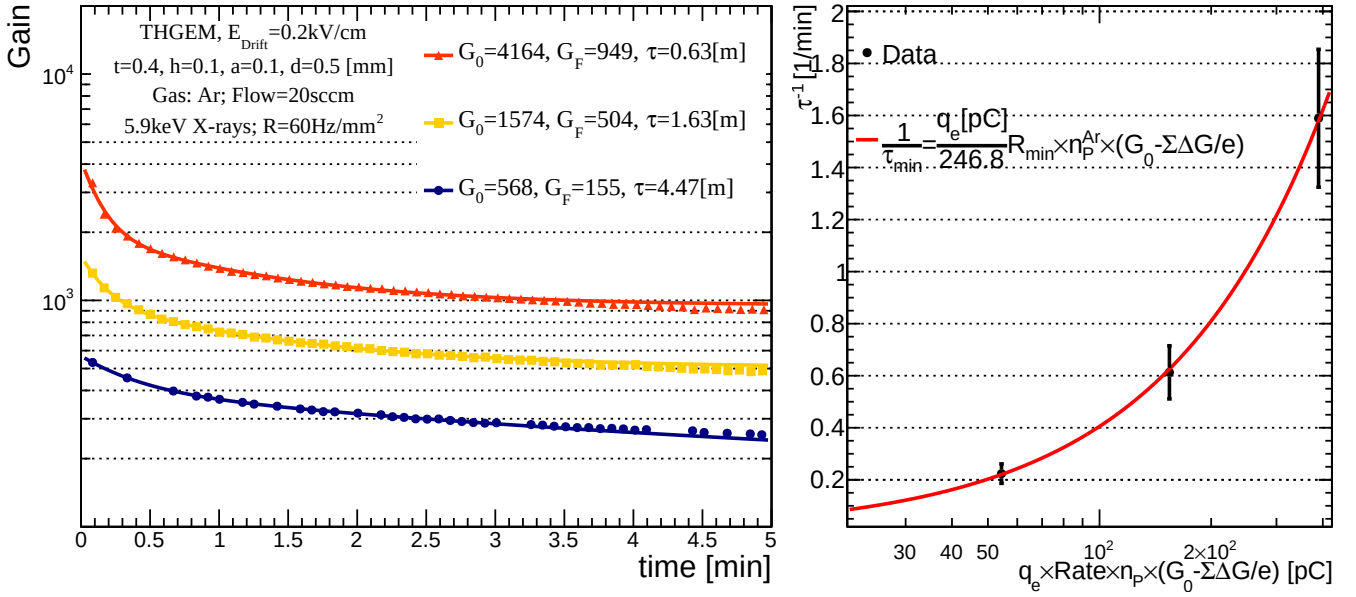


Figure 1.5.7: Left: Measured gain stabilization (in Ar) over the first 5 min, for different gain values. The characteristic time derived from the plots is defined to be the time where $G(\tau) = (G_0 + G_F)/2$. Right: Linear fit of the inverse time with the product of the gain by the rate.

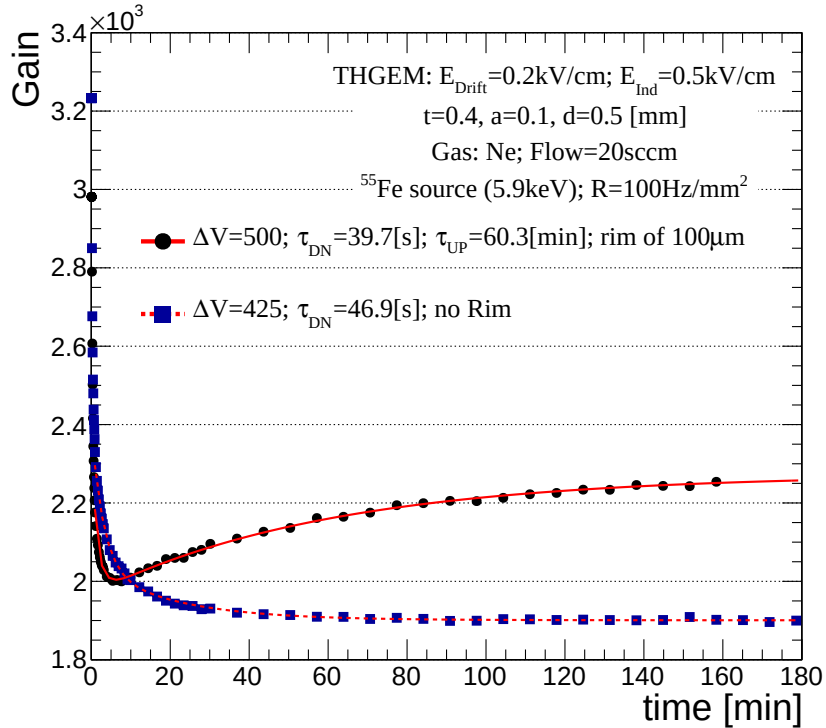


Figure 1.5.8: Measured gain stabilization over time in Ne, at an X-ray rate of 100 Hz mm^{-2} for an electrode with hole-rim (black) and without rim (blue). The red lines are fit results of the measurement to a triple-exponential function (equation 1.5.4) or double-exponential function (equation (1.5.2)) respectively.

While charging-up of the inner surface of the holes, and that of the bottom rim, is responsible for the short-term stabilization time, the top-rim charging up is associated with the long-term stabilization time. The difference between long and short timescales found to be consistent with the difference between long and short time-scales obtained in the simulations (figure 1.4.2). Further investigation of the ratio between the short and the long timescales will be discussed next.

1.5.6.1 Charging-up of the top-rim

The drift field permits drifting and focusing the primary electron cloud into the THGEM holes. With an increased drift field the electron transfer efficiency (ETE) of the primary electrons decreases. It is a known fact that at higher fields a growing fraction of the electrons are collected on the top THGEM electrode, rather than entering the holes [36]. The effective gain as a function of drift field is shown in figure 1.5.9

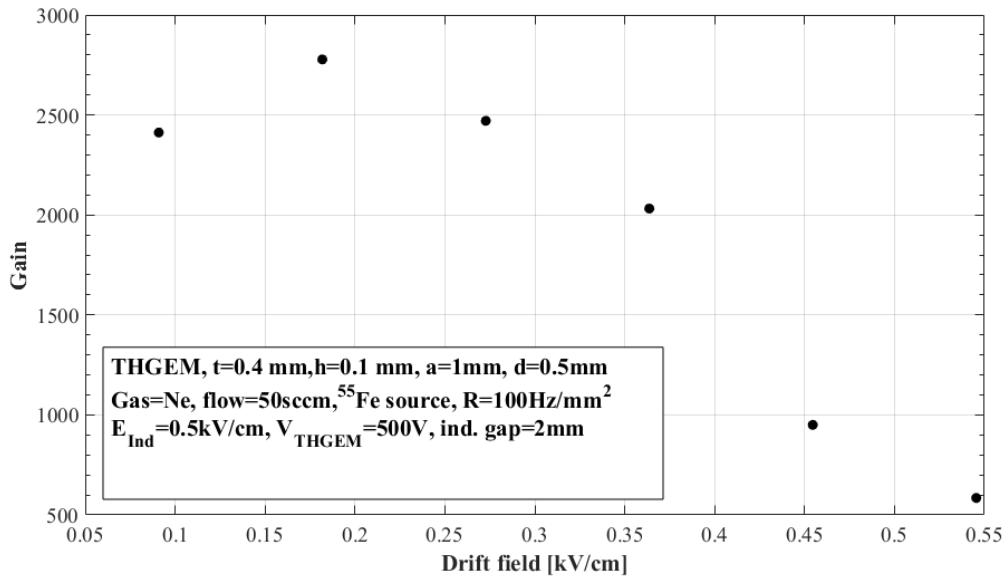


Figure 1.5.9: Measured effective THGEM (with hole rim) gain in Ne, as a function of a drift field. The signals were measured from the anode, under an induction field of 0.5 kV cm^{-1} .

The maximum effective gain in Ne was achieved at drift fields of $\sim 0.2 \text{ kV cm}^{-1}$, under a drift field of 0.35 kV cm^{-1} , the pulse-height being affected the strongly decreasing *ETE*, thus a fraction of the primary charge that is not focused into THGEM holes is collected on the top electrode or accumulated on the top-rim. figure 1.5.10 depicts the long-term gain stabilization at drift fields of 0.2 kV cm^{-1} and 0.35 kV cm^{-1} . While the effective gain of the multiplier is a product of ETE and the detector's gain ($G_{\text{eff}} = G \times (\text{ETE})$), the ratio of the long- to short-term stabilization time is proportional to:

$$\frac{\tau_{\text{UP}}}{\tau_{\text{DN}}} \propto \frac{G \times \text{ETE}}{(1 - \text{ETE})} \quad (1.5.6)$$

For higher drift-field values, two parameters are changing: the detector gain increases, and the ETE decreases. The effective gain is usually a product of the detector's gain and ETE, so the decrease of the effective gain between 0.2 and 0.35 kV cm^{-1} of 25% (figure 1.5.9) will result in higher increase of the ratio between long-term and short-term characteristic time scales as it shown in figure 1.5.10. However, the loss of primary electrons due to reduced ETE will affect the energy resolution. According to the simulation results (figure 1.4.1) a few pC of charge are needed to charge up completely the “top rim”, then the long-term stabilization time will be given by:

$$P \times n_p \times q_e \times R \times \tau_{\text{UP}} = Q_{\text{top-rim}} \quad (1.5.7)$$

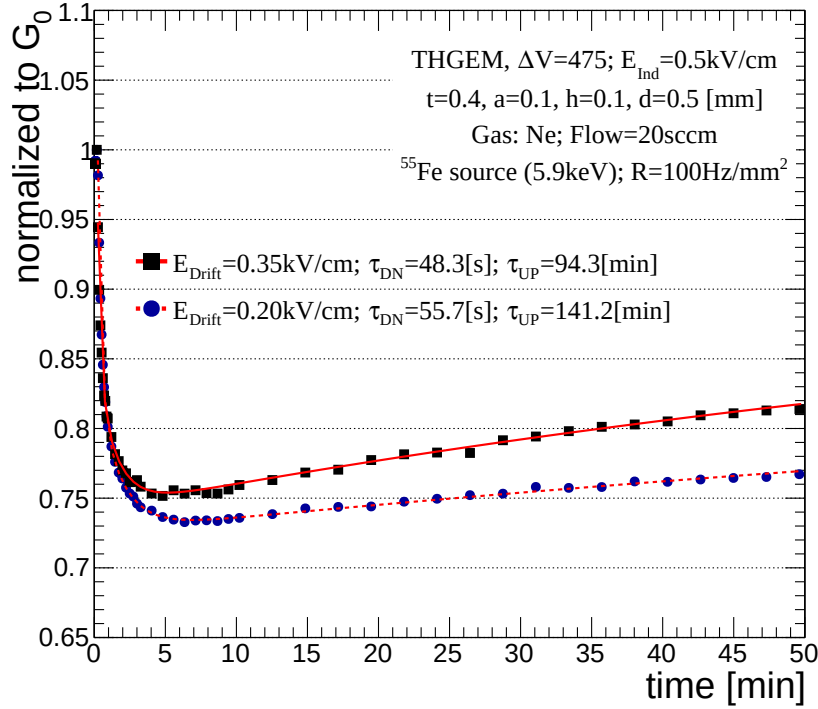


Figure 1.5.10: Measured gain stabilization over time in Ne, at an X-ray rate of 100 Hz mm^{-2} for $E_{\text{Drift}}=0.35 \text{ kV cm}^{-1}$ (blue) and $E_{\text{Drift}}=0.2 \text{ kV cm}^{-1}$ (black). The red lines are fit results of the measurement to a triple-exponential function (1.5.4).

Where P is the probability of the primary electron to end up on the “*top rim*”, and the $Q_{\text{top-rim}}$ is the total charge accumulated on the top-rim (usually of few pC).

1.5.6.2 Charging-up of the bottom-rim

The charging-up rate of the “*bottom rim*” is similar to that of the THGEM holes; therefore, the gain increase induced by the charged “*bottom rim*” is suppressed by its decrease due to charging up of the THGEM-hole walls. The typical value of the induction field, 1 kV cm^{-1} , assures large fraction of the induced signal to be recorded by the detector’s anode (up to 100%). A reverse or a small induction field draws avalanche electrons to the bottom-THGEM face. At the vicinity of the detector’s “*bottom rim*”, the electric field causes additional multiplication of the avalanche electrons; therefore, a fraction of the generated avalanche ions is usually attached to the “*bottom rim*”.

The detector gain, derived from signals measured from the top electrode and the anode, for varying induction-field values and the ratio between the signals are shown in figure 1.5.11. Ratio values above one are a result of small charge multiplication in the induction field and the collection of part of the ions on the bottom electrode.

Gain stabilization was measured for a reverse induction field, where all the avalanche electrons are collected at the bottom-THGEM electrode, compared to one with $E_{\text{IND}}=1 \text{ kV cm}^{-1}$, where most of the avalanche electrons are drawn towards the anode, as shown in figure 1.5.12.

With reversed induction field, avalanche electrons that undergo additional multiplication at the vicinity of the “*bottom rim*” increase the rate of the bottom-rim charging up (compared to that of THGEM holes). In this case, the timescale of charging up of the “*bottom rim*” is higher, which result in an initial increase of the gain. The “*bottom rim*” is fully charged, while the detector’s walls continue to charge up, and after initial increase of the gain, the gain drop in the timescale of several minutes. As one can note the stable-gain value is higher for the induction field of 1 kV cm^{-1} . At

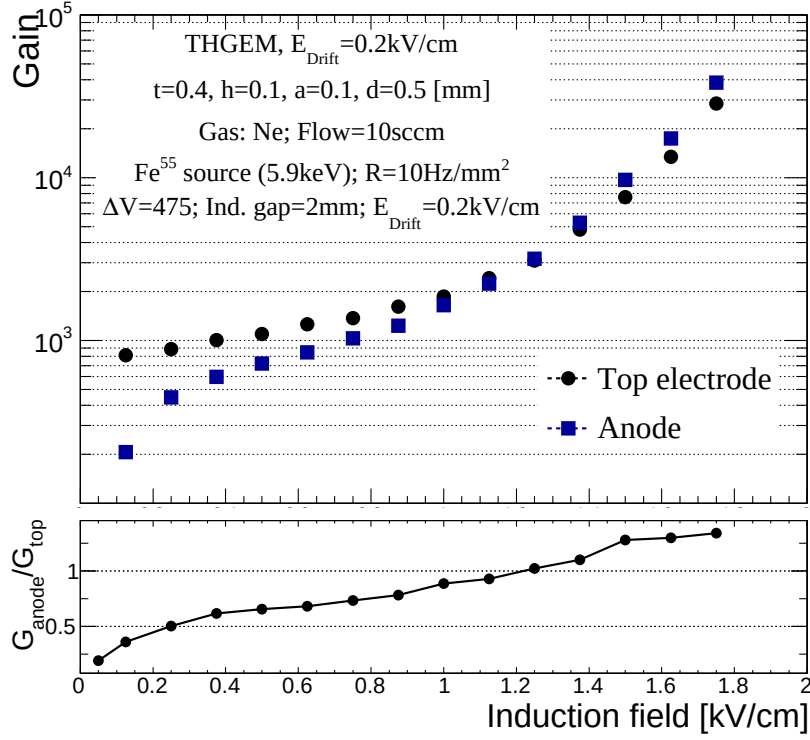


Figure 1.5.11: Detector gain, resulting of signal measured from the top THGEM-electrode and from the anode, vs induction-field values. The bottom plot is the ratio between measured anode gain to the measured top gain.

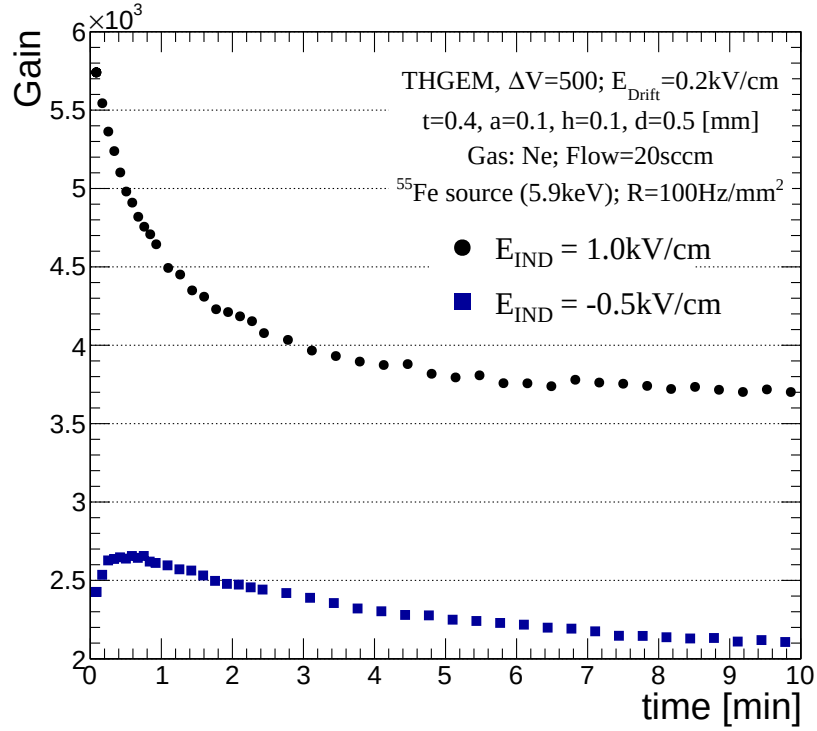


Figure 1.5.12: Measured THGEM gain stabilization over time in Ne, at an X-ray rate of 100 Hz mm^{-2} for $E_{\text{IND}}=1 \text{ kV cm}^{-1}$ (black) and reverse induction field $E_{\text{IND}}=-0.5 \text{ kV cm}^{-1}$ (blue).

high induction (or transfer) fields, the strength of the electric field just outside the hole is higher; this results in an increase of the detector gain, due to additional small charge multiplication in the induction gap [37].

1.6 Summary

The results of a systematic study that explored the effect of charging up in THGEM-based detectors are presented. A simulation package has been adapted for modeling gain stabilization in THGEM-based detectors, and a phenomenological study conducted to characterize this phenomenon in various aspects. Simulations reveal that the hole-rim introduces an additional long-term gain stabilization characteristic time compared to the relatively short one in the absence of the hole-rim in the THGEM electrodes. The short-term gain stabilization typically occurs in few- to few-tens of minutes depending on several parameters of the THGEM-electrodes. Higher voltages applied across the THGEM-electrode require a larger amount of change to modify the electric field within detector holes, resulting in longer gain-stabilization characteristic times. On the other hand, in thicker electrodes, the avalanche is broader due to the expansion of the avalanche-electrons inside the holes, and the charging-up of the electrode's insulating surface occurs faster. Most of the simulation studies were carried at relatively low voltages (low gains). It was observed that the rate of the charge accumulation is somehow linear with the detector's gain (up to small dependence on the operational voltages). Therefore, the conclusions derived at low gains can be extended to a wider range of detector gains.

Gain stabilization processes of THGEM-based detectors were measured following the methodology developed in [24]. The measurement results were systematically compared to the simulated ones, based on the model suggested in [1]. This model attributes the gain variations to the charging up of the detector's insulator substrate at the initial operation period.

While modeling the charging-up process using a single-exponential function could fit the simulation results, the experimental data were better fitted to a double-exponential model (figure 1.5.4). The difference in the shape of the respective graphs in figure 1.5.4 could have originated from experimental conditions, electrode's inhomogeneity or small amounts of gas impurities – all capable of affecting the gain stabilization [21, 24]. It was found that charging-up processes can be quantitatively modeled through basic parameters such as “characteristic time” – the time it takes the gain to reach half of its total variation, or “characteristic charge” – the total amount of charge passing through the THGEM holes during the relaxation period (1.5.5). The later could also indicate the rate of stabilization.

We found a linear dependence between gain-stabilization time and irradiation rate, supporting the argument that the main mechanism affecting THGEM-based detector's gain evolution is the charging-up of the insulator surfaces. We also show that detector stabilization time depends linearly on the inverse of the detector's gain.

The effect of the hole-rim on the detector's gain stabilization was systematically investigated; it was found that the “*top rim*” introduces a long-term gain-stabilization time, typically two-fold different compared to the short one. Both simulation and experimental data indicate that the long-term stabilization time can be order of magnitude larger than the short-term one. For detector's electrodes having hole-rims, a short-term stabilization time appears as an initial gain decrease, while the long-term one is reflected by a slow increase in the detector's gain. It has also been shown that the rate of charging-up of the “*top rim*” depends on the focusing of the primary-electrons cloud into the THGEM's holes, and it can vary by an order of magnitude in time at a measured rate of 100 Hz mm^{-2} . The charging-up of the “*bottom rim*” reduces the total gain drop due to an accumulation of avalanche-ions on the “*bottom rim*” surface. In figure 1.4.2, simulated results show an exponential decrease in both cases: when the “*bottom rim*” is charged-up and when the charges are not allowed to accumulate on the “*bottom rim*” surface. The simulations suggest that the charging-up of the “*bottom rim*” increases the gain, as confirmed by the measurements with

reversed induction field. Once reversed, the charging-up rate of the “*bottom rim*” became higher than that of the hole’s walls, resulting in an initial gain increase (figure 1.5.12). The measurements show that the charging-up transients relate only to initial detector’s operation period, and were not observed during long-term operation.

Part II

ATLAS detector performance studies

CHAPTER 2

The ATLAS detector

This chapter is a short description of the ATLAS detector. It does not contain original work, yet, needed to supplement the original work described in chapters 3, 5 and 7.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [38] is the world's highest energy accelerator, used for Particle Physics research. LHC sits in a circular tunnel spanning 27 km at the CERN¹ near Geneva. The tunnel is buried 50 to 175 m underground, and straddles the Swiss and French borders on the outskirts of Geneva.

The concept of the LHC has been discussed since the beginning of the 1980s [39], yet only in March 2010 did the LHC finally accelerate the protons to 3.5 TeV energy, initiating collisions at $\sqrt{s} = 7$ TeV.

To keep the proton beam in a circular trajectory, the beams are confined using strong superconducting magnets producing magnetic fields of 8.3 Tesla. The protons are extracted from hydrogen gas and first accelerated up to 50 MeV in a linear accelerator LINAC2. Protons are transferred to the Proton Synchrotron Booster (PSB), where they are separated into bunches by the radio frequency cavities which accelerate them to 1.4 GeV. The protons from the Booster enter into the Proton Synchrotron (PS). Here they are accelerated to 25 GeV before passing into the Super Proton Synchrotron (SPS), which accelerates the proton beams to up to 450 GeV. The final acceleration is done by injecting them to the LHC ring, where they reach the energy up to 6.5 TeV per beam

LHC was designed to provide proton beams of 1.15×10^{11} protons per bunch, with 2808 bunches and bunch spacing of 25 ns producing instantaneous luminosity² of $\mathcal{L} = 1 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ which is 25 times more than the maximal intensity delivered by the Tevatron. LHC run parameters during

¹European Organization for Nuclear Research: www.cern.ch

²*Luminosity*: is proportionality factor which is relate the differential rate to differential cross section: $\frac{dR}{d\Omega} = \mathcal{L} \frac{d\sigma}{d\Omega}$

2011-2017 operation period are shown in Table 2.1. The work is based on the data recorded during the 2012, and the 2015-2016 data taking periods.

Table 2.1: LHC proton running conditions for 2011-2017 operation period.

	protons/bunch [$\times 10^{11}$]	number of bunches (max)	bunch spacing [ns]	peak luminosity [Hz/nb]	Delivered integrated luminosity [fb^{-1}]
2011	1.3	1380	50	3.5	5.5
2012	1.7	1380	50	7.7	22.8
2015	1.1	2244	25	5.1	4.2
2016	1.1	2220	25	15.3	41
2017	1.15	2556	25	20.6	50.4

The delivered data (or total integrated luminosity) is expressed in units of inverse cross section, so the total number of events can be calculated from:

$$N_{events} = \sigma \times \mathcal{L} \quad (2.1.1)$$

where σ is the process cross section, $\mathcal{L}$ is the integrated luminosity defined by $\mathcal{L} = \int \mathcal{L} dt$. The amount of data as a function of time is shown in figure 2.1.1. The LHC is designed with four separate

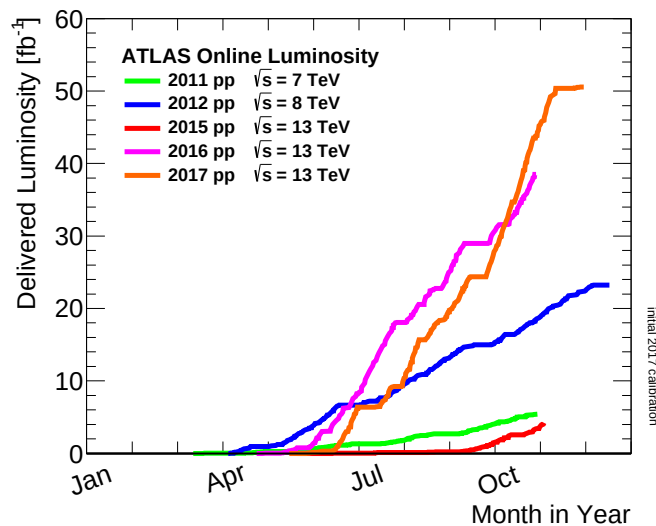


Figure 2.1.1: LHC delivered Luminosity during stable beams for 2011-2017, for high energy p-p collisions.

collision points for the four detectors built at these points. One of these detectors is A Toroidal LHC ApparatuS, or ATLAS.

2.2 ATLAS detector

The ATLAS (A Toroidal LHC ApparatuS) detector [40] is a multi-purpose particle physics detector, designed to detect particles and measure their properties. A sketch of the detector is shown in Figure 2.2.1, where one can see its main parts.

The main parts of the detector are the Inner detector, which is designed to measure tracks of charged particles; The Electromagnetic calorimeter (ECAL) which is responsible for measuring the energy of electrons and photons whereas hadrons deposit most of their energy in the Hadronic calorimeter (HCAL); and the Muon spectrometer (MS) which designed to measure the momenta of muons with high precision.

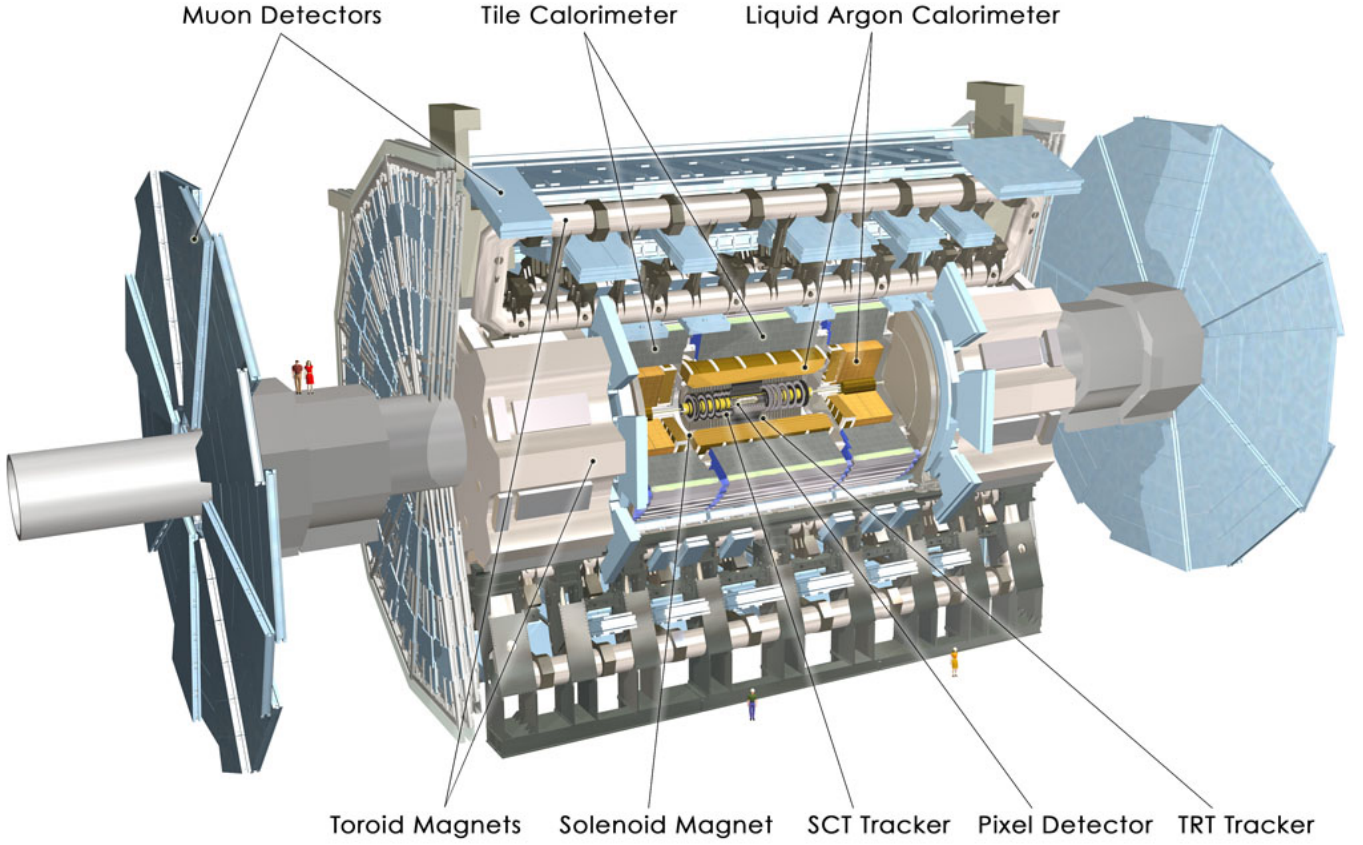


Figure 2.2.1: The ATLAS detector [40]. The dimensions of the detector are 25 m in height and 46 m in length. The overall weight of the detector is approximately 7000 tonnes.

2.2.1 The Inner detector

The cylindrical inner detector, which has a length of 7 m and a diameter of 2.3 m is the innermost part of the ATLAS detector, covering pseudorapidity³ up to $|\eta| \leq 2.5$. The entire tracker is contained within a 2T solenoidal magnet. Since the magnetic field is directed along the beam axis, the paths of charged particle bend according to their transverse momentum. It is able to reconstruct tracks of above a p_T threshold of 100 MeV. The Inner detector consist of three independent and complementary subsystems. These are, from the innermost layer out:

- The pixel detector - a high granularity silicon detector. Initially, the pixel detector was consisting of three layers in the barrel region and 5 disks in both end-cap regions. The detector part closest to the interaction point was the B-layer at a radius of 5.5cm. In May 2014 the fourth layer of pixel detector, the Insertable B-layer (IBL) was successfully installed at a radius of ≈ 3.5 cm. Precise measurements of the tracks at this region allows for the measurement of impact parameters, and therefore for the reconstruction of secondary vertices.
- The semiconductor tracker (SCT) - a precision silicon microstrip detector. Although the SCT has the same underlying technology as the pixel detector, it is designed to be optimized to the decreased track density at larger radii.
- Transition radiation tracker (TRT) - The TRT is a drift tube system was initially designed to be filled with a Xenon-based gas mixture of 70% Xe, 27% CO₂ and 3% O₂. During 2012,

³Pseudorapidity is a spatial coordinate describing the angle of a particle relative to the beam axis. It is defined as $\eta = -\ln \left[\tan \frac{\theta}{2} \right]$.

several leaks developed in the gas pipes. Due to a high cost of this gas mixture, straws belonging to affected modules with massive gas leaks were filled with an Argon-based gas mixture of 70% Ar, 27% CO₂ and 3% O₂. Transition radiation photons that are produced when ultra-relativistic charged particles cross a boundary between materials with different dielectric constants are absorbed by the Xenon or Argon gas and yield a typically larger signal than a charged particle. By supporting two different thresholds, the readout electronic can distinguish between both signals. Therefore, it contributes to the track reconstruction as well as to the electron identification. The TRT operation with either a xenon-based or an argon-based gas mixture was found to have similar tracking performance.

2.2.2 The Calorimeters

The calorimeters are designed to provide an accurate energy measurement of electrons, photons and jets (hadrons). There are two types of calorimeters:

- The Electromagnetic Calorimeter (ECAL) - an accordion-shaped sampling geometry with lead as an absorber and liquid argon as a sensitive component that is used to detect electromagnetically interacting particles with $|\eta| < 3.2$. It is divided into a barrel section, covering the pseudorapidity region $|\eta| < 1.475$, and two end-cap sections, covering the pseudorapidity regions $1.375 < |\eta| < 3.2$. The transition region between the barrel and the end-caps, $1.37 < |\eta| < 1.52$, has a significant amount of material upstream of the first active calorimeter layer. The EM calorimeter is composed, for $|\eta| < 2.5$, of three sampling layers, longitudinal in shower depth. The first layer has a thickness of about 4.4 radiation lengths (X_0). The fine η granularity of the strips (0.003×0.0982 in $\Delta\eta \times \Delta\phi$) is sufficient to provide reasonable discrimination between single photon showers and two overlapping showers coming from the decays of π^0 and η mesons. The second layer has a thickness of about $17X_0$ and granularity of 0.025×0.0245 in $\Delta\eta \times \Delta\phi$. It collects most of the energy deposited by electromagnetically interacting particles. The third layer has a depth of about $2X_0$, and it is used to correct for the leakage beyond the ECAL. A sketch of a barrel module of the electromagnetic calorimeter is shown in Figure 2.2.2.
- The Hadronic calorimeter (HCAL) - detects high energy hadrons. The hadron calorimeter absorbs energy from particles that pass through the EM calorimeter, but do interact via the strong force. In the region $\eta < 1.7$, which comprises the barrel and extended barrel components, a sampling concept with steel as absorber and scintillating tiles as active medium is used. The hadronic end-cap (HEC) and the forward calorimeter (FCAL), covering the range of $1.5 < \eta < 3.2$ and $3.1 < \eta < 4.9$ respectively, suffer from a much higher radiation flux. Therefore, the intrinsically radiation hard liquid argon (LAr) technology is employed. An important aspect in the design of the hadronic calorimetry is a sufficiently large thickness (10 interaction length λ) to minimize the punch-through of high energetic particles into the muon system.

2.2.3 The Muon spectrometer

Whereas electrons, photons and hadrons are absorbed by the calorimetry system, muons with a $p_T > 3$ GeV can penetrate the detector and reach the muon spectrometer. A large magnetic system is used (with an average magnetic field strength of 0.6 Tesla) in order to measure the momentum of the muons with high accuracy.

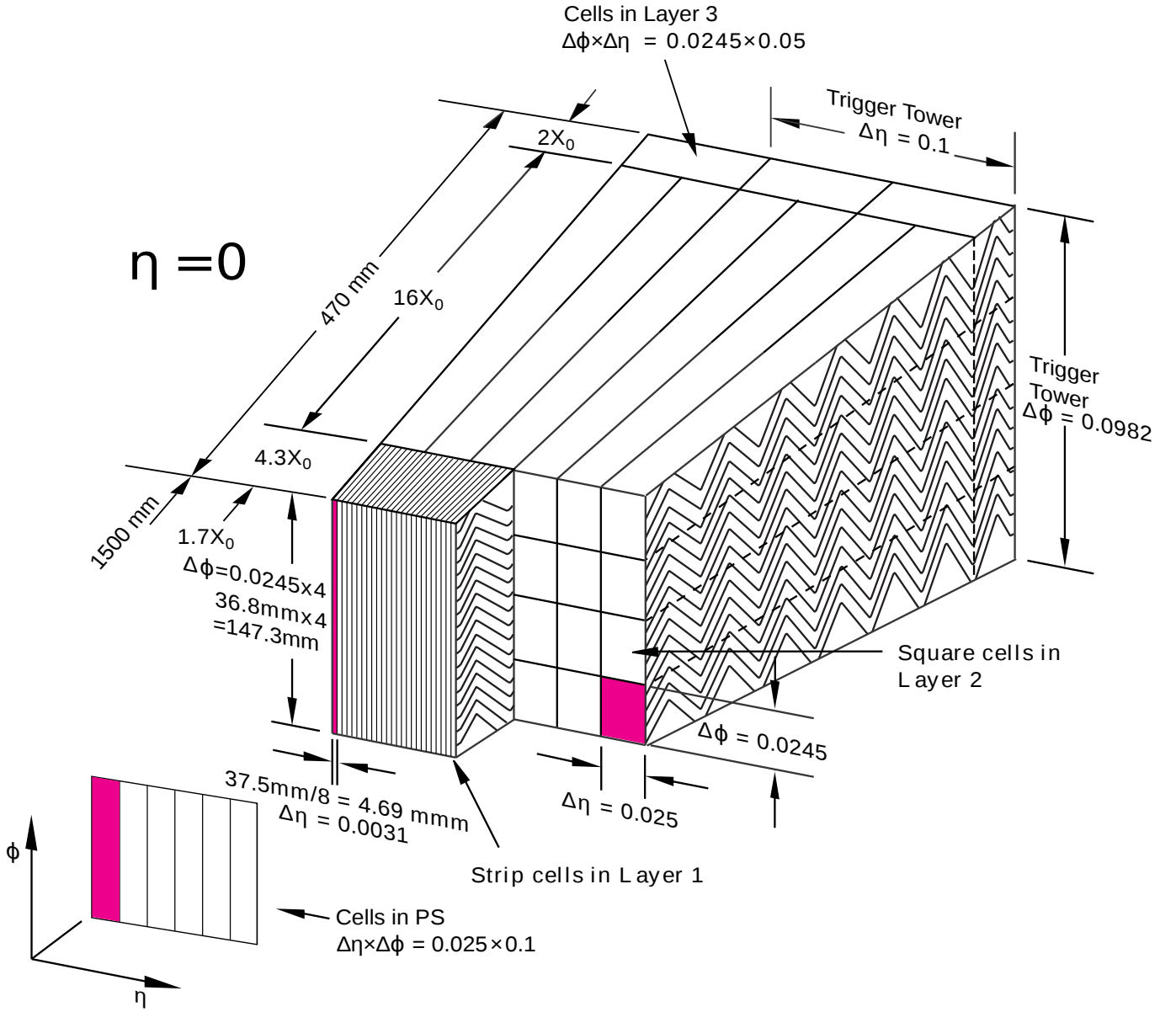


Figure 2.2.2: Sketch of a barrel module (located at $\eta=0$) of the ATLAS electromagnetic calorimeter. The different longitudinal layers are depicted. The granularity in η and ϕ of the cells of each layer and the trigger towers is also shown. From Ref. [5]

CHAPTER 3

Measurement of the identification efficiency of isolated photons using the matrix method with the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV

This chapter is based on reference [5]: “*Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run-1 data*”. **My work** is described in section 5.3 and the result is presented in section 6 of the publication.

My contribution: In the present chapter, a data-driven measurement of prompt photon tight identification efficiency using the “matrix method” with data collected by ATLAS detector in 2012 is presented. The method was first used with 2011 ATLAS data [41], but failed with the 2012 data, mostly due to a high pileup environment. My work was to study and to modify the method, also with the 2012 data.

3.1 Introduction

Photon identification (ID) efficiency is a necessary ingredient in measurements of various physical processes involving prompt photons, like the inclusive prompt photon [42–44] and diphoton [45] cross sections, measurements of properties of Higgs boson in the two photon decay [46–48] or when setting limits on the production cross section of hypothetical processes involving isolated photons in the final state, when the photons are required to pass identification criteria [49–51].

The photon identification in ATLAS is based on a set of rectangular cuts on several discriminating variables (DV) computed from the lateral and longitudinal shower development in the electromagnetic calorimeter and the shower leakage fraction in the hadronic calorimeter of the candidate photon.

Photons can convert into an electron-positron pair in the inner detector (called *converted photons* in the following), or arrive at the electromagnetic calorimeter without creating an electron-positron pair (called *unconverted photons* in the following). Different selection criteria are used for converted and unconverted photons; the selection also differs in different pseudorapidity intervals, to account for different $|\eta|$ - in front of the calorimeter.

Two sets of identification criteria are provided, with different photon efficiencies and jet rejections: a *loose* and a *tight* one. The loose criteria are similar to those used at trigger level and are designed to provide high efficiency with modest jet rejection; the tight criteria are those optimized for background rejection and are typically applied in the off-line analysis. The description of the variables and the selection criteria used in the two "menus" (tight and loose) is provided in Ref. [5].

The ATLAS photon identification efficiency is estimated from the simulation, after correcting ("fudging") the distributions of the calorimeter shower shape distributions in Monte Carlo (MC) by the difference observed between data and Monte Carlo in some control samples. The corrections ("fudge factors") result in simple shifts of the simulated distributions by the difference of the means of the distributions in data and Monte Carlo. The identification efficiency (ϵ_{ID}) is validated using three different independent data-driven methods. Radiative Z decays – relies on the use of a pure photon sample selected from the radiative decays of the Z boson. The electron-extrapolation method – electrons from Z boson decays are used to obtain a pure sample of electromagnetic showers from data where the DVs measured for the electrons are mapped to those valid for photons. The matrix method which uses the track isolation for signal and background candidates, as a discriminating variable to extract the sample purity before and after the tight cuts are imposed. Each of these methods can measure the photon identification efficiency in complementary but overlapping E_T regions with varying precision. While the Radiative Z decays and the electron-extrapolation methods exploit E_T region up to 80 GeV or 100 GeV respectively (due to limited p_T spectra of the Z bosons), the matrix-method is performed in the E_T range between 20 GeV to 1500 GeV, where the upper limit corresponds to the highest measured E_T of the selected photons during the 2012 data taking period.

In this chapter, the measurement of the photon identification efficiency using the matrix method during the 2012 data taking period is described, emphasizing the modifications concerning the 2011 approach.

3.2 Event selection and Monte Carlo samples

The measurement presented here is based on the full ATLAS dataset collected in 2012. The events are required to pass any of the ATLAS inclusive photon triggers, passing standard data quality requirements.

The identification efficiency is measured for isolated photons, which are defined as those having the topological cluster based isolation variable lower than 4 GeV. This quantity is computed from positive-energy three-dimensional topological clusters of calorimeter cells [52] within a cone of a radius¹ $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around the cluster barycenter. The topological clusters include cells from the EM and hadronic calorimeter. The energy from the core of the cone in the electromagnetic calorimeter is subtracted. Only photons with transverse energy $E_T > 20$ GeV in the pseudorapidity regions within the calorimeter acceptance ($|\eta| < 1.37$ or $1.52 \leq |\eta| < 2.37$) were considered. Converted photon candidates reconstructed from tracks passing through dead modules of the innermost pixel layer are rejected, strongly decreasing the misidentification of electrons as

¹ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector, and the z-axis along the beam line. The x-axis points from the IP to the center of the LHC ring and the y-axis points upwards. Cylindrical coordinators (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam line. Observables labeled "transverse" are projected into the x-y plane. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\log \tan(\theta/2)$

converted photons.

For the measurements, and to estimate systematic uncertainties, signal and background processes modeled with Pythia8 generator [53] and pass full ATLAS simulation.

3.3 Identification efficiency measurement with the matrix method

3.3.1 Identification efficiency measurement technique

The efficiencies of the tight identification criteria are measured, for each pseudorapidity and transverse momentum interval, in the following way. Suppose that, after the preselection, N_{all}^T photon candidates – consisting of N_{all}^S prompt photons and N_{all}^B fake photons – are selected, of which N_{pass}^T photon candidates – consisting of N_{pass}^S prompt photons and N_{pass}^B fake photons – pass the tight identification criteria².

The tight ID efficiency is

$$\varepsilon^{tight-ID} = \frac{N_{pass}^S}{N_{all}^S}. \quad (3.3.1)$$

Introducing the signal purity in data, for photon candidates passing the tight cut:

$$P \equiv \frac{N_{pass}^S}{N_{pass}^T}, \quad (3.3.2)$$

and for photon candidates in the inclusive sample:

$$A \equiv \frac{N_{all}^S}{N_{all}^T}, \quad (3.3.3)$$

one can see with some algebra that the tight ID efficiency can be also rewritten as:

$$\varepsilon^{tight-ID} = \frac{P \cdot N_{pass}^T}{A \cdot N_{all}^T}. \quad (3.3.4)$$

The matrix method, with the track isolation as the discriminating variable, was used to estimate N_{all}^S and N_{pass}^S (together with N_{all}^B and N_{pass}^B), or equivalently the purities P and A . The track isolation variable is defined as the number or sum of transverse momentum (p_T) of the tracks, with $p_T > 0.5$ GeV, in the cone of $\Delta R < \{0.2, 0.3, 0.4\}$ around the direction of a photon candidate, subtracting energy deposited within an inner cone of $\Delta R = 0.1$. An impact parameter cuts which constrain the tracks to come from the same vertex associated to the photon, make the track isolation variable to be more pileup robust. The track isolation variables used in the matrix-method were sum of p_T of the tracks within a cone of $\Delta R = 0.3$ to be lower than 1.2 GeV for unconverted photons, and requirement of number of the tracks within a cone of $\Delta R = 0.4$ to be equal to zero for converted photons. The photon track isolation variables based on the impact parameter cuts were introduced only during the 2012 data taking period.

By definition, we have:

$$N_{pass}^T = N_{pass}^S + N_{pass}^B \quad (3.3.5)$$

$$N_{all}^T = N_{all}^S + N_{all}^B \quad (3.3.6)$$

²These definitions differ from those used in the 2011 analysis, where only photons that fail tight selection are chosen as a second sub-sample. By inverting the narrow strip variables, only 70% of the photons were considered, while choosing the “fail” region as a control sample for the inclusive selection more than 85% of the photons were considered, resulting in a lower systematic uncertainty for this kind of selection as will be explained in section 3.3.2.2

Let us denote the number of isolated candidates with N_{pass}^{Iso} (N_{all}^{Iso}) if they pass the tight identification criteria (and for all photons). Let ε_p^s (ε_a^s) be the track isolation efficiency for prompt photons passing the tight identification criteria (for all photons), and ε_p^b (ε_a^b) be the track isolation efficiency for fake photons passing the tight identification criteria (all photons), respectively. We have therefore:

$$N_{pass}^{Iso} = \varepsilon_p^s * N_{pass}^S + \varepsilon_p^b * N_{pass}^B \quad (3.3.7)$$

$$N_{all}^{Iso} = \varepsilon_a^s * N_{fail}^S + \varepsilon_a^b * N_{fail}^B \quad (3.3.8)$$

If we know the four track isolation efficiencies ε_p^s , ε_a^s , ε_p^b and ε_a^b , from equations 3.3.5–3.3.8 we can get both N_{pass}^S and N_{all}^S from the observed number of events N_{all}^T , N_{all}^{Iso} , N_{pass}^T and N_{pass}^{Iso} in data:

$$N_{pass}^S = \frac{N_{pass}^{Iso} - \varepsilon_p^b * N_{pass}^T}{\varepsilon_p^s - \varepsilon_p^b} \quad (3.3.9)$$

$$N_{all}^S = \frac{N_{all}^{Iso} - \varepsilon_a^b * N_{all}^T}{\varepsilon_a^s - \varepsilon_a^b} \quad (3.3.10)$$

From equations 3.3.9 and 3.3.10 we can therefore extract the signal purity in the data sample after the tight cut:

$$P = \frac{\varepsilon_p - \varepsilon_p^b}{\varepsilon_p^s - \varepsilon_p^b}, \quad (3.3.11)$$

where $\varepsilon_p \equiv \frac{N_{pass}^{Iso}}{N_{pass}^T}$ is the fraction of tight photon candidates that pass the track isolation criteria. Similarly, the purity of the inclusive sample is:

$$A = \frac{\varepsilon_a - \varepsilon_a^b}{\varepsilon_a^s - \varepsilon_a^b}, \quad (3.3.12)$$

where $\varepsilon_a \equiv \frac{N_{all}^{Iso}}{N_{all}^T}$ is the fraction of photon candidates in the inclusive data sample.

In conclusion the efficiency of the tight identification criteria can be obtained using equation 3.3.4:

$$\varepsilon^{tight-ID}(N_{pass}^T, N_{all}^T, \varepsilon_p^s, \varepsilon_a^s, \varepsilon_p^b, \varepsilon_a^b, \varepsilon_p, \varepsilon_a) = \frac{\frac{\varepsilon_p - \varepsilon_p^b}{\varepsilon_p^s - \varepsilon_p^b} \cdot N_{pass}^T}{\frac{\varepsilon_a - \varepsilon_a^b}{\varepsilon_a^s - \varepsilon_a^b} \cdot N_{all}^T}. \quad (3.3.13)$$

3.3.2 Measurement of the photon track isolation efficiency

The prompt photon track isolation efficiencies are estimated from simulated samples of prompt photons, and the fake photon track isolation efficiencies are estimated from a data sample enriched with fake photons selected by reversing the tight identification criteria on some shower shape variables for the “fake” photons that pass the tight identification criteria. The photons which fail tight identification criteria chosen to estimate the track isolation efficiency for the “fake” photons in all sample (according to MC simulations “fake” photons that fail the tight selection criteria are roughly 85% from the inclusive sample).

3.3.2.1 Track isolation efficiency for prompt photons

The prompt photon track isolation efficiencies (ε_p^s and ε_a^s) are estimated from prompt photon MC simulated samples. Events are reweighed as a function of the average number of interactions per bunch crossing to take into account the differences between the pileup conditions in data and simulation.

3.3.2.2 Track isolation efficiency for fake photons

The fake photon track isolation efficiencies (ε_p^b and ε_a^b) are estimated from a data which contains almost fake photons, selected by reversing a few cuts on shower-shape variables or by choosing a sub-sample with a low signal photon purity. In [54] it was shown that a fake photon control sample could be obtained by reversing the variables based on the lateral energy deposition pattern in a few strips near the hottest one in the first compartment of the LAr electromagnetic calorimeter: F_{side} , w_{s3} , ΔE , E_{ratio} . These variables are only weakly correlated (linear correlations of few %) with the photon track isolation. This group of variables will be denoted as “narrow-strip” variables. Clearly, no candidate passes the tight identification criteria but fails at the same time the subset of cuts on the “narrow-strip” variables. Therefore for the fake photon track isolation efficiency measurement relaxed tight criteria is used, based on the nine quantities R_{had} , R_η , R_ϕ , $w_{\eta 2}$, F_{side} , w_{s3} , $w_{s\text{tot}}$, ΔE , E_{ratio} , by dropping the requirements on the narrow-strip variables. This selection criterion is denoted as “relaxed-tight” selection. Because of the very small correlation between the track isolation and the narrow-strip variables, fake photon track isolation efficiency is expected to be similar to photon passing tight or relaxed-tight criteria. This hypothesis is tested with “fake” MC samples; the differences are included in the systematic uncertainties. The impact of the systematic uncertainty on the tight selection efficiency can be estimated from the purity calculation, assume the correct efficiency varies by $\Delta\varepsilon_b$ from its true value, then the purity from equations 3.3.11–3.3.12, can be expanded as a function of the error on the $\Delta\varepsilon_b$ to obtain:

$$P + \Delta P = \frac{\varepsilon - (\varepsilon_b + \Delta\varepsilon_b)}{\varepsilon_s - (\varepsilon_b + \Delta\varepsilon_b)} \quad (3.3.14)$$

$$= \frac{\varepsilon - \varepsilon_b}{\varepsilon_s - \varepsilon_b} + \Delta\varepsilon_b \left| \frac{\varepsilon_s - \varepsilon}{(\varepsilon_s - \varepsilon_b)^2} \right| + \mathcal{O}(\Delta^2) \quad (3.3.15)$$

While the error on the tight selection efficiency is proportional to the error on the estimated purity - $\Delta\varepsilon_{\text{ID}}/\varepsilon_{\text{ID}} \propto (\Delta P/P + \Delta A/A)$, a higher fraction of the prompt photons in the selected region gives lower systematic uncertainty on the tight efficiency.

An illustration of the photon candidate classification according to their identification criteria is shown in figure 3.3.1:

- region 1+3 contains the photon candidates passing relaxed-tight criteria
- region 2+4 contains the photon candidates failing relaxed-tight criteria
- region 1+2 contains the candidates that pass the cuts on the narrow-strip variables
- region 3+4 contains the candidates that fail the cuts on the narrow-strip variables
- region 1 corresponds to photons that “pass” the tight selection
- region 2+3+4 corresponds to photons that “fail” the tight selection

Candidates in region 3 pass the relaxed-tight cuts but fail the criteria on the narrow-strip variables. The candidates in this region are used to estimate the fake photon track isolation efficiency for fake candidates that pass tight identification criteria (region 1). Candidates in region 2+3+4, which fail tight identification criteria, are used to estimate the track isolation efficiency of inclusive photons sample (region 1+2+3+4). The signal contribution to the control regions 3 and 2+3+4 is significantly suppressed, but residual contamination exists. It is estimated using prompt photon MC samples to determine the fraction of the signal in regions 3 and 2+3+4 concerning the signal in region 1, and subtracted from the data yields as described below.

Introduce a few definitions according to figure 3.3.1:

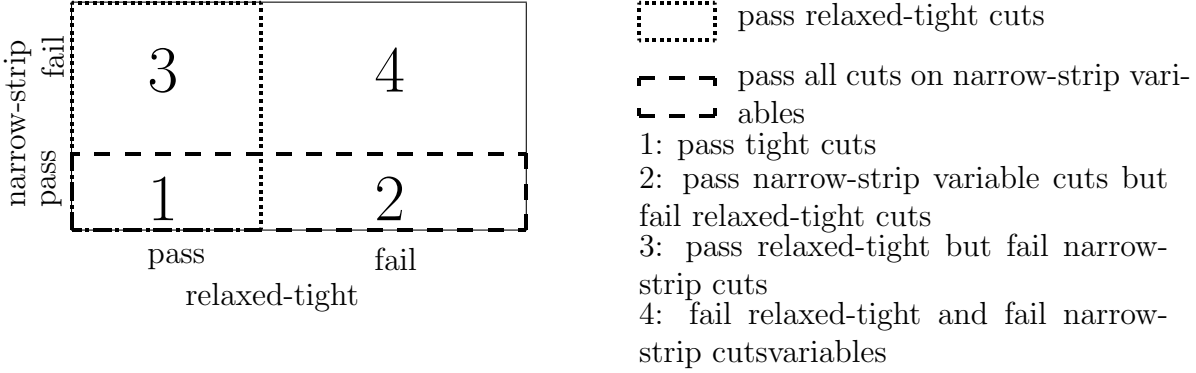


Figure 3.3.1: A graphical illustration of photon candidate classification in the data sample. Candidates in region 3 and region 2+3+4 on the graph are used to estimate the track isolation efficiencies for background ε_p^b and ε_a^b respectively after subtracting residual signal photons.

- R_p : the fraction of the photon candidates in data in region 3.
- R_a : the fraction of photon candidates in data that fail tight criteria (region 2+3+4).
- ε_p : the fraction of photon candidates that are isolated in the tracker after passing tight criteria (region 1).
- ε_a : the fraction of photon candidates that are isolated in the tracker (region 1+2+3+4).
- ε_p^{b+} : the fraction of photon candidates in region 3 that are isolated in the tracker.
- ε_a^{b+} : the fraction of photon candidates in region 2+3+4 that are isolated in the tracker.

Remind the previous definitions of:

- N_{pass}^T : the total number of photon candidates that pass tight criteria (region 1).
- N_{all}^T : the total number of photon candidates (region 1+2+3+4).

From the prompt photon MC sample one can extract the following quantities:

- f_p : the fraction of prompt photons that leak in region 3.
- f_a : the fraction of prompt photons that leak in region 2+3+4³.
- ε_p^s : the track isolation efficiency of prompt photons in region 1.
- ε_a^s : the track isolation efficiency of prompt photons in region 1+2+3+4.
- ε_p^{s+} : the track isolation efficiency of prompt photons in region 3.
- ε_a^{s+} : the track isolation efficiency of prompt photons in region 2+3+4.

The fractions f_p and f_a are typically below 10% for unconverted photons and below 5% of converted photons, and decrease with a photon E_T .

The track isolation efficiency for fake photons in regions 3 and 2+3+4 are ε_p^b and ε_a^b , respectively. To obtain the number of background events in the control region one need to subtract the signal events. Using the variables defined previously, the following equation can be written:

$$N_{3,2+3+4}^b = N_{3,2+3+4}^T - N_{3,2+3+4}^S = N_{3,2+3+4}^T - N_{all}^S \cdot f_p = N_3^T - N_{all}^T \cdot A \cdot f_p \quad (3.3.16)$$

Similarly, the equation for the isolated background events can be written as follows:

$$N_{3,2+3+4}^{b,ISO} = N_{3,2+3+4}^T \cdot \varepsilon_p^{b+} - N_{3,2+3+4}^S \cdot \varepsilon_p^{s+} = N_{3,2+3+4}^T \cdot \varepsilon_p^{b+} - N_{all}^T \cdot A \cdot f_p \cdot \varepsilon_p^{s+} \quad (3.3.17)$$

³Note that the definition of this fraction is related to the definition of the tight selection efficiency by $\varepsilon_{ID} = 1 - f_a$. Although signal contamination in the “all” control region is small and the MC uncertainties can be neglected, a future iterative approach can decrease even more the systematic uncertainty by recalculating the “fake” track isolation efficiency using the data-driven signal fraction f_a .

Using definitions above, one can write the background isolation efficiency ε_p^b and ε_a^b as follows:

$$\varepsilon_p^b = \frac{R_p \cdot \varepsilon_p^{b+} - A \cdot f_p \cdot \varepsilon_p^{s+}}{R_p - A \cdot f_p} \quad (3.3.18)$$

$$\varepsilon_a^b = \frac{R_a \cdot \varepsilon_a^{b+} - A \cdot f_a \cdot \varepsilon_a^{s+}}{R_a - A \cdot f_a} \quad (3.3.19)$$

Equation 3.3.19 is a quadratic equation $a \cdot (\varepsilon_a^b)^2 - b \cdot \varepsilon_a^b + c = 0$, with:

$$a = R_a - f_a \quad (3.3.20)$$

$$b = R_a \cdot (\varepsilon_a^s + \varepsilon_a^{b+}) - f_a \cdot (\varepsilon_a + \varepsilon_a^{s+}) \quad (3.3.21)$$

$$c = R_a \cdot \varepsilon_a^{b+} \cdot \varepsilon_a^s - f_a \cdot \varepsilon_a^{s+} \cdot \varepsilon_a \quad (3.3.22)$$

By obtaining the purity for the inclusive photon sample from equation 3.3.12, the background isolation efficiency of background photons in the region 3 (ε_p^b) can be calculated directly from equation 3.3.18.

3.3.2.3 Systematic uncertainties

The average differences between the track isolation efficiencies in data and Monte Carlo for electrons collected in the data and simulation with a tag-and-probe technique in $Z \rightarrow ee$ selection are taken as systematic uncertainties in ε_a^s and ε_p^s . The overall uncertainties in ε_a^s and ε_p^s are below 1%.

Another source of systematic uncertainty can rise from the distorted material. To estimate the error on the prompt photon isolation efficiency from the distorted material, MC simulations with the distorted material were used, and the track isolation efficiency between the nominal and distorted MC samples were compared. The dominant systematic uncertainty is coming from a linear correlation between the “narrow-strip” variables and the track isolation efficiency as mentioned before. The possible bias of fake photon track isolation efficiency which is extracted in the background control region after signal leakage correction was studied in di-jet + γ -jet simulated samples, and is included as a systematic uncertainty. The in-time pileup dependence of the photon identification efficiency has also been evaluated. The (corrected) simulation seems to reproduce it reasonably well.

3.4 Tight photon identification efficiency results

In this study, since the inclusive photon triggers are used for the preselection of the sample, what is measured with the preselected sample is the tight identification efficiency for photon candidates passing the shower shape requirements applied by the trigger

$$\varepsilon' = \frac{N_{\gamma}^{tight, reco, trig}}{N_{\gamma}^{reco, trig}} \quad (3.4.1)$$

while we are interested in the tight identification efficiency for all reconstructed isolated photons:

$$\varepsilon = \frac{N_{\gamma}^{tight, reco}}{N_{\gamma}^{reco}} \quad (3.4.2)$$

We can obtain the latter from the former by applying a multiplicative factor:

$$\varepsilon = \varepsilon' \frac{\frac{N_{\gamma}^{tight, reco}}{N_{\gamma}^{reco}}}{\frac{N_{\gamma}^{tight, reco, trig}}{N_{\gamma}^{reco, trig}}} \quad (3.4.3)$$

$$= \varepsilon' \frac{\frac{N_{\gamma}^{reco, trig}}{N_{\gamma}^{reco}}}{\frac{N_{\gamma}^{tight, reco, trig}}{N_{\gamma}^{tight, reco}}} \quad (3.4.4)$$

The correction factor, as seen from equation 3.4.3, is the ratio between the tight ID efficiency for all reconstructed photons or only for photons matching the trigger object that triggers the event, as obtained from simulated direct photon samples after correcting the shower shapes by the fudge factors. The correction factor is close to 1 except in low E_T range (typically below 50 GeV), where the maximal correction factor is of the order of 1%.

The final tight identification efficiencies for reconstructed photons after the calorimeter isolation requirement with a comparison to MC expectation are shown in figure 3.4.1 for unconverted and in figure 3.4.2 for converted photons. We propagate the statistical and systematic uncertainties to the final uncertainty of the tight ID efficiency using error propagation. In the high E_T bins, due to the statistical uncertainties on ϵ , the uncertainties of the final identification efficiency are rather large.

3.5 Summary

The photon tight identification efficiency has been measured in the 2012 data using the matrix method, based on the photon track isolation to discriminate between prompt and fake candidates. The method is applied to photons with $20 < E_T < 1500$ GeV.

The main contribution to the total systematic uncertainty is the uncertainty on the track isolation efficiency for “fake” photons. The systematic uncertainties on the signal track isolation efficiency are negligible compared to the other ones. Because of the rapidly falling E_T spectrum of prompt photons produced in proton collisions, the yield is rather low at high E_T , and the statistic uncertainty becomes not negligible for $E_T > 600$ GeV.

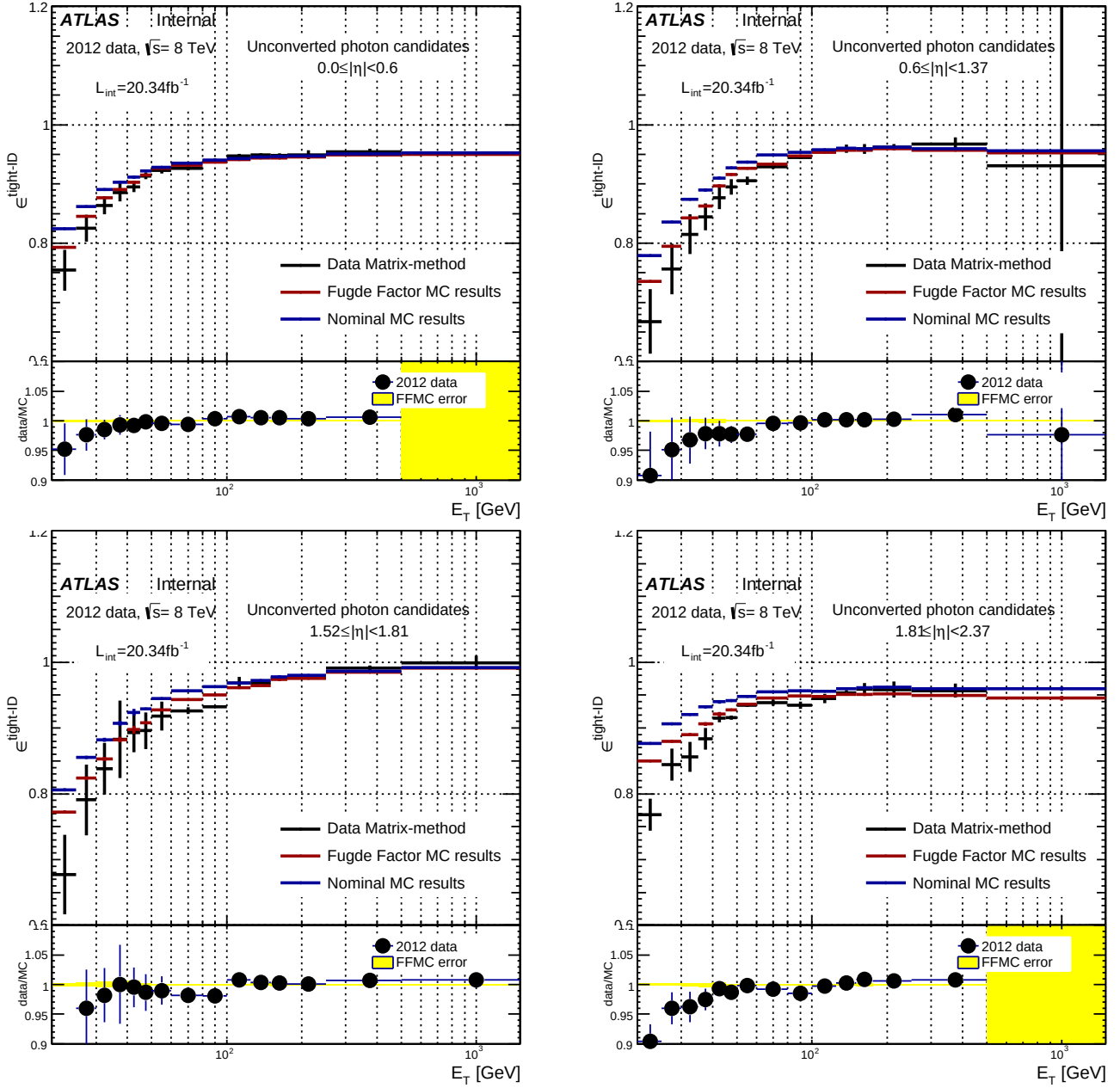
The results are compared to those obtained from Monte Carlo, either uncorrected or after applying corrections (“fudge factors”) to the simulated shower shapes. The photon identification efficiencies in the simulation with a corrected shower-shape variables, are agree with the ones from data to within 2-3% in the E_T range between 30-40GeV, and are typically below 1% for photons with $E_T > 40$ GeV. For the low E_T range, since this region is dominated by the “fake” photons, that contributing to higher background systematic uncertainty, the poorer agreement between the data and the corrected MC predictions is associated with relatively larger errors of the tight identification efficiency obtained with the matrix method. For the last E_T bin ($E_T > 600$ GeV) the statistical uncertainty is dominated, especially for photons with $1.52 < |\eta| < 1.81$.

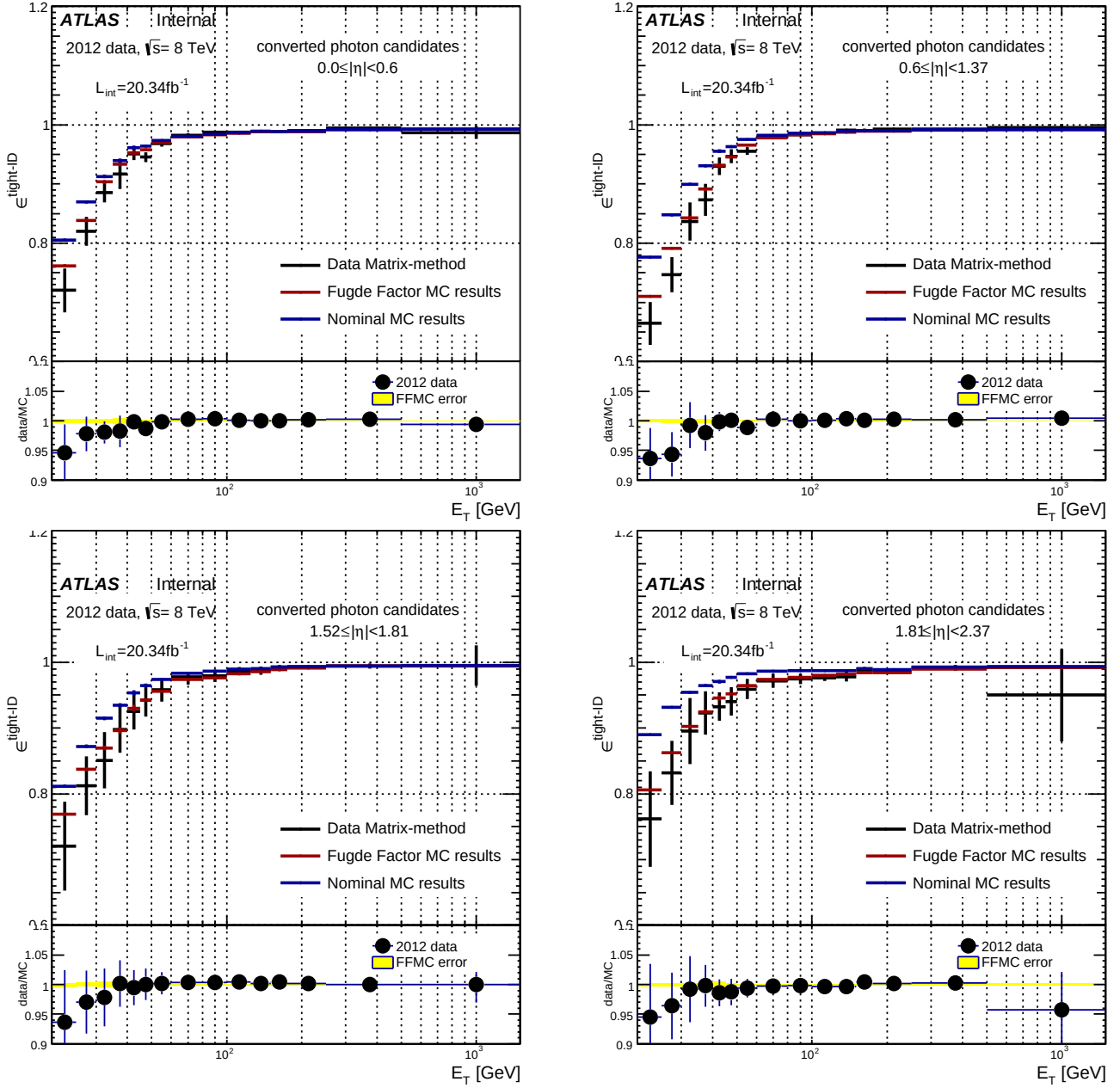
The in-time pileup dependence of the photon identification efficiency has also been evaluated. The (corrected) simulation seems to reproduce it reasonably well.

The identification efficiency measurements for $\sqrt{s} = 8$ TeV are obtained using three different data-driven techniques are shown in figures 3.5.1 and 3.5.2.

In the photon transverse momentum regions in which the different measurements overlap, the results from each method are consistent with each other within the uncertainties.

The combined photon identification efficiency increases from 50–65% (45–55%) for unconverted (converted) photons at $E_T \approx 10$ GeV to 94–100% at $E_T \gtrsim 100$ GeV, and is larger than about 90% for $E_T > 40$ GeV. The absolute uncertainty in the measured efficiency is around 1% (1.5%) for unconverted (converted) photons for $E_T < 30$ GeV and around 0.4–0.5% for both types of photons above 30 GeV for the most precise method in a given bin. These results were published in [5].





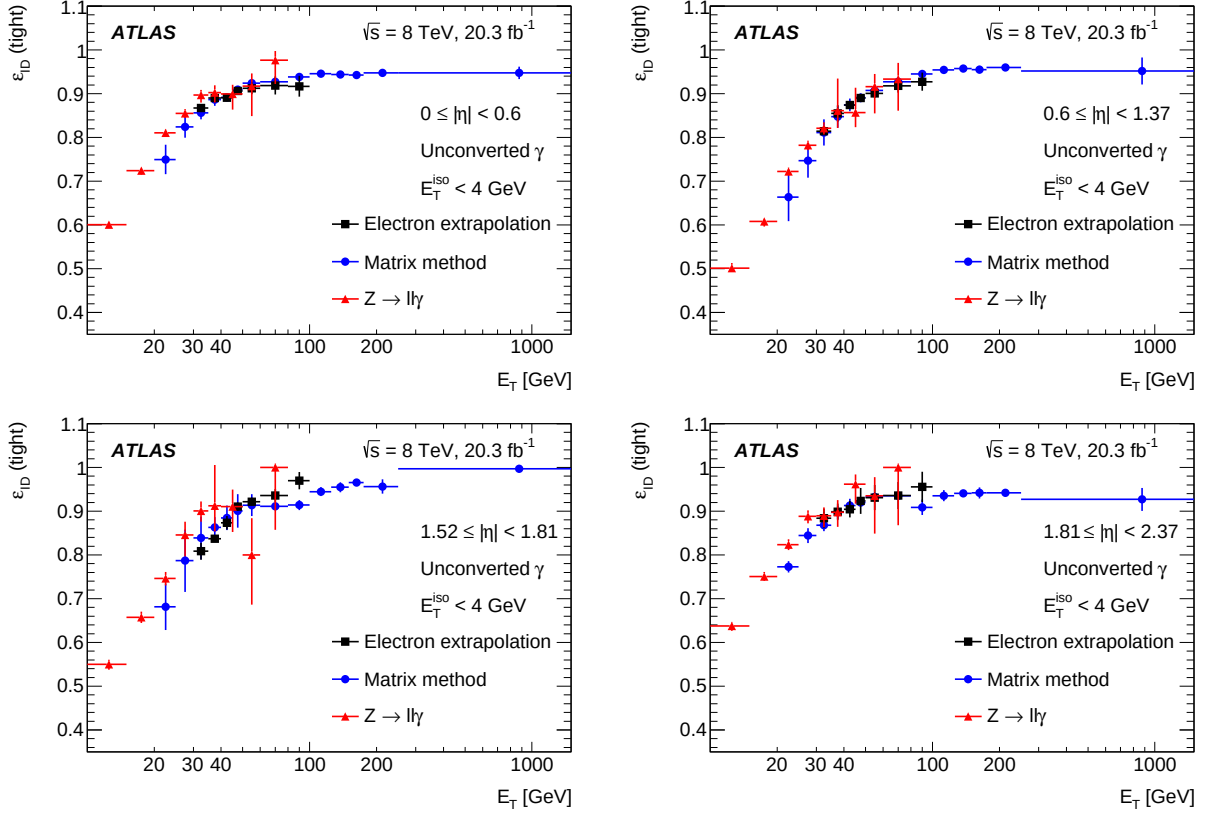


Figure 3.5.1: Comparison of the data-driven measurements of the identification efficiency for unconverted photons as a function of E_T in the region $10 \text{ GeV} < E_T < 1500 \text{ GeV}$, for the four pseudorapidity intervals (a) $|\eta| < 0.6$, (b) $0.6 \leq |\eta| < 1.37$, (c) $1.52 \leq |\eta| < 1.81$, and (d) $1.81 \leq |\eta| < 2.37$. The error bars represent the sum in quadrature of the statistical and systematic uncertainties estimated in each method. My contribution to the photon identification efficiency measurement is with the Matrix-method. This figure was published in Ref. [5].

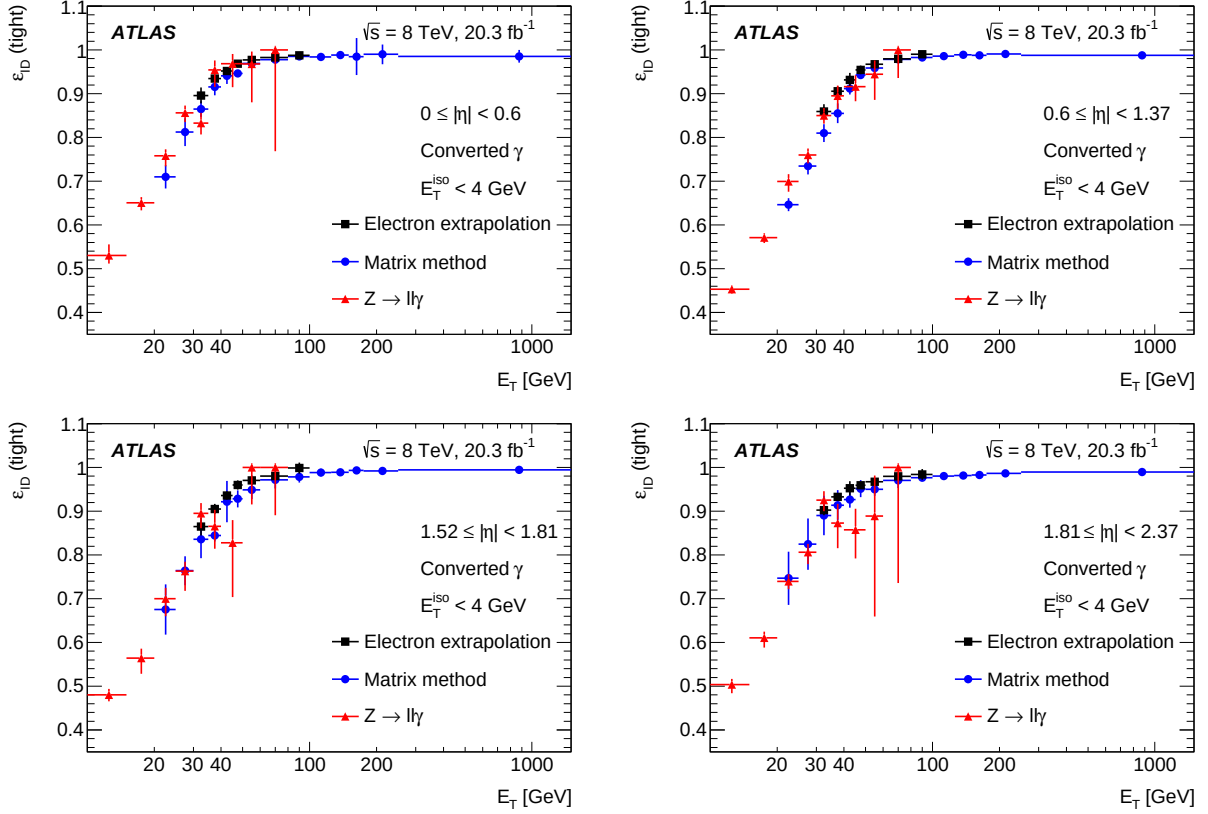


Figure 3.5.2: Comparison of the data-driven measurements of the identification efficiency for converted photons as a function of E_T in the region $10 \text{ GeV} < E_T < 1500 \text{ GeV}$, for the four pseudorapidity intervals (a) $|\eta| < 0.6$, (b) $0.6 \leq |\eta| < 1.37$, (c) $1.52 \leq |\eta| < 1.81$, and (d) $1.81 \leq |\eta| < 2.37$. The error bars represent the quadratic sum of the statistical and systematic uncertainties estimated in each method. My contribution to the photon identification efficiency measurement is with the Matrix-method. This figure was published in Ref. [5].

Part III

Data analysis

CHAPTER 4

Standard model of particle physics

This chapter contains no original work. It describes the Standard Model of Electro-Weak interactions which is a background material for chapters 5 and 7.

4.1 Overview

The Standard Model describes particle interactions as a result of local gauge symmetries [55]. It incorporates three of the four known fundamental forces: the electromagnetic force, the strong force and the weak force¹. The Standard Model gauge theory is based on the symmetry group

$$G_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \quad (4.1.1)$$

Gluons, the gauge bosons of quantum chromodynamics $SU(3)_c$, mediate the strong interactions at the fundamental level. The $SU(2)_L \otimes U(1)_Y$ part is called the *ElectroWeak theory* (EW), and is spontaneously broken (we will review the EW theory below). Gauge bosons are outlined in table 4.1.

Table 4.1: Gauge bosons in the Standard Model [56]

boson	mass [GeV]	electric charge [e]	symmetry group
g	0	0	$SU(3)_c$
γ	0	0	$SU(2)_L \otimes U(1)_Y$
Z	91.1876	0	$SU(2)_L \otimes U(1)_Y$
$W^\pm$	80.399	± 1	$SU(2)_L \otimes U(1)_Y$

The particles in the Standard Model can be categorized according to their spin: There are *fermions* with half-integer spin, and *bosons* with integer spin. Fermions are further divided into

¹Gravity is too weak at the scales with which particle physics is concerned and is not incorporated in the Standard Model.

leptons which do not interact via the strong force and *quarks* which undergo strong interactions. Furthermore, the fermions come in three different generations which behave identically under the symmetry transformation explained below and differs only in the masses of the contained particles.

There are always two different pairs of leptons and quarks per generation which yields in total 12 fermions as shown in table 4.2.

Table 4.2: Fermionic particle content of the Standard Model [56]

type	first generation		second generation		third generation	
	flavor	mass	flavor	mass	flavor	mass
leptons	ν_e	$< 2 \text{ eV}$	ν_μ	$< 2 \text{ eV}$	ν_τ	$< 2 \text{ eV}$
	e	511 keV	μ	105.658 MeV	τ	1776.82 MeV
quarks	u	$1.7\text{-}3.1 \text{ MeV}$	c	1.29 GeV	t	172.9 GeV
	d	$4.1\text{-}5.7 \text{ MeV}$	s	100 MeV	b	4.19 GeV

In the next sections the electroweak (EW) sector of the SM and the Higgs mechanism are discussed in more detail.

4.2 Electroweak Gauge Theory

In Standard model the electroweak interactions is based on gauge group $SU(2)_L \times U(1)_Y$, with gauge bosons W_μ^i , $i = 1, 2, 3$, and B_μ for the $SU(2)_L$ and $U(1)_Y$ respectively, and the corresponding gauge coupling constants g and g' . The EW Lagrangian is shown in equation 4.2.1.

$$\mathcal{L}_{EW} = \sum_i i \bar{\psi}_i \gamma^\mu D_\mu \psi_i \quad (4.2.1)$$

where the covariant derivative for this particular symmetry group is given as:

$$D_\mu = \partial_\mu + ig'YB_\mu + ig\frac{1}{2}\vec{\tau}_L \cdot \vec{W}_\mu \quad (4.2.2)$$

with $\vec{\tau}$ are the *Pauli matrices* - generators of the $SU(2)_L$ group and Y is the *weak hypercharge* - the generator of the $U(1)_Y$ group.

The particles within the EW theory are required to be massless. Unfortunately, this contradicts the experimental observation that shows the fermions and gauge bosons posses a mass. Therefore, a mechanism is needed to describe massive fields and introduce mass terms in a way that is compatible with the requirement of local gauge invariance.

4.3 Higgs mechanism and the EW symmetry breaking

The “Higgs”² mechanism [57–62] postulates an additional isospin doublet Φ of a complex scalar fields with the potential:

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \text{ where } \mu^2, \lambda > 0 \quad (4.3.1)$$

Then the Lagrangian for the Higgs sector is given by:

$$\mathcal{L}_{Higgs} = (D^\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi) \quad (4.3.2)$$

which is invariant under $SU(2)_L \times U(1)_Y$ transformations. Higgs doublet has the form:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (4.3.3)$$

²Named after Peter W. Higgs

For $\mu^2 > 0$, the potential $V(\Phi)$ has infinite degenerate minima corresponding to

$$\Phi^\dagger \Phi = -\frac{\mu^2}{2\lambda} = \frac{v^2}{2} \quad (4.3.4)$$

One can choose a particular direction for the minimum of Φ . Since no positive charged permanent background field is observed, the ground state must take the form:

$$\Phi_0 = \langle 0|\Phi|0\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad (4.3.5)$$

The vacuum has zero eigenvalue for the electric charge operator $Q\Phi_0 = 0$ and is, therefore invariant under the $U(1)_{EM}$.

$U(1)_{EM}$ remains unbroken, and in this broken phase, we customarily choose Φ to be represented by :

$$\Phi = \begin{pmatrix} 0 \\ \frac{v+h(x)}{\sqrt{2}} \end{pmatrix} \quad (4.3.6)$$

where $h(x)$ is the massive spin 0 field which is called *Higgs boson*.

In equation 4.3.2 the covariant derivative for Higgs field in it ground state is given by:

$$(D^\mu \Phi)^\dagger (D_\mu \Phi) = \left| \frac{1}{2} \begin{pmatrix} gW_3^\mu + g'B^\mu & g(W_1^\mu - iW_2^\mu) \\ g(W_1^\mu - iW_2^\mu) & -gW_3^\mu + g'B^\mu \end{pmatrix} \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \right|^2 \quad (4.3.7)$$

defining the new fields:

$$\begin{aligned} W_\pm^\mu &= \frac{1}{\sqrt{2}}(W_1^\mu \mp iW_2^\mu) \\ \tan \theta_W &= g'/g \\ \begin{pmatrix} Z^\mu \\ A^\mu \end{pmatrix} &= \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B^\mu \\ W_3^\mu \end{pmatrix} \end{aligned} \quad (4.3.8)$$

equation 4.3.7 yields:

$$(D^\mu \Phi)^\dagger (D_\mu \Phi) = \frac{g^2 v^2}{4} \left[W_+^\mu W_{-\mu} + \frac{1}{\cos^2 \theta_W} Z^\mu Z_\mu \right] \left(1 + \frac{h}{v} \right)^2 + \frac{1}{2} (\partial^\mu h) (\partial_\mu h) \quad (4.3.9)$$

from which one can identify the gauge boson masses

$$\begin{aligned} M_W^2 &= \frac{1}{4} g^2 v^2 \\ M_Z^2 &= \frac{1}{4} (g^2 + g'^2) v^2 = \frac{g^2 v^2}{4 \cos^2 \theta_W} \\ M_A^2 &= 0 \end{aligned} \quad (4.3.10)$$

Expanding the term for the Higgs potential, the mass of the Higgs boson at tree level is found to be

$$M_H = \sqrt{2\lambda} v \quad (4.3.11)$$

After spontaneous symmetry breaking the Lagrangian for the fermion fields, ψ_i , is:

$$\begin{aligned} \mathcal{L}_F &= \sum_i \bar{\psi}_i \left(i\gamma^\mu \partial - m_i - \frac{gm_i H}{2M_W} \right) \psi_i \\ &- \frac{g}{2\sqrt{2}} \sum_i \bar{\Psi}_i \gamma^\mu (1 - \gamma^5) (T^+ W_\mu^+ + T^- W_\mu^-) \Psi_i \\ &- e \sum_i q_i \bar{\psi}_i \gamma^\mu \psi_i A_\mu \\ &- \frac{g}{2 \cos \theta_W} \sum_i \bar{\psi} \gamma^\mu (g_V^i - g_A^i \gamma^5) \psi_i Z_\mu \end{aligned} \quad (4.3.12)$$

where $e = g \sin \theta_W$ which is the positron electric charge. T^+ and T^- are the weak isospin raising and lowering operators. The vector and axial-vector couplings are

$$g_V^i = t_{3L}(i) - 2q_i \sin^2 \theta_W \quad (4.3.13)$$

$$g_A^i = t_{3L}(i) \quad (4.3.14)$$

where $t_{3L}(i)$ is the weak isospin of fermion i ($+1/2$ for u_i and ν_i ; $-1/2$ for d_i and e_i) and q_i is the charge of ψ_i in units of e .

The vacuum expectation value (VEV) constrained to $v = \frac{\mu}{\sqrt{\lambda}} = (\sqrt{2}G_F)^{-1/2} \approx 246$ GeV, where $G_F = 1.167 \times 10^{-5} \text{GeV}^{-2}$ is the fermi constant. The fact that the ground state does not exhibit the full symmetry of the Lagrangian in equation 4.3.2 is called *Spontaneous Symmetry Breaking (SSB)*.

4.4 $m\bar{\psi}\psi$ mass terms

The fermion mass terms cannot be added by hand in the Standard Model Lagrangian. These mass terms would not be local gauge invariant. However, by using the Higgs field that we introduced before, we can construct a Yukawa interaction term that does remain gauge invariant under local $SU(2)_L \times U(1)_Y$ transformations. The corresponding part for the i^{th} fermion generation is³:

$$\mathcal{L}_{Yukawa} = \lambda_{e_i} \bar{L}^i \Psi e_R^i + \lambda_{d_i} \bar{Q}^i \Psi d_R^i + \lambda_{u_i} \bar{Q}^i \Psi^C u_R^i + \text{h.c.} \quad (4.4.1)$$

The fermion masses are given by $M_f = \lambda_f \frac{v}{\sqrt{2}}$ and the coupling to Higgs field is proportional to fermion masses:

$$g_{Hff} = \frac{m_f}{v} \quad (4.4.2)$$

4.5 Higgs production

The Higgs boson was observed in 2012 with a measured mass of $m_H = 125.09 \pm 0.24 \text{GeV}$ [63–65]. At the LHC, the Higgs boson is mainly produced through the following four main mechanisms: gluon fusion through a heavy quark triangular loop (ggH), vector boson fusion (VBF), associated production with vector bosons W or Z (VH), and production in association with a top-quark pair. The production diagrams are shown in figure 4.5.1, and the production cross section are shown in figure 4.5.2. The production mode with a highest rate is the gluon-gluon fusion (ggF). The VBF production mode is one order below, followed by the associated production with a vector boson (Higgs-Strahlung). The Higgs boson production in association with a top-quark is suppressed at low center-of-mass energies, due to a large mass of the top quark, yet this process makes a challenge which we face as part of this thesis (see next chapter). Higgs production cross-sections for different production mechanisms are shown in figure 4.5.2 and table 4.3.

4.6 Decay Modes of the Higgs Boson

Due to its short lifetime ($\tau_H = \frac{\hbar}{\Gamma_H} \approx 1.6 \times 10^{-22} \text{sec.}$, with $\Gamma_H = 4.07 \text{MeV}$), Higgs boson cannot be observed directly, but only via its decay products. The branching ratios of SM Higgs decay modes and their total uncertainties are listed in table 4.4.

³ $\Psi^C = i\sigma^2 \Psi^*$

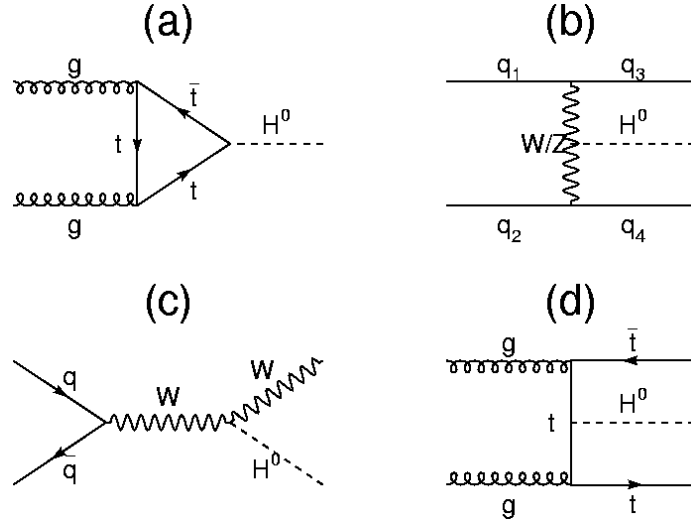


Figure 4.5.1: Higgs production at hadron colliders: (a) Gluon fusion through a heavy quark triangular loop, (b) Vector boson fusion, (c) Associative production with W, (d) Production in association with a top-quark pair. The cross-section decreases from (a) to (d).

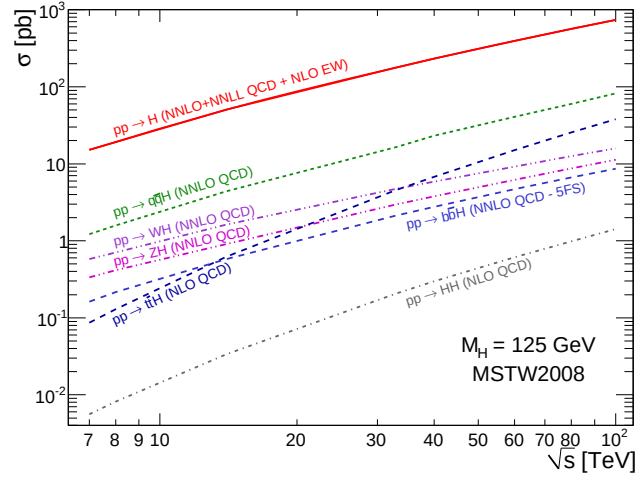


Figure 4.5.2: Production cross-sections of the Higgs boson as a function of the center-of-mass energies [66]

Table 4.3: Higgs production cross-section from Ref. [66]

production mode	cross-section [pb]				
	7TeV	8TeV	13TeV	13.5TeV	14TeV
ggF	15.11	19.24	43.92	46.67	49.47
VBF	1.222	1.579	3.748	3.986	4.233
WH	0.577	0.7027	1.380	1.452	1.522
ZH	0.3341	0.4142	0.9753	1.034	1.0933
$b\bar{b}H$	0.1555	0.2030	0.5116	0.5460	0.5805
$t\bar{t}H$	0.08611	0.1290	0.5085	0.5608	0.6113

Table 4.4: Standard Model Higgs branching ratios and their total uncertainties (expressed in percentage) from Ref. [66]

Process	bb	WW	gg	$\tau\tau$	cc	ZZ	$\gamma\gamma$	$Z\gamma$	$\mu\mu$
BR	54.7	21.5	8.57	6.3	2.91	2.64	0.228	0.154	0.02
unc.(%)	3.3	4.3	10.1	5.7	12.2	4.3	5	8.9	6

CHAPTER 5

Search for the Standard Model Higgs boson production in association with a pair of top quarks in the $H \rightarrow \tau\tau$ decay mode

This chapter is based on reference [7]: “*Search for the associated production of the Higgs boson with a top quark pair in multilepton final states with the ATLAS detector*”. **My work** is described in sections 6.5 and 7.5, and the result is presented in section 9 of the publication.

My contribution to the search is with the $1\ell 2\tau_{\text{had}}$ channel, which is highly sensitive to the $H \rightarrow \tau\tau$ decay mode. In this chapter, I will describe in detail the analysis performed with this channel.

5.1 Introduction

The discovery of a new particle with a mass of about 125 GeV in searches for the Standard Model Higgs boson at the LHC was reported by the ATLAS [63] and CMS [64] Collaborations in July 2012. Using the data, collected by the ATLAS and CMS collaborations, during 2011 and 2012 data taking periods; the new particle has been observed in the decays $H \rightarrow \gamma\gamma$ [46, 67], $H \rightarrow ZZ \rightarrow 4\ell$ [68, 69] and $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ [70, 71], and evidence has been reported for $H \rightarrow \tau\tau$ [6, 72], consistent with the rates expected for the SM Higgs boson.

The observation of the process in which the Higgs boson is produced in association with a pair of top quarks ($t\bar{t}H$) would permit a direct measurement of the top quark Higgs boson Yukawa coupling in a process that is tree-level at the lowest order, which is otherwise accessible primarily through loop effects. A search for this process, has been performed using $\mathcal{L} = 20.3\text{fb}^{-1}$ of proton-proton collision

data recorded by the ATLAS experiment at $\sqrt{s} = 8$ TeV during 2012.

The analysis targeted $t\bar{t}H$ production mode in multilepton final states. Five final states were considered according to the number of light leptons (e, μ) and to the number of hadronically decaying τ leptons. The exact definition of these channels is given in table 5.1. The analyses are expected to be sensitive to all of the three Higgs decay modes are shown in table 5.2

Table 5.1: Definition and name of the channels based on the number of leptons and their charge in the $t\bar{t}H \rightarrow$ multilepton analysis.

Channel Name	e, μ requirements	τ_{had} requirement
Same-sign	$= 2 \text{ } Q(\ell\ell)=\pm 2$	$= 0$
1 τ	$= 2 \text{ } Q(\ell\ell)=\pm 2$	$= 1$
3 leptons	$= 3 \text{ } Q(\ell\ell\ell)=\pm 1$	$= 0$
1 ℓ 2 τ_{had}	$= 1$	$= 2$
4 leptons	$= 4 \text{ } Q(4\ell)=0$	ignored

Our contribution to this search was with the 1 ℓ 2 τ_{had} channel. This chapter has the following structure: Section 5.2 describes the event and object selection. The optimization of the τ_{had} selection is described in section 5.3. Section 5.4 covers the background estimation method. The results obtained with the 1 ℓ 2 τ_{had} channel are summarized in section 5.5 while the combination with the all other channels of the search are presented in section 5.6.

5.2 Object and event selection

5.2.1 Object definitions

The objects used in the analysis are described below:

5.2.1.1 Jet definitions and b-tagging

Jets are reconstructed in the calorimeter using the anti- k_t [73] algorithm with a distance parameter of 0.4 using locally calibrated topologically clusters as input (LC Jets). Events with any LooserBad jet are vetoed. Jets are required to have transverse momentum (p_T) greater than 25 GeV and $|\eta| < 2.5$. Soft jets with $p_T < 50$ GeV, are required to be associated with the primary vertex, the “jet vertex fraction” (or JVF), which is the fraction of track p_T associated with the jet that comes from the primary vertex [74], must exceed 0.5 (or there must be no track associated with the jet).

B-jets are tagged using a Multi-Variate Analysis (MVA) method called MV1 [75], and relying on information of the impact parameter and the reconstruction of the displaced vertex of the hadron

Table 5.2: Fraction of expected $t\bar{t}H$ signal arising from different Higgs boson decay modes in each analysis category. The six $\ell\ell 0\tau_{\text{had}}$ categories are combined together, as are the two 4ℓ categories. The numbers may not add to 100% due to rounding.

Category\H decay mode	WW	$\tau\tau$	ZZ	other
$\ell\ell 0\tau_{\text{had}}$ (Same-Sign)	80%	15%	3%	2%
2 ℓ 1 τ_{had} (1 τ)	35%	62%	2%	1%
3 ℓ (3 leptons)	74%	15%	7%	4%
1 ℓ 2 τ_{had} (2 τ s)	4%	93%	0%	3%
4 ℓ (4 leptons)	69%	14%	14%	4%

decay inside the jet. The output of the tagger corresponds to a 70% b-jet efficiency Working Point (WP).

5.2.1.2 Electron definitions

The electrons are reconstructed by a standard algorithm of the experiment [76] and the electron cluster is required to be with $|\eta_{cluster}| < 2.47$. Electrons in the transition region, $1.37 < |\eta_{cluster}| < 1.52$, are vetoed. Electrons passing the VeryTight Likelihood algorithm are selected. On top of the standard identification, additional relative calorimeter and tracking isolation as well as track impact parameter cuts are applied. The tracking isolation variable ($PtCone20/P_T$) used is common among all analyses: All tracks within a cone size of $\Delta R = 0.2$ around the electron candidate with momentum greater than 400 MeV contribute to the isolation energy. The impact parameter cuts used the longitudinal projection along the beam line ($z0 \sin \theta$) and the transverse projection divided by the parameter error ($d0$ significance). These cuts are used in particular to suppress the heavy-flavor and conversion backgrounds.

5.2.1.3 Muon definitions

The “tight” identification working point is used, which effectively requires the muon tracks to be a combined fit of inner detector hits and muon spectrometer segments. Muons are further required to pass standard inner detector track hit requirements [77].

Relative Tracking and calorimeter isolation as well as track impact parameter cuts are also applied. The tracking isolation variable used is similar to the one used by the electrons and discussed above. In addition a cell-based $EtCone20/P_T$ relative isolation variable was also used. A pile-up energy subtraction based on the number of reconstructed vertices in the event is applied. As for electrons, impact parameter, $d0$ significance, and $z0 \sin \theta$ cuts are also applied.

5.2.1.4 Hadronic tau definitions

Hadronically decaying τ candidates (denoted as “hadronic τ ” or τ_{had}) are reconstructed using clusters in the electromagnetic and the hadronic calorimeters [78]. Hadronic tau candidates are seeded with the anti- k_t algorithm described in the jet section. They are required to have p_T greater than 25 GeV and a pseudo-rapidity $|\eta| < 2.47$. Hadronic taus are identified using the *medium* a working point of a Boosted Decision Tree (BDT) method.

Hadronic tau candidates are further asked to have a charge ± 1 and to have either one or three prongs. Electron veto, with *loose* BDT working point, is applied to reject electrons.

5.2.1.5 Overlap Removal

Overlap removal is applied to all fully identified objects, based on overlapping cones in ΔR . The order and the ΔR cut is given in table 5.3. μ -jet overlap removal cut is tuned to $\Delta R < 0.04 + k_T/p_T^\mu$, where p_T^μ is the muon transverse momentum and k_T is an empirical scale parameter (here $k_T = 10$ GeV is used) optimised for multijet background rejection. This due to the decreasing angular distance between the charged lepton and the b-quark as the top quark Lorentz boost increases.

5.2.2 Event selection

All events considered in this analysis are required to pass single-lepton trigger. Selected events are required to include exactly one light lepton with $p_T > 25$ GeV, and exactly two hadronic τ candidates (τ_{had}), with $p_T > 25$ GeV. The τ_{had} candidates must have opposite charge. In order to suppress the $t\bar{t}$ +jets and $t\bar{t} + V$ backgrounds, events must include at least three reconstructed jets. To suppress diboson and single-boson backgrounds, at least one of the jets must be b-tagged. This final state

Table 5.3: Object Overlap Removal Cuts

Static Object	Removed Object	ΔR Cut
Muon	Electron	0.1
Electron	Jet	0.3
Jet	Muon	$0.04 + \frac{10\text{GeV}}{p_T}$
Electron	Tau	0.2
Muon	Tau	0.2
Tau	Jet	0.3

is primarily sensitive to $H \rightarrow \tau^+\tau^-$ decays, allowing use of the invariant mass of the visible decay products of the $\tau_{\text{had}}\tau_{\text{had}}$ system (m_{vis}) as a signal discriminant. Signal events are required to satisfy $60 < m_{\text{vis}} < 120$ GeV.

5.3 Optimisation of the τ_{had} selection

In the $1\ell 2\tau_{\text{had}}$ channel, we found that the optimal selection is: τ_{had} candidates that pass Loose electron veto and medium tau ID, with a symmetric p_T cut of 25 GeV. This optimization study is described in details below.

The significance and expected signal event yields were checked for different configurations of the tau p_T , tau ID quality, and the lepton vetoes, and separately for loose, medium and tight tau ID. Also, the effect when including tau triggers was checked. The optimization study was done by requiring the $1\ell 2\tau_{\text{had}}$ channel preselection cuts – at least four jets where one of the jets is a b-jet and with at least one lepton matched to one of the applied triggers. The significance is checked for either assuming no systematic uncertainties or assuming 30% on ttbar and 20% on ttV backgrounds.

Figure 5.3.1 shows the results when omitting or applying different electron vetoes (electron veto BDT). While no veto gives the largest yield and larger sensitivity, yet a Loose electron veto is essential for rejecting electrons faking hadronic τ s. Thus a loose electron veto is kept for the τ_{had} selection. This study was done using a tau p_T cut of 15 GeV.

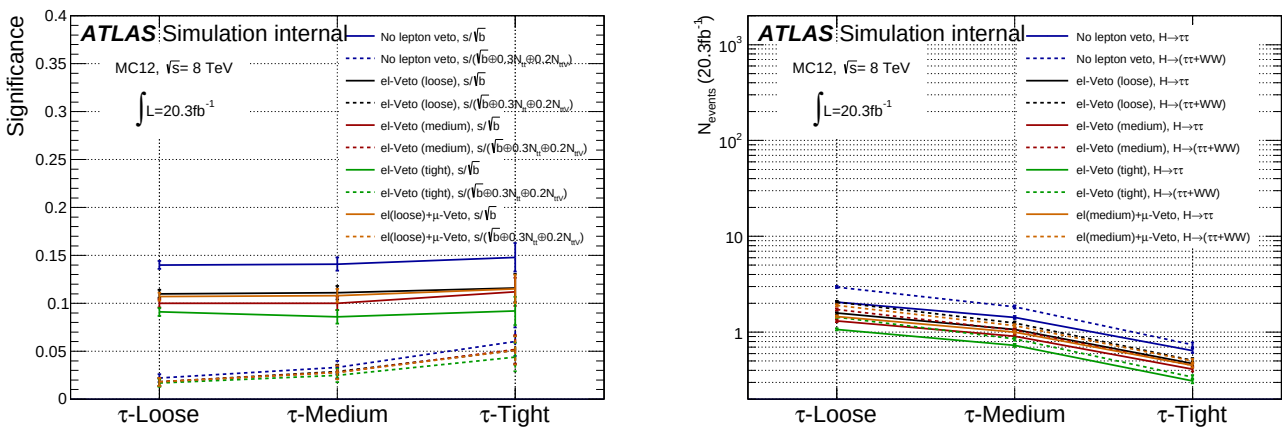


Figure 5.3.1: Significance (left) and event yields (right) for different electron vetoes and tauID qualities. Loose electron veto and medium taus gives the best performance.

Figure 5.3.2 shows the results when varying the p_T cut on the tau objects. This is done either by applying the same cut on both objects or by varying the cuts independently. The lowest possible p_T cut is 15 GeV, as recommended from the tau performance group, so the cut can only be tightened. A symmetric cut of 25 GeV was chosen as the best result.

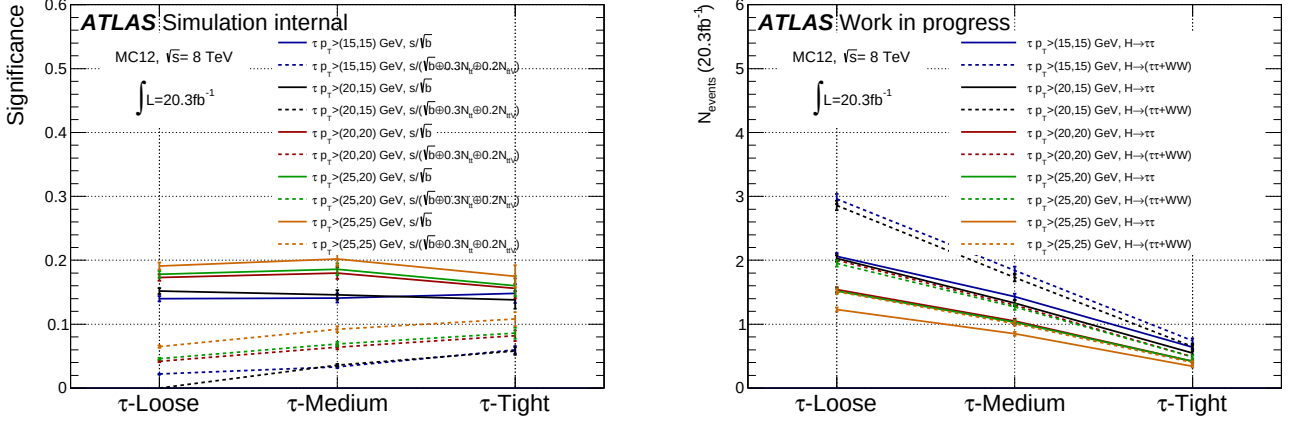


Figure 5.3.2: Significance (left) and event yields (right) when varying the p_T cut on the τ_{had} objects. A good performance is achieved for symmetric cuts of 25 GeV for both τ_{had} .

Figure 5.3.3 shows the results when including next τ_{had} -triggers¹ For lepton-tau triggers, leptons p_T were reduced to 20 and 17 GeV for electrons and muons respectively, and for di-tau trigger, the leading tau was selected with a $p_T > 30$ GeV. It has been studied for different minimum transverse momentum cuts. In the nominal analysis, only single lepton triggers are considered. It is found that though the tau triggers increase the event yield, and improve the sensitivity about $\sim 20\%$. Still, the advantage of the τ_{had} -triggers might be not significant due to the uncertainty of the τ_{had} -triggers.

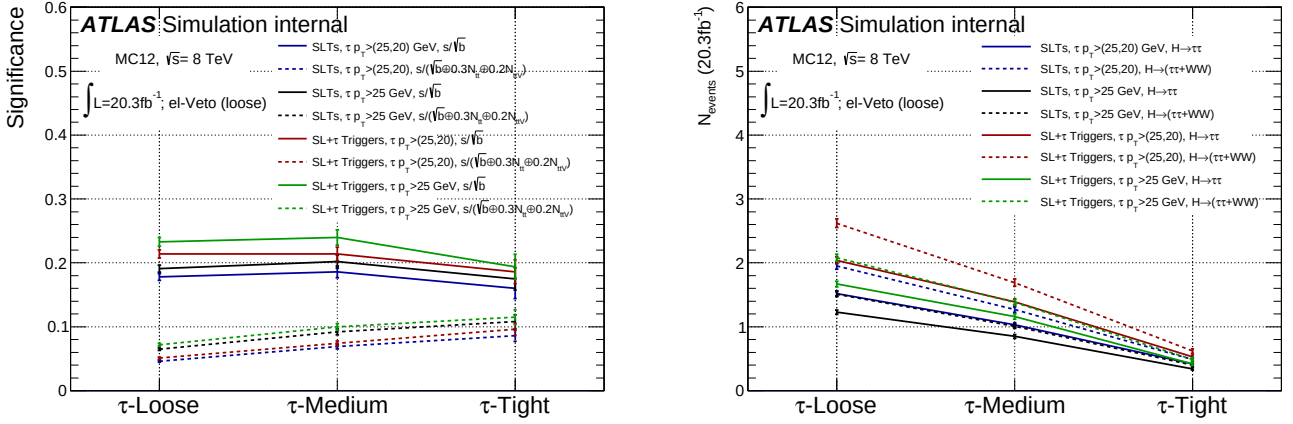


Figure 5.3.3: The significance (left) and event yields (right) when including also tau triggers in addition to single lepton triggers (SLT). At this point while $\sim 20\%$ improvement of sensitivity is achieved by adding τ triggers.

In conclusion, the cuts that found to be optimal are: Loose electron veto, medium tau ID, τp_T cut of 25 GeV. Tau trigger was not used in the analysis due to uncovered systematic uncertainty.

¹EF_tau20Ti_medium1_e18vh_medium1, EF_tau20Ti_medium1_mu15i, EF_tau29Ti_medium1_tau20Ti_medium1.

5.4 Background modelling

5.4.1 Strategy to estimate fake τ 's

The $1\ell 2\tau_{\text{had}}$ channel targets the signal process $t\bar{t}H \rightarrow \tau^+\tau^-$, where the pair of top quarks decays semi-leptonically. To select this process, we require two reconstructed hadronic τ s, one isolated lepton and at least three jets of which at least one needs to be b-tagged. The inclusive signal region is defined as follows:

- Exactly two Medium ID τ_{had} with opposite sign.
- Exactly one isolated electron or muon that is matched to the single lepton trigger.
- At least three jets and at least one of them is b-tagged.
- $60 \text{ GeV} < m_{\text{vis}}^{\tau\tau} < 120 \text{ GeV}$.

The reconstruction of τ_{had} is based on several discriminating variables which are combined into a MVA [78]. A data-driven estimation of the τ_{had} fake rates is essential for reducing potential systematic uncertainties. In this chapter, we describe the data-driven method for the estimation of the fake τ_{had} contribution to the signal region, which is derived using the matrix-method approach.

5.4.1.1 Estimation of the fakes

The estimation of the backgrounds with at least one fake reconstructed τ_{had} is derived from the matrix-method (MM) approach. Under several assumptions, the MM formalism can be simplified to the ABCD method, which is described in detail in Appendix A.

In the analysis we select two reconstructed τ_{had} objects, that pass *Medium* ID selection criteria. The pair of reconstructed τ_{had} s is required to have opposite charges. Therefore, each one of the τ_{had} will have either same or opposite charge with respect to the reconstructed lepton. Denote by SCS- τ - reconstructed τ_{had} with same charge sign to the reconstructed lepton, and by OCS- τ - reconstructed τ_{had} which has an opposite charge sign to the reconstructed lepton.

The ABCD approach relies on relaxing the τ_{had} ID selection criteria from *Medium* to *Loose*, and defines 4 orthogonal regions:

- region A - both OCS and SCS τ_{had} pass *Medium* tau ID - which is the SR
- region B - both OCS and SCS τ_{had} pass *Loose* tau ID, but only the OCS τ_{had} passes *Medium* tau ID.
- region C - both OCS and SCS τ_{had} pass *Loose* tau ID, but only the SCS τ_{had} passes *Medium* tau ID.
- region D - both OCS and SCS τ_{had} pass *Loose* tau ID, but fail *Medium* tau identification cut.

As it will be shown here, the SCS- τ_{had} is always a non-prompt τ_{had} for backgrounds where at least one fake τ_{had} is involved. This is because the dominant fake contribution arises from $t\bar{t}$ decay, where only the τ_{had} with the opposite sign to the reconstructed lepton can be a prompt τ . Therefore, the efficiency to pass *Medium* tau ID is independent of nature and reconstruction efficiency of the OCS- τ or in other words $N_A/N_B = N_C/N_D$. In the ABCD method, the contribution of the irreducible backgrounds (with a prompt lepton and a pair of prompt τ_{had} candidates) is subtracted from the data.

Hence, the contamination of the fake τ_{had} backgrounds in the SR can be estimated from:

$$N_A^{\text{fakes}} = \theta \times (N_B - N_{\text{irred}}^{\text{MC}}) \quad (5.4.1)$$

where $\theta = N_C/N_D$ is the fake-factor, that transforms the fake background kinematics from region B into the SR. N_B is the number of data events in region B. N_{irred}^{MC} is the contamination of region B with irreducible processes containing two prompt τ_{had} candidates, such as VV, ttV or ttH, which are estimated from the MC. The irreducible backgrounds scaled with the fake rates are subtracted from the region B. To keep the same jet multiplicities between the region AB and CD, events with exactly two *Loose* τ_{had} are considered, and in the derivation of the fake estimation, the jets that overlap with the *Loose* τ_{had} are rejected.

5.4.1.2 Fake τ_{had} sources

The dominant background in the $1\ell 2\tau_{\text{had}}$ channel is the $t\bar{t}$ production, where one or two τ_{had} are fakes from various sources: b-jets, hadronic W boson decays, or jets from a parton shower not originating from $t\bar{t}$ decay. The selected lepton is in 98% a prompt lepton (real lepton coming from the $t\bar{t}$ decay). The two selected τ_{had} candidates (which must have opposite sign to each other) are categorized with respect to the lepton charge as defined above (OCS and SCS). Using $t\bar{t}$ MC, we study the origin of the τ_{had} candidates for these two categories, which is displayed in figure 5.4.1.

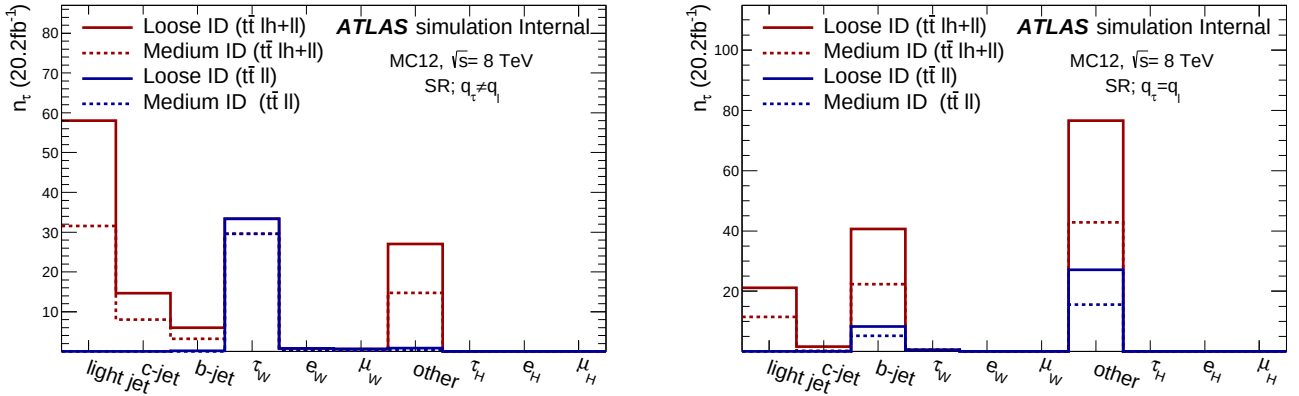


Figure 5.4.1: Sources of τ_{had} , calculated from $t\bar{t}$ MC truth information, for events passing all selection cuts. The plots show the expected number of τ_{had} candidates that pass *Loose* (solid line) or *Medium* (dashed line) identification criteria. The plots also show the contribution from the fully-leptonic $t\bar{t}$ decay mode (blue line) with respect to the semi-leptonic and fully-leptonic $t\bar{t}$ decays modes. Left: The τ_{had} charge is opposite to the lepton charge; Right: The τ_{had} charge is the same as the lepton charge. “other” stands for a fake τ_{had} that is not originating from the hard process.

The same information is also shown in table 5.4, where the fraction of the various origins of our tau candidates is listed for the two categories with respect to the lepton charge. One should note, that the τ_{had} with the same charge as the reconstructed lepton is almost always a “fake” one.

5.4.1.3 Fake rate estimation

The fake rates (also called fake factors), θ , are estimated from regions C and D. The fake factor is defined as the ratio of events in C over D, i.e., $\theta = N^C/N^D$. Since the statistics in these regions C and D are very limited, we relax our selection criteria by dropping $n_{\text{jet}} \geq 3$ and $n_{\text{b-jet}} \geq 1$ cuts. This dedicated “fake-enriched” control region (which will also be called fake CR in the text) is defined as follows:

- Exactly two Loose ID and opposite sign τ_{had}
- Exactly one isolated electron or muon that has been matched to a single lepton trigger.

Table 5.4: The fraction of various sources for τ_{had} , obtained from the truth information of the $t\bar{t}$ MC sample. In our channel, we select two OS taus and one lepton. Therefore, one of the taus always has the same charge as the lepton ($Q_\tau = Q_\ell$), and the other one has opposite charge to the lepton ($Q_\tau \neq Q_\ell$). As can be seen from this table, the origin of the taus is different for these two charge correlations. In particular, in the case of $Q_\tau = Q_\ell$, the taus are almost entirely fake. “Other” labels those taus which are not originating from the hard process, these are for example jets from the parton shower which fake taus.

Source	$Q(\tau_{\text{had}}) = Q(\ell)$		$Q(\tau_{\text{had}}) \neq Q(\ell)$	
	Loose	Medium	Loose	Medium
real τ_{had}	0.38%	0.69%	23.75%	33.70%
W+jets	16.23%	15.16%	51.59%	45.03%
b-jets	28.94%	28.83%	4.27%	3.64%
“other”	54.44%	55.30%	19.24%	16.75%

The fake-factors are then calculated using only those hadronic τ s that are same signed to the selected lepton. We will show later on a closure test to prove the validity of the method even in the presence of non-uniformities (i.e., different numbers of jets) between the SR and this fake CR, see section 5.4.1.4. The fake CR contains $\sim 97\%$ of fake τ_{had} . The composition of this region is shown in figure 5.4.2. The small contamination of this region with real τ_{had} of 3% introduces a negligible systematic uncertainty compared to the statistical uncertainties of the regions used.

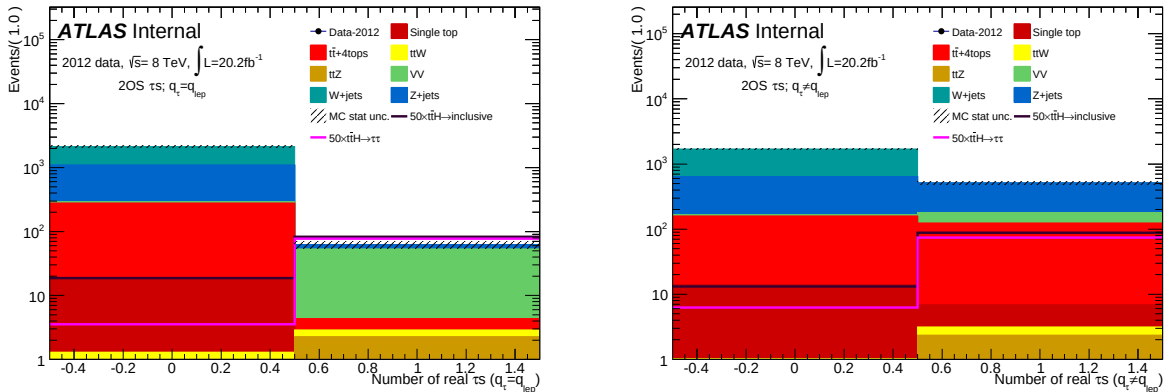


Figure 5.4.2: A number of real τ_{had} for various processes. The left figure shows those tau candidates that have same sign with the lepton. This is the region which is used to extract the fake factors. The right figure shows the same breakdown, but for those hadronic τ s which have an opposite sign to the lepton, this region is not used in the fake estimation.

The fake factors were then obtained from the data in two bins of p_T and two bins of η of the τ_{had} , and also separately for one- and three-prong τ_{had} candidates. In addition to that, the fake factors were also derived separately for two bins of the MV1 (b-tagging) weight. The usage of the MV1 weight for this estimation is motivated as follows: B-jets that are misidentified as hadronic τ s have a different reconstruction efficiency as compared to light jets. Hadronic τ s (mainly 3 track candidates) can have displaced secondary vertices (similar to B-hadrons), resulting in high b-tag weights. Therefore, the τ_{had} MV1 weight of the associated jet is used to distinguish between these different types of jets. The two MV1 bins (*light flavor* and *heavy flavor*) are defined by a cut of 0.7892, which corresponds to a 70% working point. Recall, that no cut on the τ_{had} candidate MV1 weight is used in the actual event selection, only for the estimation of the fake factors. Using these

parametrized fake-factors, the expected number of fake tau events in the signal region can then be obtained by:

$$N_{fakes}^{tt} = \Sigma_{\text{regionB}} (\theta(p_T, \eta, N_{\text{trk}}, \text{MV1})) \times \Sigma_{\text{regionB}} (N^{tj}(p_T, \eta, N_{\text{trk}}, \text{MV1}) - N_{\text{irred}}^{MC}) \quad (5.4.2)$$

Count the events of region B that fall into the categories used for the parametrization, multiply this number by the corresponding θ , and sum it up. This number is then corrected for the amount of irreducible, prompt- τ_{had} processes (VV, ttV, ttH) which is estimated from MC, and amounts to $N_{\text{irred}}^{MC} = 0.73$ events.

The parameterized fake factors for different τ_{had} selections and their fraction in the fake control region are shown in figure 5.4.3 in bins of the p_T and in figure 5.4.4 in bins of η of the tau.

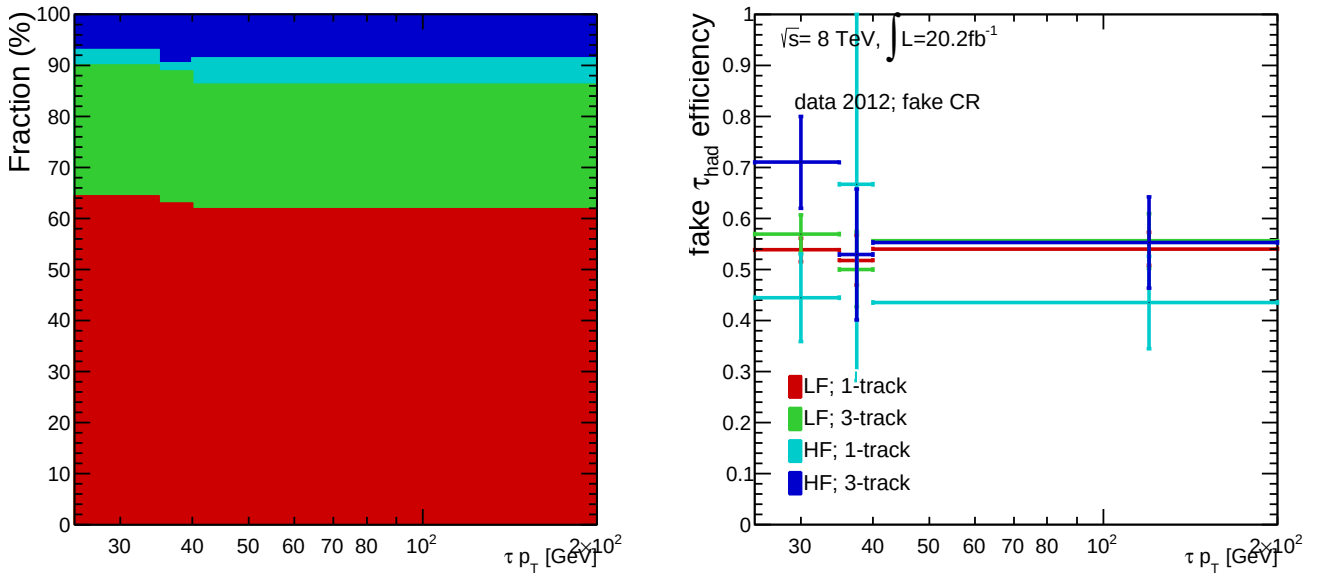


Figure 5.4.3: Fake τ_{had} efficiency to pass MediumID selection criteria ($N_{\text{MediumID}}^{\tau}/N_{\text{LooseID}}^{\tau}$), calculated as a function of τ_{had} transverse momentum for different tau selection (right) and the fraction of the selected τ_{had} in the control region (left). LF denotes τ candidates that has MV1 weight < 0.7892 (light flavor), and HF denotes the τ with MV1 weight > 0.7892 (heavy flavor).

5.4.1.4 Closure tests

The fake factors can have a systematic uncertainty due to the different jet composition between the dedicated fake CR and the signal region (SR) or from small contamination of prompt τ_{had} in the dedicated fake CR. To assess these systematic effects, the following closure tests are performed:

- MC-to-MC: We compare the fake efficiency which is estimated from MC using the fake factor method ($\theta/(1 + \theta)$) to that efficiency which is directly estimated from MC from the regions ABCD ($A/(A + B)$). In the top plots and the bottom left plot of Fig. 5.4.5, the red lines show $\theta/(1 + \theta)$, and the black lines show $A/(A + B)$. For the red lines, the fake factors are not extracted from data, but from MC, using our dedicated fake CR.
- MC-to-Data: We compare the fake efficiency from the fake factor method ($\theta/(1 + \theta)$) between data (black) and MC (red). This is shown in the bottom right plot of Fig. 5.4.5.

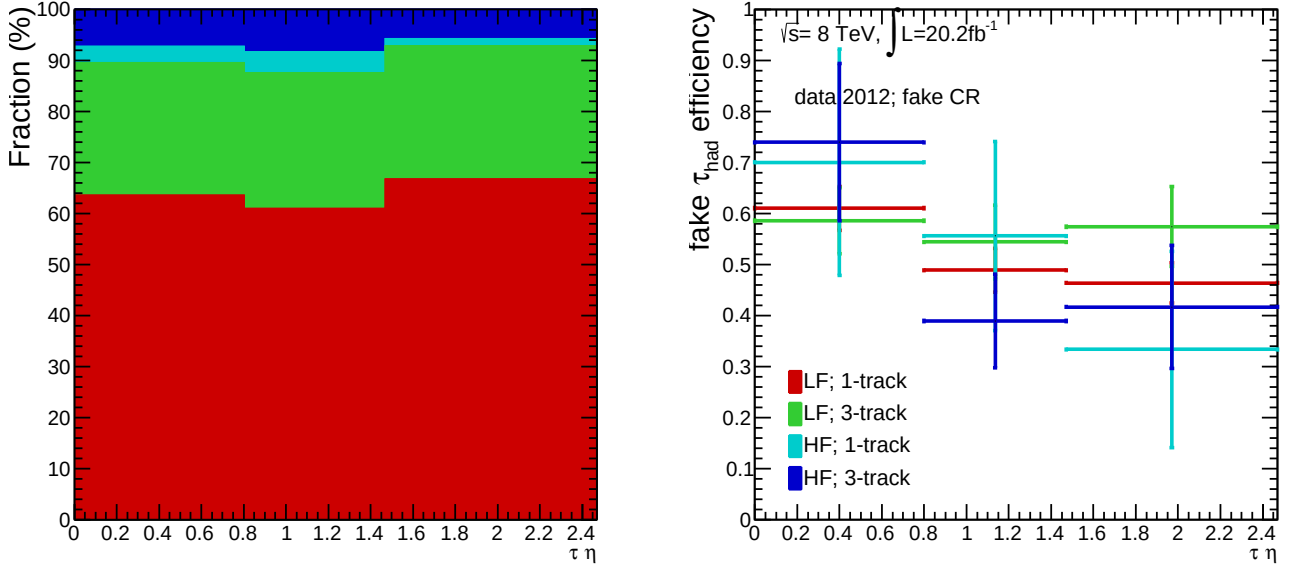


Figure 5.4.4: Fake τ_{had} efficiency to pass MediumID selection criteria ($N_{\text{MediumID}}^{\tau}/N_{\text{LooseID}}^{\tau}$), calculated as a function of η for different τ_{had} selection (right) and the fraction of the selected τ_{had} in the control region (left).

figure 5.4.5 shows these closure tests with different sets of cuts. Good closure of the method is observed for any tested selection within the statistical uncertainties.

No systematic error was applied from the closure tests since the statistical errors are much larger than the systematic non-closures.

5.4.2 Systematic uncertainties and result

The systematic uncertainty of the fake background estimation has two uncorrelated contributions:

- Statistical uncertainty of region B (26%)
- Statistical uncertainty of the fake CR (12.8%)

The uncertainties are considered to be uncorrelated, therefore the total systematic uncertainty is the quadratic sum of these two components. The dominant uncertainty of the method is the statistical uncertainty of region B, which is taken as the square-root of the number of observed events in B times θ .

The observed number of events in the data in regions BCD, and the number of events estimated from MC in regions ABCD (for both full and fast simulation) are shown in figure 5.4.6.

The deficit of events in the region B has been studied with data-MC comparisons, and these comparisons were repeated in regions C and D. Figure 5.4.7 shows the distribution of events in the data compared to the MC expectation for region B and C+B, as a function of lepton type and jet multiplicity. Figure 5.4.8 shows the same distributions in a region with more statistics, after dropping the $n_{\text{jet}} \geq 3$ cut, but keeping the $n_{b-\text{jet}} \geq 1$ cut, in order to enhance the $t\bar{t}$ background. In addition we compare the distribution of the τ types in region B between data and MC in table 5.5.

One notable observation is the discrepancy of observed and expected events for the lepton charge: In MC one can expect about the same size of positive and negative charged leptons, but in data in region B only 4 events have negative charged leptons.

The resulting expected number of fake- τ_{had} events and the systematic uncertainty in the SR is $18.53 \pm 4.8\text{stat}_B \pm 2.37\text{stat}_{\text{fakeCR}} = 18.53 \pm 5.35$ events. We arrive at 18.53 events by multiplying the

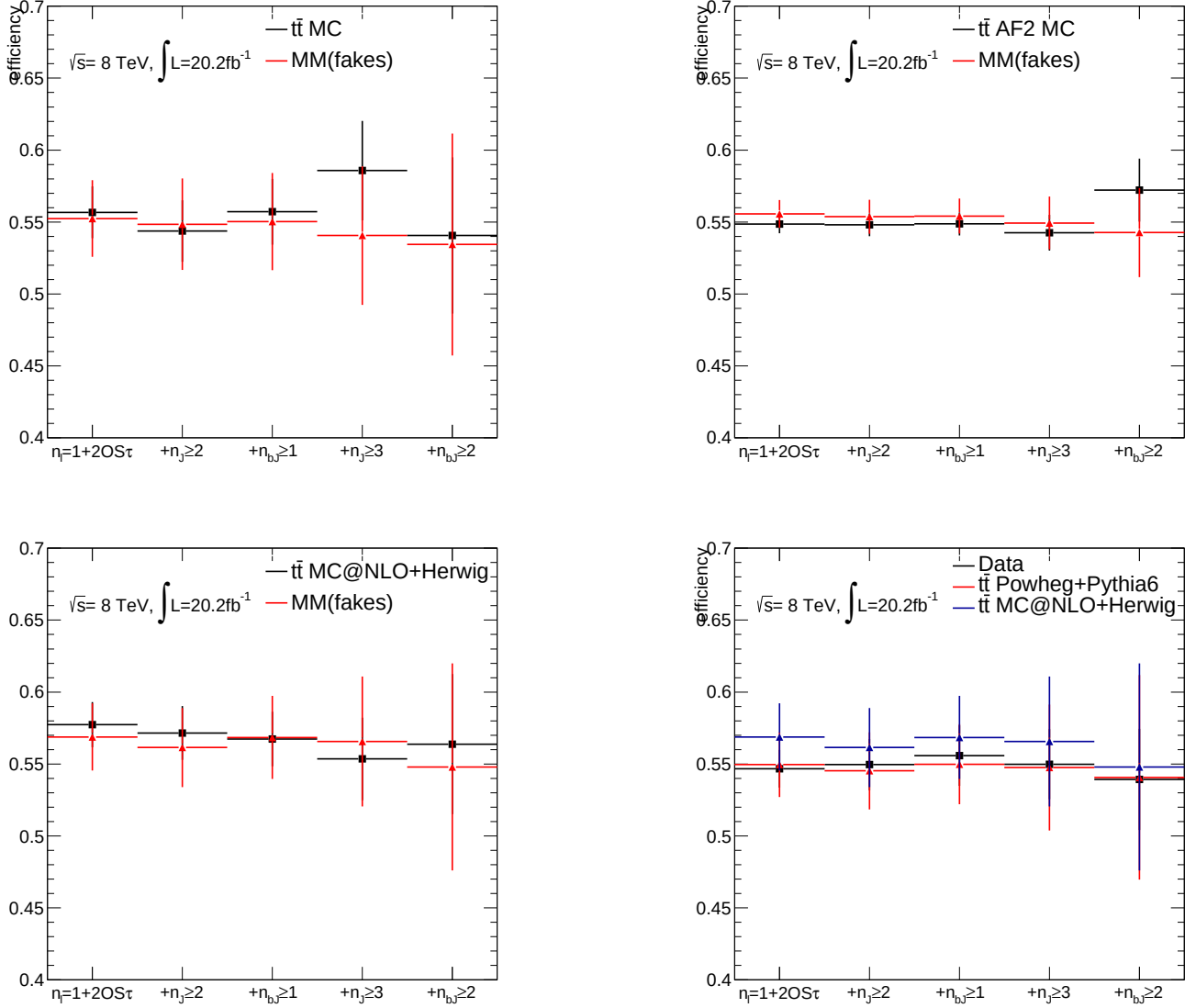


Figure 5.4.5: Fake τ_{had} efficiencies for various selections. The top plots and bottom left plot compare in red the efficiency estimated from MC from the fake factor method ($\theta/(1+\theta)$), and in black the direct MC estimate ($A/(A+B)$). Top left shows Powheg full sim, top right Powheg fast sim, and bottom left MC@NLO+herwig $t\bar{t}$. In the bottom right plot, we compare the fake efficiency estimated from the fake factor method ($\theta/(1+\theta)$) between data (black) and MC (red). These comparisons are done for various selections. A suitable closure is observed within the statistical uncertainties.

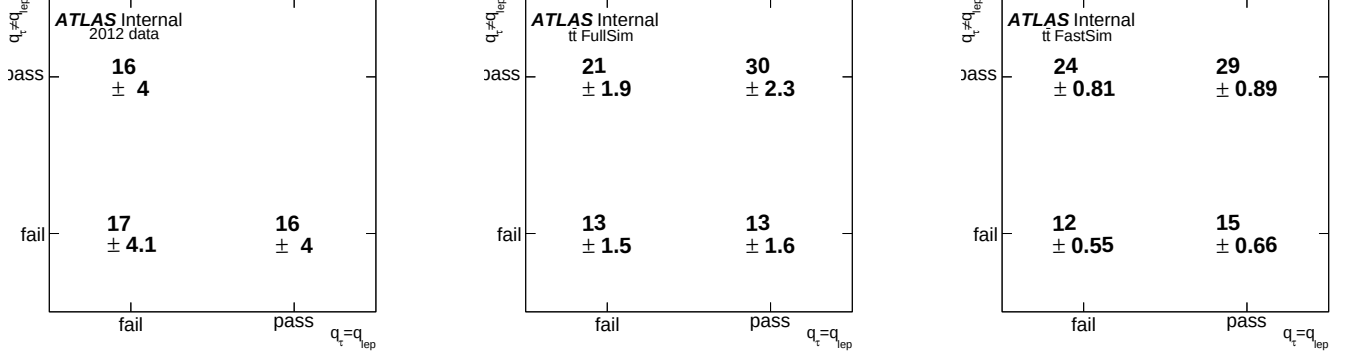


Figure 5.4.6: Event distribution for regions ABCD for data (left), full $t\bar{t}$ simulation (middle) and Fast $t\bar{t}$ simulation (right). The uncertainties are statistical only. In these plots the upper right corner is region A, the upper left one is B, the bottom right is C, and the bottom left is D. In region B 16 events are observed, while 21 events are expected from full MC.

Table 5.5: Distribution of SS τ_{had} types of the data events in region B averaged over p_T and η bins, as a function of MV1 weight (LF - τ_{had} with $MV1 < 0.7892$, HF = τ_{had} with $MV1 \geq 0.7872$) and as a function of number of tracks, compared to the MC predictions. The fake factors estimated from the fake CR in data (DD) or MC and their systematic uncertainty are also shown. The contamination of the region B with irreducible prompt- τ_{had} background (VV, $t\bar{t}V$, $t\bar{t}H$) amounts to 0.74 events, which was estimated from MC, and this is subtracted from the fake estimation.

τ_{had} parametrization	data events	θ_{DD}	MC weighted events	θ_{MC}
LF and 1 track	9	1.15 ± 0.09	13.29	1.07
HF and 1 track	1	0.83 ± 0.23	2.12	0.89
LF and 3 track	5	1.25 ± 0.15	5.25	1.30
HF and 3 track	1	1.71 ± 0.31	3.19	1.57

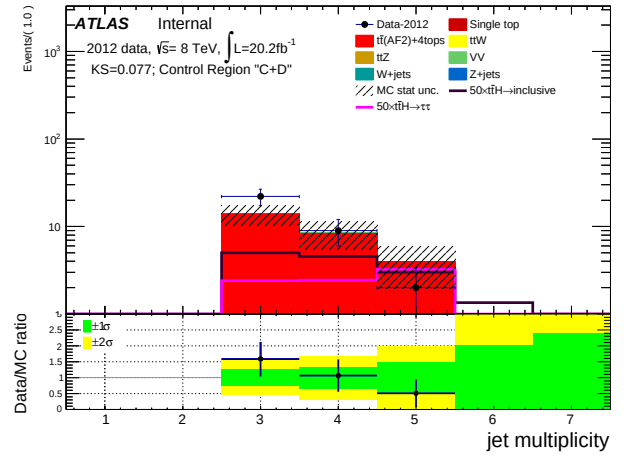
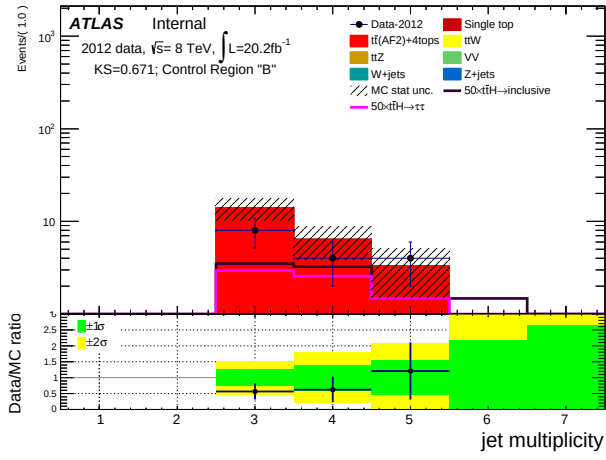
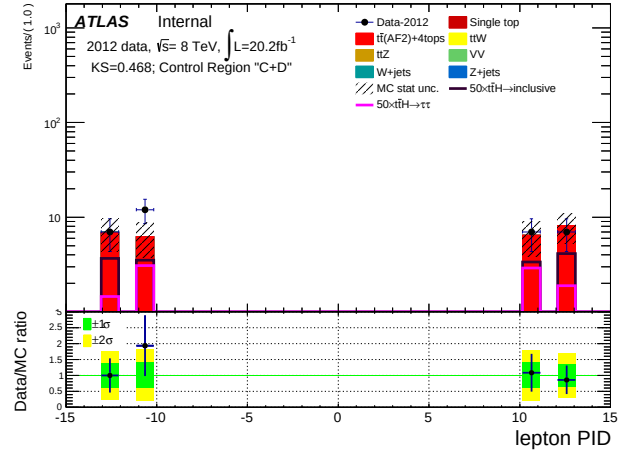
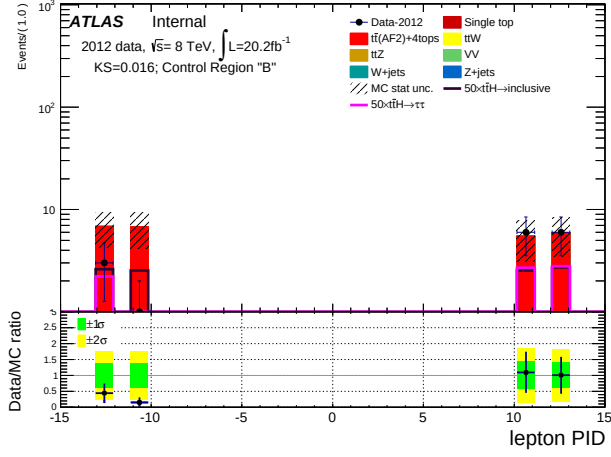


Figure 5.4.7: Distribution of jet multiplicity and lepton PID in the B and C+D control regions, compared to MC predictions. In the DATA/MC ratio plots the green and yellow bands represent statistical uncertainties for 1σ and 2σ , respectively.

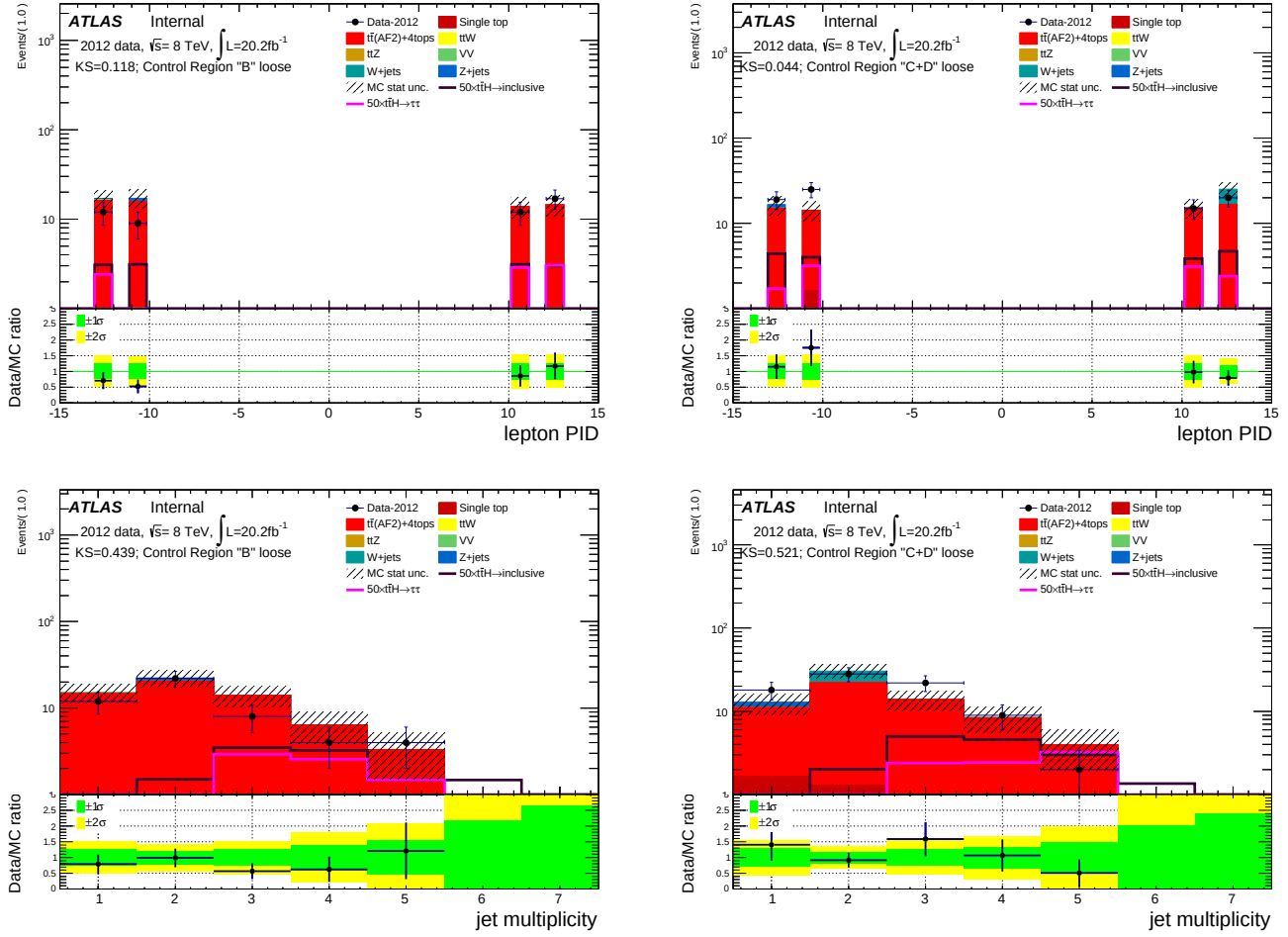


Figure 5.4.8: Distribution of jet multiplicity and lepton PID in the “loose” B and C+D control regions - w/o jet cut, compared to MC predictions. In the DATA/MC ratio plots the green and yellow bands represent statistical uncertainties for 1σ and 2σ , respectively.

observed number of events in B (16 events) with the fake factor θ which is parameterized in various bins (equation 5.4.2). The deficit in region B drives this overall result of the fake estimation in the signal region. The estimated number of fakes is notably smaller than the number of events expected from $t\bar{t}$ MC (29.3 events).

5.4.2.1 Control plots

The results of estimating the fake background using the fake scale factors are shown in this section. Figure 5.4.9 show various kinematical variables obtained at the preselection, while figure 5.4.10 shows several kinematical variables obtained at the preselection + at least 2 jet events. The shapes of the data-driven fake estimations are taken from the data from region B.

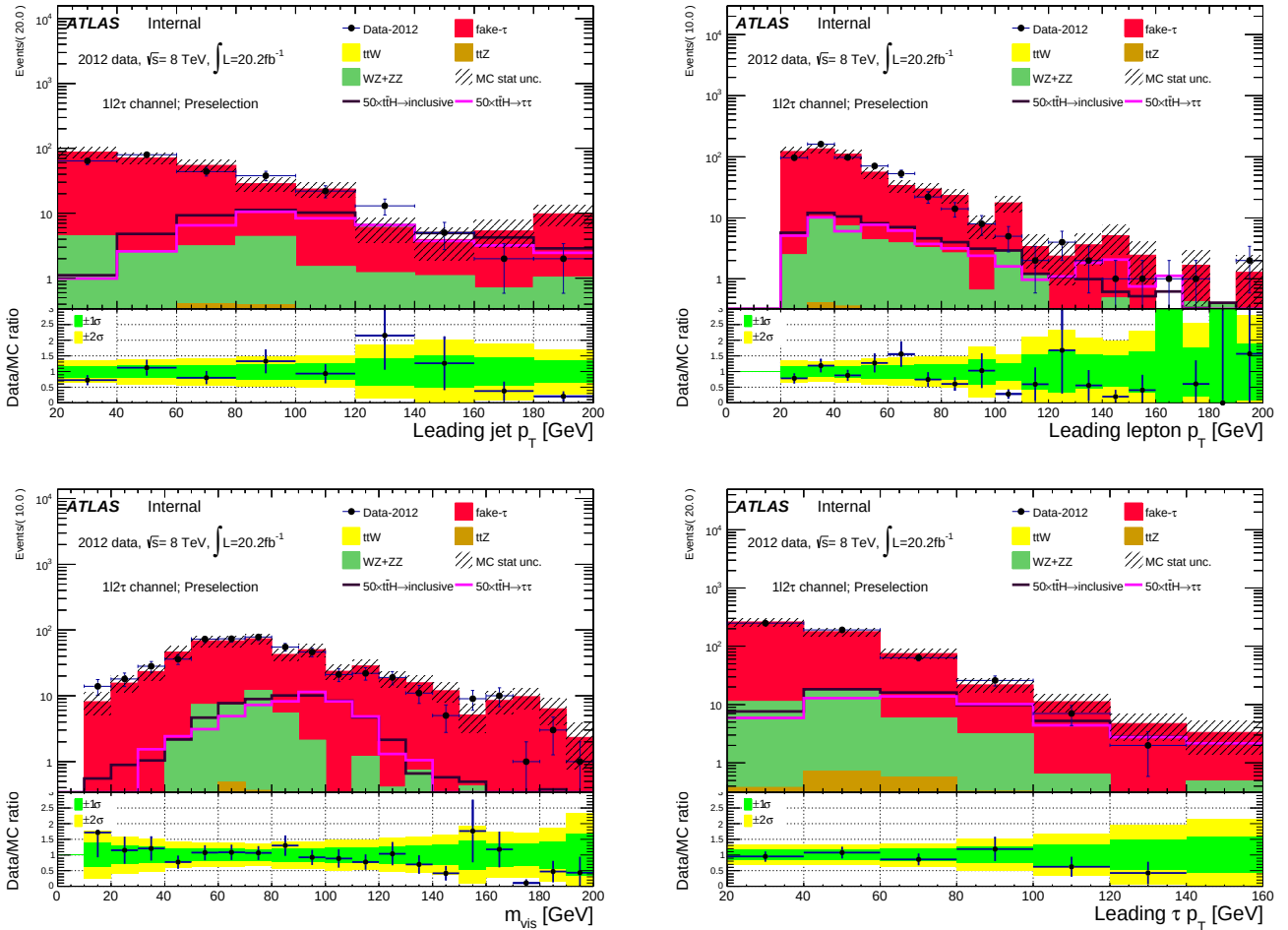


Figure 5.4.9: Distribution of several kinematical variables in the fake CR, where the fake τ_{had} contribution is estimated from the data. In the DATA/MC ratio plot green and yellow bands represent statistical uncertainty for 1σ and 2σ respectively.

A reasonable agreement between data and the estimated backgrounds is achieved with the data-driven fake estimation method.

5.4.2.2 Final background estimate in the tight SR

In order to not get biased by the deficit observed in region B, the fake estimate in the tight SR was not used. Instead, the central value of the $t\bar{t}$ background is estimated from fast-sim MC, and the difference to the fake estimate is assigned as a systematic uncertainty. The difference between the MC estimation and the data-driven fake estimation is calculated in the inclusive SR. The sum

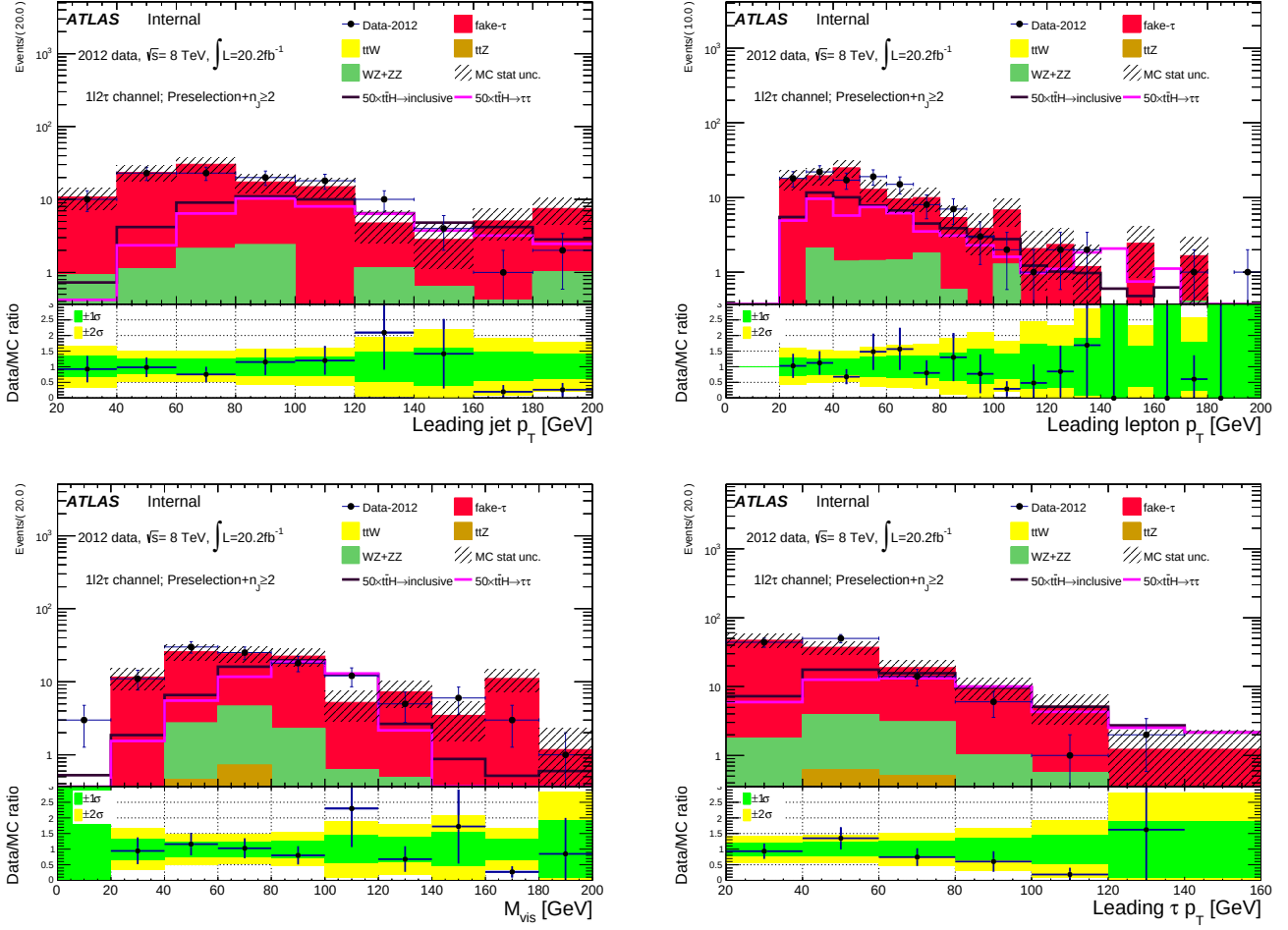


Figure 5.4.10: Distribution of several kinematical variables after preselection level, where the fake τ_{had} contribution is estimated from the data. In the DATA/MC ratio plot green and yellow bands represent statistical uncertainty for 1σ and 2σ respectively.

of the MC estimate (which contains the processes $t\bar{t}b\bar{b}$, VV , $4t\text{ops}$, and $V+\text{jets}$) is 29.04 events. The fake estimate is 18.53 events. The difference is 10.5 events. The relative uncertainty on the MC estimate is therefore 36%. Hence, in the tight SR, we predict $15.1 \pm 5.4(\text{total})$ $t\bar{t}b\bar{b}$ events, which is our most-dominant background. Other MC processes sum up to $1.3 \pm 0.3(\text{stat})$ events.

5.5 Results of the $1\ell 2\tau_{\text{had}}$ channel

The observed yields, and a comparison with the expected backgrounds and $t\bar{t}H$ signal, in $1\ell 2\tau_{\text{had}}$ channel, are shown in Table 5.6.

Table 5.6: Expected and observed yields in $1\ell 2\tau_{\text{had}}$ channel. Uncertainties shown are the sum in quadrature of systematic uncertainties and Monte Carlo simulation statistical uncertainties. “Non-prompt” includes the misidentified τ_{had} background. Rare processes are not shown as a separate column but are included in the total expected background estimate.

Category	Non-prompt	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Expected bkg.	$t\bar{t}H$ ($\mu = 1$)	Observed
$1\ell 2\tau_{\text{had}}$	15 ± 5	0.17 ± 0.06	0.37 ± 0.09	0.41 ± 0.42	16 ± 5	0.68 ± 0.13	10

The jet and electron multiplicities in the events passing the $1\ell 2\tau_{\text{had}}$ signal region selection are shown in figure 5.5.1.

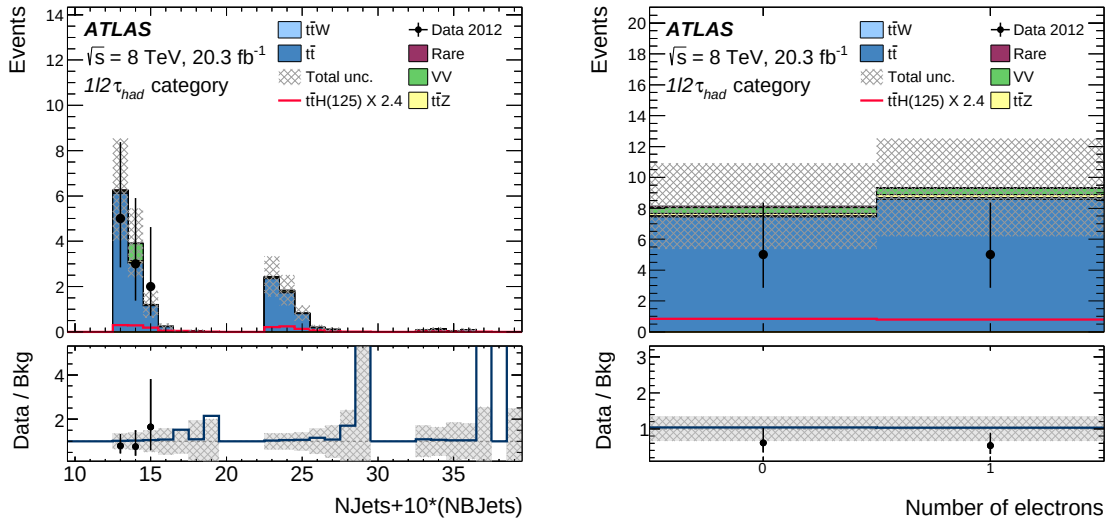


Figure 5.5.1: Jet and electrons multiplicities in the signal region of $1\ell 2\tau_{\text{had}}$ category. The number of jets is $10 \times$ the number of b-tagged jets plus the total number of jets. The hatched bands show the total uncertainty on the background prediction in each bin. The non-prompt spectra are taken from simulation of $t\bar{t}$, single top, $Z+\text{jets}$, and other small backgrounds. The overlaid red line shows the $t\bar{t}H$ signal from the Standard Model. For visibility, the $t\bar{t}H$ signal is multiplied by a factor of 2.4 in the plots. These plots were published in Ref. [7].

In figure 5.5.2, the unblinded $m_{\text{vis}}^{\tau\tau}$ spectrum is displayed. For the sensitivity estimate, only tight SR is considered.

An ATLAS event display for an event that pass all event selection of the $1\ell 2\tau_{\text{had}}$ channel is shown in Figure 5.5.3.

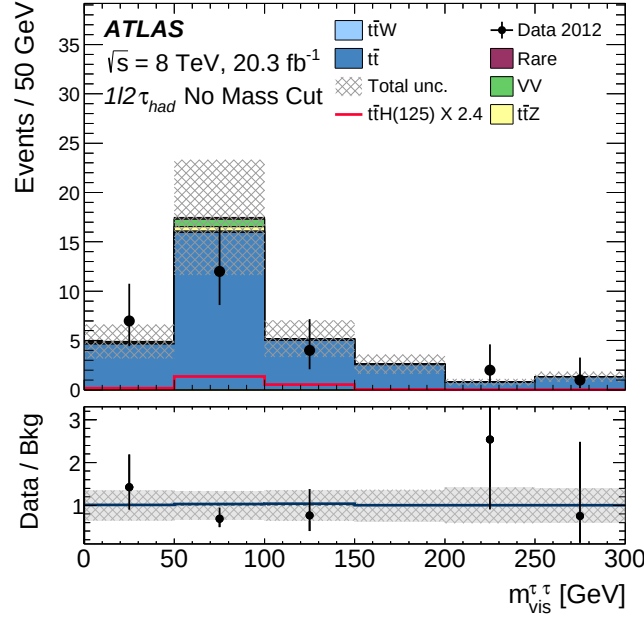


Figure 5.5.2: Fully unblinded the $\tau_{\text{had}}\tau_{\text{had}}$ invariant mass $m_{\text{vis}}^{\tau\tau}$. The background is modelled with MC. The hatched region shows the total uncertainty on the background prediction in each bin and is centred on the total background prediction. The red line shows the $t\bar{t}H$ signal from the Standard Model. For visibility, the $t\bar{t}H$ signal is multiplied by a factor of 2.4. This plot was published in Ref. [7].

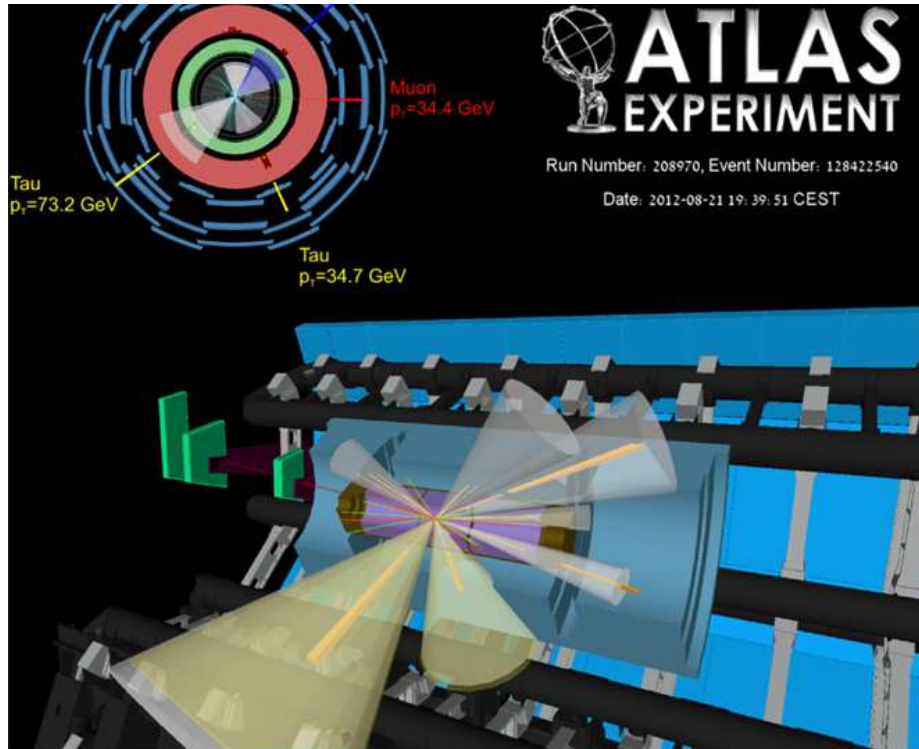


Figure 5.5.3: Event display for a candidate event in the $1\ell 2\tau_{\text{had}}$ category. The $\tau_{\text{had}}\tau_{\text{had}}$ system has $m_{\text{vis}}^{\tau\tau} = 66$ GeV. This plot was published in Ref. [7].

5.6 Final results of all channels in $t\bar{t}H \rightarrow$ multilepton search

The final expected limits with their 1 and 2 σ errors and with or without signal injection are give in table 5.7 and illustrated in figure 5.6.1.

Channels	Obs	Median Signal Injected	Median	68% CL Range	95% CL Range	CMS
$2\ell 0\tau$	6.7	5.0	3.9	[2.8;5.7]	[2.1;8.4]	(9.1/3.6/3.4)
$3l$	6.8	5.1	3.8	[2.7;5.7]	[2.0;8.5]	(6.7/4.7/3.8)
$2\ell 1\tau$	7.5	10.0	8.4	[6.1;13]	[4.5;21]	(6.7/4.7/3.8)
$4l$	18	17	15	[11;23]	[8;39]	(6.8/11.9/8.8)
$1\ell 2\tau_{\text{had}}$	13	19	18	[13;26]	[10;40]	(13.2/-/14.2)
Combined	4.7	3.7	2.4	[1.8;3.6]	[1.3;5.3]	(6.6/-/2.4)

Table 5.7: Expected limits with their 68% and 95% CL errors, expected limits with signal injected, and observed limits. Comparison with available CMS limits (observed/median signal injected/median). **My contribution is the $1\ell 2\tau_{\text{had}}$ channel**, which is marked in red.

The best-fit value of the signal strength $\mu = \sigma_{\text{obs}}^{t\bar{t}H} / \sigma_{\text{SM}}^{t\bar{t}H}$ is determined using a maximum likelihood fit to the data yields of the different analysis categories, which are treated as independent Poisson terms in the likelihood. The $\mu = 1$ hypothesis assumes Standard Model Higgs boson production and decay with $m_H = 125$ GeV; for all other values of μ only the $t\bar{t}H$ production cross section is scaled (the Higgs boson branching fractions are fixed to their SM values). The results of the fit are shown in figure 5.6.2. Combined over all categories, the value of μ is found to be $2.1_{-1.2}^{+1.4}$. In the presence of a signal of SM strength, the combined fit is expected to return $\mu = 1.0_{-1.1}^{+1.2}$. The $\mu = 0$ hypothesis has an observed (expected) p -value of 0.037 (0.18), corresponding to 1.8σ (0.9σ). The $\mu = 1$ hypothesis (the SM) has an observed p -value of 0.18, corresponding to 0.9σ . The observed (expected) upper limit, combining all channels, is $\mu < 4.7$ (2.4).

A full extraction of limits on the top quark Yukawa coupling including the relevant modifications of single top plus Higgs boson production was reported in Ref. [79].

The results are sensitive to the assumed cross sections for $t\bar{t}W$ and $t\bar{t}Z$ production and use theoretical predictions for these values as experimental measurements do not yet have sufficient precision. The best-fit μ value as a function of these cross sections is

$$\mu(t\bar{t}H) = 2.1 - 1.4 \left(\frac{\sigma(t\bar{t}W)}{232 \text{ fb}} - 1 \right) - 1.3 \left(\frac{\sigma(t\bar{t}Z)}{206 \text{ fb}} - 1 \right) \quad (5.6.1)$$

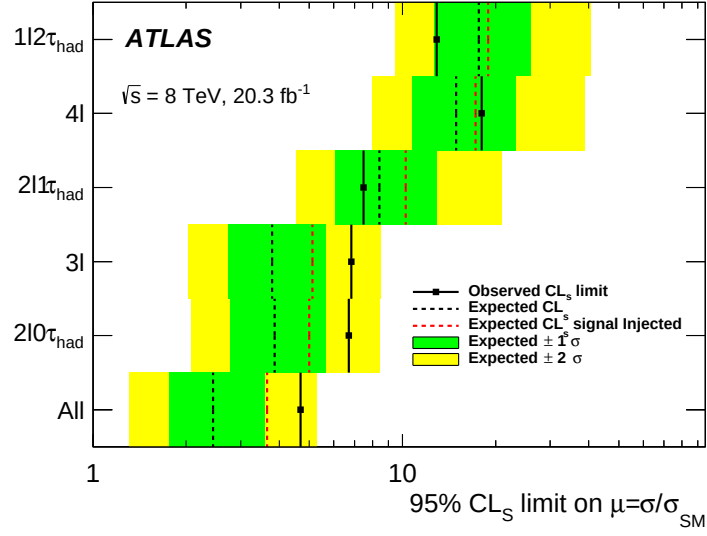


Figure 5.6.1: 95% CL upper limits on μ , determined via the CLs method, for various categories and the combined result. **My contribution is the $1\ell 2\tau_{\text{had}}$ channel.**

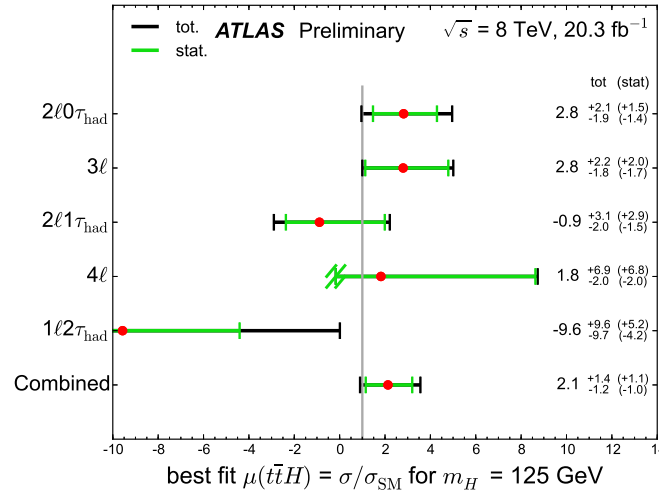


Figure 5.6.2: Best fit values of the signal strength parameter $\mu = \sigma_{ttH}/\sigma_{ttH}^{SM}$ For the 4ℓ Z-depleted category, $\mu < -0.17$ results in a negative expected total yield and so the lower uncertainty is truncated at this point. **My contribution is the $1\ell 2\tau_{\text{had}}$ channel.** This plot was published in Ref. [7].

CHAPTER 6

Two Higgs doublet models (2HDM)

This chapter contains no original work. It describes the Two Higgs doublet model (2HDM) which is background material for chapter 7.

6.1 Introduction

The Higgs sector of the SM can be easily extended by introducing a second complex doublet of the Higgs field. Then, from the eight degrees of freedom introduced by the two complex doublets, three become longitudinal states of the Z and W bosons after electroweak symmetry breaking, and five physical Higgs bosons remain: two charged (H^+, H^-), two neutral CP-even scalars (H, h) and one CP-odd neutral pseudoscalar (A).

There are four types of 2HDM commonly discussed. In type-I, all fermions couple to one of the Higgs doublets. In type-II, up-type quarks couple to a different Higgs doublet than down-type quarks (and charged leptons). In the lepton-specific type, all leptons couple to one of the Higgs doublets, and the quarks to the other. In the flipped-model, up-type quarks and charged leptons couple to the same doublet.

6.2 Production and decays of the Charged Higgs boson in 2HDM

In a type-II 2HDM, which corresponds to the Higgs sector of the Minimal Supersymmetric Standard Model (MSSM) [80–84], the production and decay of the charged Higgs bosons¹ are partly dependent on its mass $m_{H^\pm}$. For H^+ masses below the top-quark ($m_{H^+} < m_{\text{top}}$, where m_{top} is the top-quark

¹In the following, charged Higgs bosons are denoted $H^\pm$ with the charge-conjugate $H^\mp$ always implied. Generic symbols are also used for particles produced in association with charged Higgs bosons and in their decays.

mass), the primary production mechanism is through the decay of a top quark, $t \rightarrow bH^+$. The leading source of top quarks at the LHC is via $t\bar{t}$ production. For H^+ masses above the top-quark mass ($m_{H^+} > m_{\text{top}}$), the leading H^+ production mode at the LHC is in association with a top quark which can be described as either in the four-flavor (4FS) or the five-flavor scheme (5FS). In the former, the bottom quark mass is considered to be on the same order of magnitude as the other hard scales involved in the process, then the bottom quark is not endowed with a parton distribution function (PDF) and emerges from an additional gluon splitting ($gg \rightarrow tHb$). Instead, in five-flavor scheme, the bottom quark mass is treated as a massless parton, thus the tree-level diagram is initiated by a bottom-quark ($gb \rightarrow tH$). For H^+ masses close to the mass of the top quark ($m_{H^+} \sim m_{\text{top}}$) finite top-width effects as well as the interplay between top-quark resonant and non-resonant diagrams cannot be neglected. Therefore, the full process $pp \rightarrow H^\pm W^\mp b\bar{b}$ (with massive bottom quarks) including non-resonant, single-resonant and double-resonant contributions, has to be considered (see figure 6.2.1).

The production and decays of the charged Higgs boson are also controlled by the parameter $\tan \beta$, defined as the ratio of the vacuum expectation values of the two Higgs doublets. Figure 6.2.2 shows typical production cross sections for heavy charged Higgs bosons in a type-II 2HDM at $\sqrt{s} = 13$ TeV. An overview of the cross-section estimation in the intermediate-mass region is given in reference [85], where several production modes and their interference are taken into account. Figure 6.2.3 shows a two-dimensional plot of production cross section as a function of $\tan \beta$ and m_{H^+} for 4FS in the 2DHM.

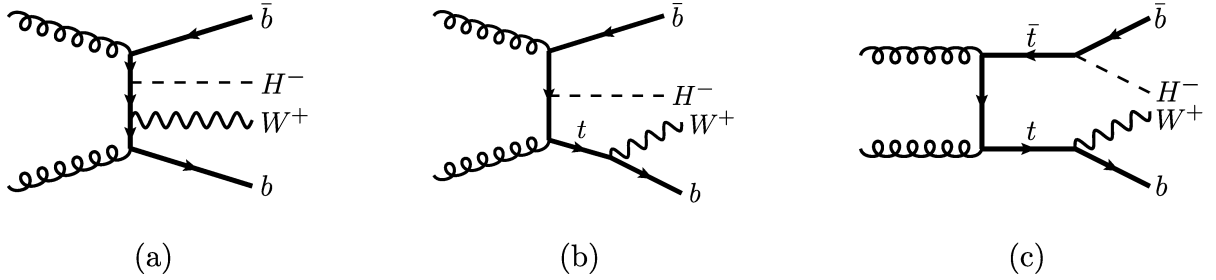


Figure 6.2.1: Sample LO diagrams for the full $pp \rightarrow H^\pm W^\mp b\bar{b}$ process: (a) non-resonant top-quark contribution; (b) single-resonant top-quark contribution; (c) double-resonant top-quark contribution. This figure is taken from Ref. [85].

In the MSSM, some benchmark scenarios have been defined, which keep a low number of free parameters in the theoretical model. In some scenarios, such as $m_h^{\text{mod}+}$ [89], the top-squark mixing parameter is chosen such that the mass of the lightest CP-even Higgs boson, m_h , is close to the measured mass of the Higgs boson that was discovered at the LHC. A different approach is employed in the hMSSM [90] scenario, in which the measured value of m_h can be used, and the non-observation of superparticles at the LHC is taken into account by setting the SUSY-breaking scale to $M_S > 1$ TeV. The branching fractions for H^+ decays into SM particles are displayed in figure 6.2.4, as a function of m_{H^+} , for $\tan \beta = 10$ and $\tan \beta = 50$, in the $m_h^{\text{mod}+}$ scenario. For $\tan \beta > 3$, light charged Higgs bosons decay mainly via $H^+ \rightarrow \tau\nu$ [91]. Above the top-quark mass, the branching fraction $\text{BR}(H^+ \rightarrow \tau\nu)$ can still be substantial (at least 10%), depending on the value of $\tan \beta$.

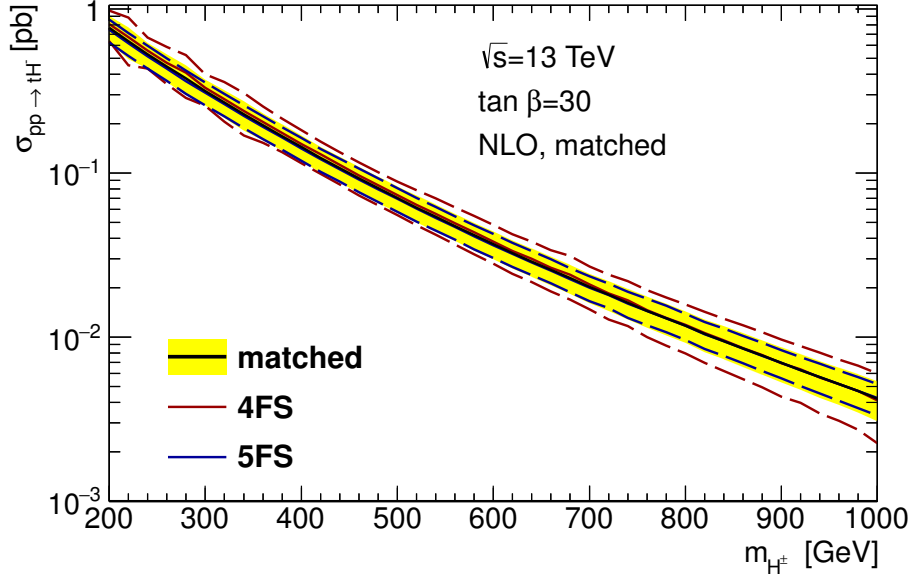


Figure 6.2.2: Production cross section for the heavy charged Higgs boson (i.e. resulting from the associated production with a top quark), as a function of m_{H^+} , in a type-II 2HDM with $\tan \beta = 30$ [86]. The predictions are shown for the four-flavor and five-flavor schemes, as well as for their combination, computed according to the Santander-matching rule [87].

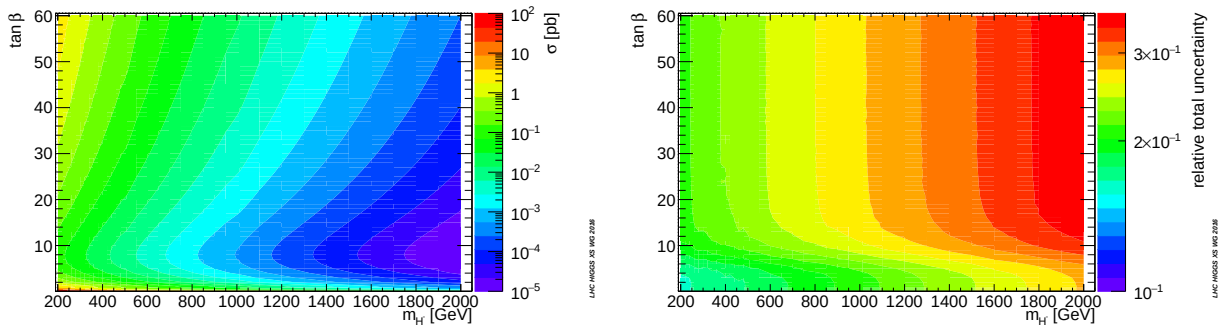


Figure 6.2.3: Two-dimensional plot of the charged Higgs boson production cross section (left) and average relative uncertainty (right) as a function of $\tan \beta$ and m_{H^+} values in the 4FS of the 2HDM. This plot is from Ref. [88].

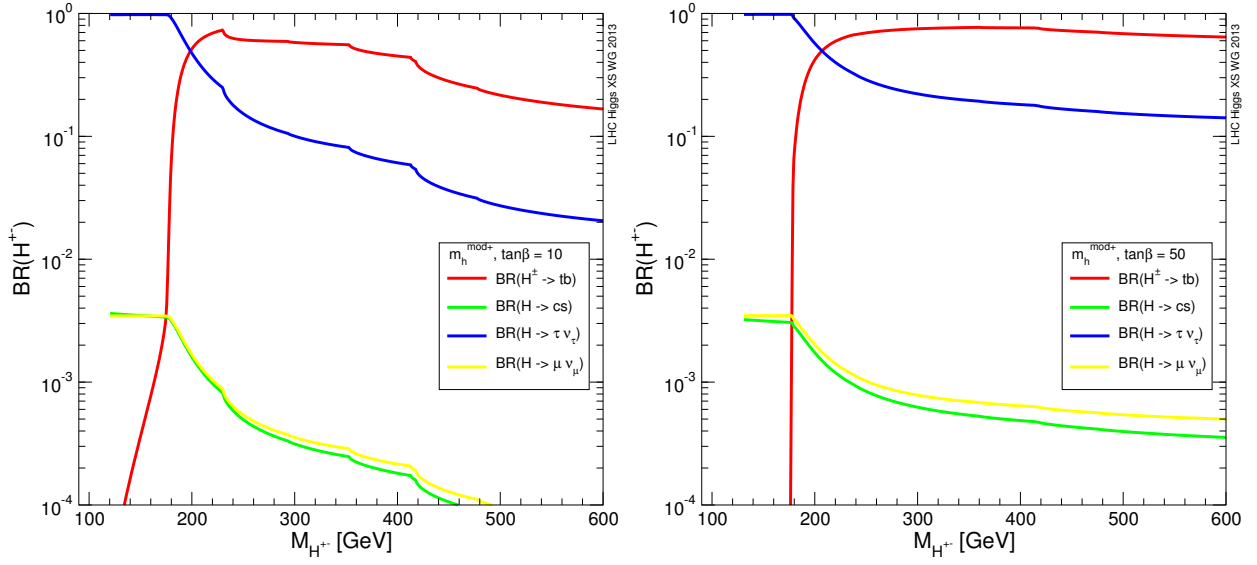


Figure 6.2.4: Branching fractions of the charged Higgs boson as a function of m_{H^+} , for $\tan\beta$ values of 10 (left) and 50 (right), in the $m_h^{\text{mod}+}$ scenario of the MSSM. This plot is from Ref. [92].

CHAPTER 7

Search for charged Higgs bosons

This chapter is based on reference [9]: “*Search for the charged Higgs bosons produced in association with a top quark and decaying via $H^\pm \rightarrow \tau\nu$ using pp collision data recorded at $\sqrt{s} = 13\text{TeV}$ by the ATLAS detector*”, and on reference [11]: “*Search for charged Higgs bosons in the τ +jets and τ +lepton final states with 36.1 fb^{-1} of pp collision data recorded at $\sqrt{s} = 13\text{TeV}$ with the ATLAS experiment*”.

My contribution: I was one of the primary authors of the first paper, and I was involved in various aspects of this publication (Development of cross-check analysis, background estimation, control region studies, derivation production, signal sample validation, theoretical interpretation of the results). I was also the analysis coordinator of the second paper, and I was once again involved in various aspects of this analysis. In the following chapter more details are given on my own analysis.

7.1 Introduction

The discovery of a new scalar particle opens the question of whether this new particle is the Higgs boson of the Standard Model (SM), or one physical state of an extended scalar sector.

The combined LEP lower limit at the 95% confidence level (CL) for the charged Higgs boson mass is about 80 GeV for a type-II 2HDM [93]. The Tevatron experiments placed upper limits in the 15–20% range on $\text{BR}(t \rightarrow bH^+)$ for m_{H^+} in the range 80–150 GeV [94, 95]. The D0 experiment at the Tevatron also searched for a heavy charged Higgs boson with a mass in the range 180–300 GeV using the $H^+ \rightarrow tb$ decay channel and interpreted their result in various types of 2HDM [96]. Light charged Higgs bosons have been searched for at the LHC by both CMS [97] (2 fb^{-1} , $\sqrt{s} = 7\text{ TeV}$) and ATLAS [98, 99] (4.7 fb^{-1} , $\sqrt{s} = 7\text{ TeV}$) in the $\tau\nu$ final state. Neither experiment found evidence for a low-mass charged Higgs boson within the limits of their data samples.

ATLAS and CMS also searched for both light and heavy charged Higgs bosons in proton-proton collisions at $\sqrt{s} = 8\text{ TeV}$ using the τ +jets final state [100, 101]. Upper limits at the 95% CL were

placed on the product $\text{BR}(t \rightarrow bH^+) \times \text{BR}(H^+ \rightarrow \tau\nu)$ at the level of 0.23–1.3% by ATLAS, and 0.16–1.2% by CMS, for $80 \text{ GeV} \leq m_{H^+} \leq 160 \text{ GeV}$. Upper limits on the production cross section times branching fraction $\sigma(pp \rightarrow tH^+ + X) \times \text{BR}(H^+ \rightarrow \tau\nu)$ were placed between 0.76 pb and 4.5 fb by ATLAS, in the charged Higgs boson mass range $200 \text{ GeV} \leq m_{H^+} \leq 1000 \text{ GeV}$, and between 0.38 pb and 25 fb by CMS, for $200 \text{ GeV} \leq m_{H^+} \leq 600 \text{ GeV}$. In addition, using the 8 TeV data, $H^+ \rightarrow WZ$ was searched for in the vector-boson-fusion production mode by the ATLAS collaboration [102]. The CMS collaboration has searched for charged Higgs bosons, using 12.9 fb^{-1} of 13 TeV data for the $H^+ \rightarrow \tau\nu$ decay mode [103] and using 15.2 fb^{-1} of 13 TeV data for the vector-boson-fusion production of H^+ decaying into a WZ pair [104]. No evidence for charged Higgs bosons was found in any of these searches.

In this chapter we will describe a search for charged Higgs bosons, with the $H^+ \rightarrow \tau\nu$ decay mode, using the 13 TeV ATLAS data, in the mass range of 90–2000 GeV (including the intermediate-mass region). The top-quark produced in association with H^+ may decay either hadronically ($t \rightarrow bW \rightarrow bqq'$ yielding a $\tau_{\text{had}} + \text{jets}$ final state) or leptonically ($t \rightarrow bW \rightarrow b\ell\nu_\ell$ yielding a $\tau_{\text{had}} + \text{lepton}$ final state where ℓ is an electron, muon, or leptonically decaying τ). The data used for this analysis are from proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$, collected with the ATLAS experiment at the LHC in 2015 and 2016 and corresponding to an integrated luminosity of 3.2 fb^{-1} and 32.9 fb^{-1} respectively. In Section 7.2, the data, and simulated samples are summarised. In Section 7.3, the reconstruction of physics objects in ATLAS is described. The analysis strategy and event selection are discussed in section 7.4. Section 7.5 deals with data-driven estimations of backgrounds with fake τ objects. Systematic uncertainties are discussed in Section 7.6. Exclusion limits on the production of a charged Higgs boson decaying via $H^+ \rightarrow \tau\nu$, at the 95% CL, are presented in section 7.7. Finally, a summary is given in Section 7.8.

7.2 Data and simulated samples

7.2.1 Monte Carlo simulations

Monte Carlo (MC) simulated samples are used to develop and validate the analysis method, to calculate the signal selection efficiency and some background contributions, as well as for the evaluation of systematic uncertainties. The MC samples are based on the ATLAS full GEANT4 simulation [105] and are reconstructed using the same analysis chain as the data.

For the generation of $t\bar{t}$ and single top-quarks, the POWHEG-BOX v2 [106, 107] generator, with the CT10 PDF [108, 109] sets in the matrix element calculations, is used. The top-quark mass is set to 172.5 GeV for all relevant signal and background samples. Events containing a W or Z boson with associated jets are simulated using SHERPA v2.2.1 [110] together with the NNPDF3.0 NNLO [111] PDF set. Diboson processes (WW , WZ and ZZ) are simulated using the POWHEG-BOX v2 generator, interfaced to the PYTHIA v8.186 parton shower model. All SM background samples are scaled by k -factors such that the total number of events corresponds to the recent theoretical predictions on the cross sections at NNLO or NLO. The simulated events are then weighted to the same number of collisions per bunch crossing as the data.

Simulated events of H^+ signal are generated in three distinct mass regions. In the mass range below the top-quark mass ($90 \leq m_{H^+} < 160 \text{ GeV}$), $t\bar{t}$ events with one top-quark decaying into a charged Higgs boson and a b -quark are generated at the leading order (LO) with MADGRAPH5 [112] (diagram (c) in figure 6.2.1). Both $t\bar{t}$ events with two $t \rightarrow bH^+$ decays and single-top-quark events with a subsequent decay $t \rightarrow bH^+$ have a negligible contribution and are not simulated. In the mass range above the top-quark mass ($200 \leq m_{H^+} \leq 2000 \text{ GeV}$), simulated events of H^+ production in association with a top-quark are generated in the 4FS at next-to-leading order (NLO) with MADGRAPH5+AMC@NLO (diagram (b) in figure 6.2.1). In the intermediate-mass region ($160 \leq m_{H^+} < 200 \text{ GeV}$), the full process $pp \rightarrow H^+Wbb$ is generated at LO with MADGRAPH5

(all diagrams of figure 6.2.1). The Dynamical QCD scales $\mu_R, \mu_F = H_T/2 = 1/2 \sum_i \sqrt{m_i^2 + p_{Ti}^2}$ are considered for charged Higgs boson masses in the range 90–160 GeV, whereas static QCD scales $\mu_R, \mu_F = m_{H^+}/3$ are chosen for the other mass hypotheses. For all H^+ signal samples, the 2HDMtypeII setting [113] is used when generating events¹. The acceptance reduction ranges from 22% for $m_{H^+} = 200$ GeV to <2.5% above 1000 GeV. Since the mass resolution is dominated by experimental effects, the H^+ narrow-width approximation is used, which also allows to quote model-independent results. In order to profit from high statistics, the signal samples are based on the ATLAS fast simulation (AtlFast-II) [115].

Signal samples generated at NLO have $\sim 40\%$ of events with negative weights. This large fraction of negative event weights affects the modelling in the signal region, due to limited statistics after subtracting the events with negative weights. It found that the shape of our final discriminant is consistent within the statistical precision between events with negative and positive weights. Therefore, the unweighted signal samples normalised to the number of expected events obtained using generator weights are used throughout the analysis. A comparison between the weighted and unweighted for the m_T shapes² is shown in figure 7.2.1 for two selected H^+ mass hypotheses.

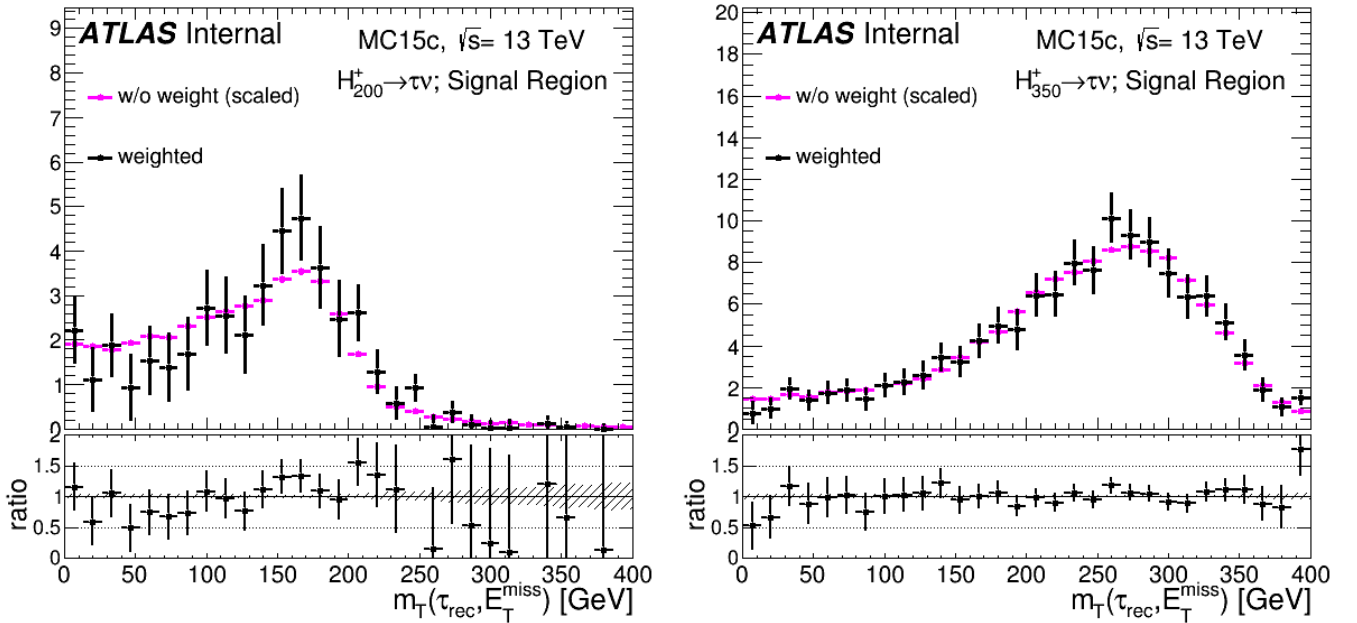


Figure 7.2.1: Comparison between weighted (black) and unweighted (magenta) distributions of the final discriminant (M_T), shown after full event selection for $m_{H^+} = 200$ GeV (left) and $m_{H^+} = 350$ GeV (right).

In order to check potential discrepancies between ATLAS fast and full simulation, distributions of key variables used in the analysis selection were compared on the $t\bar{t}$ sample generated using the POWHEG + PYTHIA as described above. The overlaid distributions obtained from the fast and the full simulations are shown in figure 7.2.2. The two simulations show very good agreement in nearly all distributions with a slight indication for bias towards lower jet multiplicity in the fast simulation. However, the signal acceptance remains in agreement for the two simulations within less than 2%.

¹Differences with respect to the latest recommendations of the LHC Higgs Cross-Section Working Group [85, 114] were found to have a negligible impact.

² m_T – was the discriminating variable used in the publication with the 2015 data [9]. See section 7.4.1 for more details.

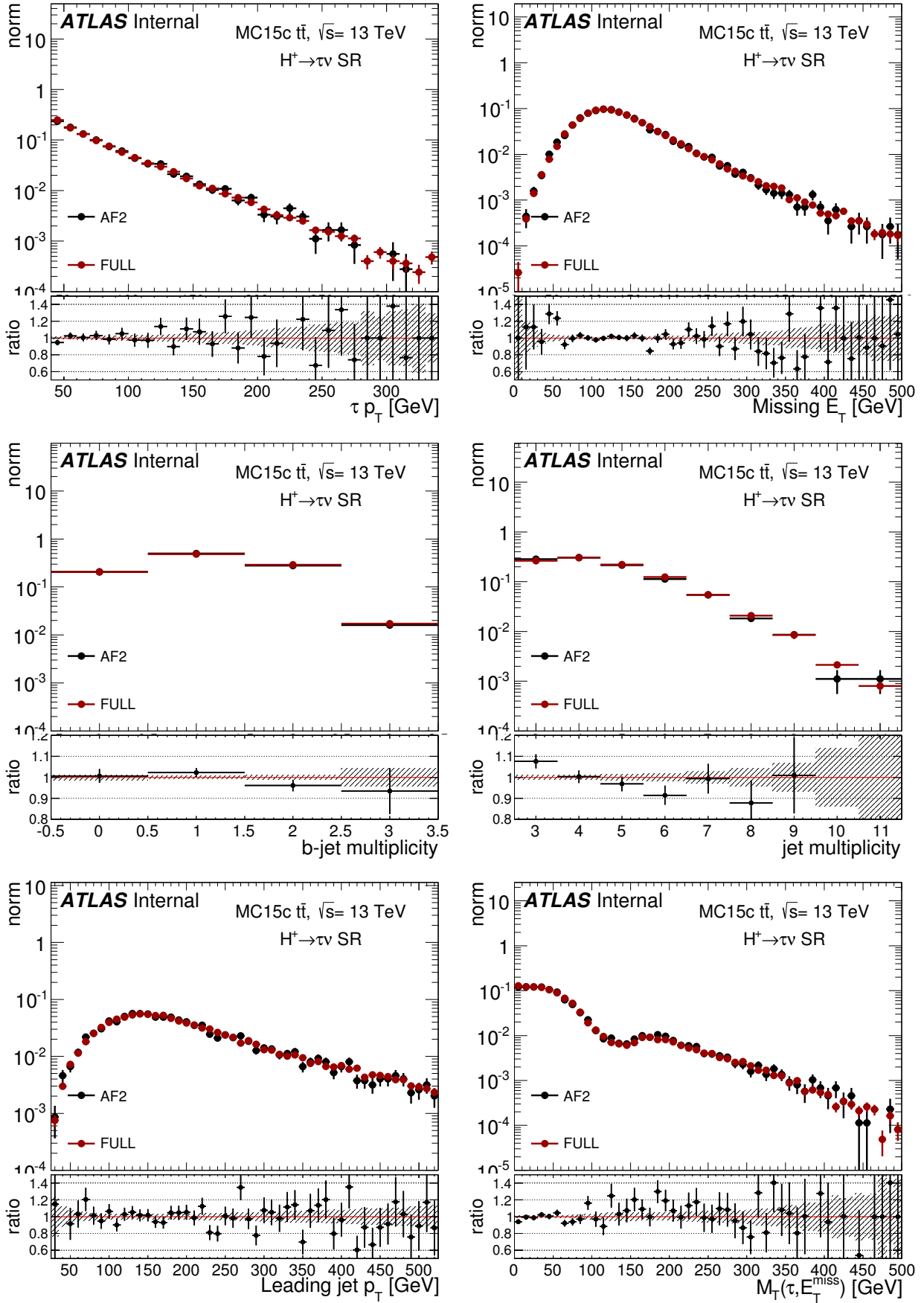


Figure 7.2.2: Comparison of the key kinematical distributions used for selection in the MC15c $t\bar{t}$ events simulated with the fast (AF2) and the full ATLAS simulation.

7.2.2 Data sample

Only events recorded with all ATLAS sub-systems fully operational are used for this analysis. Together with the requirement of having 13 TeV pp collisions with stable beams, this results in a data sample of $36.1 \pm 0.76\text{fb}^{-1}$ recorded during 2015 and 2016 data-taking periods. Data-quality criteria are applied, so that events in which jets are consistent with noise in the calorimeter or non-collision backgrounds are removed.

7.3 Physics object reconstruction

In the ATLAS experiment, hadronic jets are reconstructed from energy deposits in the calorimeters, using the anti- k_t algorithm [73] with a radius parameter $R = 0.4$. Jets are calibrated using simulation-based corrections and in-situ measurements [116]. In the following, jets are required to have a transverse momentum $p_T > 25$ GeV and $|\eta| < 2.5$. A multi-variate technique (Jet Vertex Tagger) relying on jet energy and tracking variables to determine the likelihood that a given jet originates from pile-up [74] is applied to jets with $p_T < 60$ GeV and $|\eta| < 2.4$. Jets arising from b -hadron decays are identified by using an algorithm that combines impact parameter information with the explicit identification of secondary and tertiary vertices within the jet into a b -tagging score [75, 117]. The minimal requirement imposed on the b -tagging score in this analysis corresponds to a 70% efficiency to tag a b -quark-initiated jet in $t\bar{t}$ events, with rejection rates of 381 for light-quark-initiated jets and 12 for c -quark-initiated jets, enhanced with respect to Run 1 by the use of the IBL and an improved algorithm.

Candidates for identification as hadronically decaying τ leptons (τ_{had}) arise from jets that have $p_T > 10$ GeV and for which one or three charged-particle tracks are found within a cone of size $\Delta R = 0.2$ around the axis of the τ_{had} candidate [78, 118]. These objects are further required to have a visible transverse momentum (p_T^{vis}) of at least 30 GeV and to be within $|\eta| < 2.3$ (the transition region between the barrel and end-cap calorimeters, $1.37 < |\eta| < 1.52$, is excluded). The output of boosted decision tree (BDT) algorithms is used in order to distinguish τ_{had} candidates from jets not initiated by hadronically decaying τ -leptons. This is done separately for decays with one or three charged-particle tracks, and for varying values of the identification efficiency [118]. In this analysis, a working point corresponding to a 55% (40%) efficiency for the identification of 1-prong (3-prong) τ_{had} objects is used, with rejection rates of $\mathcal{O}(10^2)$ for jets. A looser selection of τ_{had} candidates is also used in the analysis, obtained using the BDT working point with an efficiency of about 70% and a jet rejection factor about 2–5 times smaller than for the nominal working point. The τ_{had} candidates that fulfil this alternative selection are referred to as *loose*.

Electron candidates are reconstructed from energy deposits (clusters) in the electromagnetic calorimeter, associated with a reconstructed track in the inner detector [76, 119]. The pseudorapidity range for the electromagnetic clusters covers the fiducial volume of the detector, $|\eta| < 2.47$ (the transition region between the barrel and end-cap calorimeters, $1.37 < |\eta| < 1.52$, is excluded). Quality requirements on the electromagnetic clusters and the tracks, as well as isolation requirements in a cone around the electron candidate based on its transverse energy and the tracking information, are then applied in order to reduce contamination from jets. Muon candidates are reconstructed from track segments in the muon spectrometer, and matched with tracks found in the inner detector within $|\eta| < 2.5$. They must fulfil quality requirements including a p_T -dependent track-based isolation requirement in a cone of variable size around the muon, which has good performance under high pile-up conditions and/or when a muon is close to a jet [77].

When several objects overlap geometrically, the following procedure is applied. A τ_{had} object is removed if found within $\Delta R < 0.2$ of a selected electron or a muon with loose identification criteria and $p_T > 7$ GeV. Any calorimeter-tagged muon sharing an inner-detector track with an electron is removed and electrons sharing an inner-detector track with a remaining muon are then discarded.

Next, electrons and muons are removed if found within $\Delta R < 0.4$ of a b -tagged jet. Finally, jets are discarded if they are within $\Delta R < 0.2$ of the highest- p_T τ_{had} candidate or remaining muons and electrons.

The magnitude E_T^{miss} of the missing transverse momentum [120] is reconstructed from the negative vector sum of transverse momenta of reconstructed and fully calibrated objects (collected in the hard term), as well as from reconstructed tracks associated with the hard-scatter vertex which are not in the hard term (collected in the soft term).

7.4 Analysis strategy

The charged Higgs boson decays into τ_{had} and neutrinos, while the top-quark may decay either hadronically or leptonically. Hence, two orthogonal channels are defined, depending on the top-quark decay: $\tau_{\text{had}} + \text{jets}$ (for hadronically decaying top quark) or $\tau_{\text{had}} + \text{lepton}$ (for leptonically decaying top quark). The τ_{had} candidate could potentially come from the top-quark via a W boson decaying into τ_{had} and neutrinos. In that case, H^+ may either give rise to an electron or muon via a leptonic τ decay or fail detection. The largest fraction of selected signal events where the τ_{had} candidate does not come from H^+ is about 20%, for a mass of 100 GeV, in the $\tau_{\text{had}} + \text{jets}$ channel.

7.4.1 Event selection in the $\tau_{\text{had}} + \text{jets}$ channel

The analysis of the $\tau + \text{jets}$ channel is based on events accepted by an E_T^{miss} trigger with a threshold at 70, 90 or 110 GeV, depending on the data-taking period ($E_T^{\text{miss}} > 70$ GeV for the 2015 data, $E_T^{\text{miss}} > 90$ GeV for periods A-D3 and $E_T^{\text{miss}} > 110$ GeV for periods D4-L of the 2016 data). The efficiency of such triggers is measured in data and used to reweight simulated events as described in Ref. [9]. At least one vertex with two or more associated tracks is required.

For the selected events, the transverse mass M_T of the τ_{had} and E_T^{miss} is defined as:

$$M_T = \sqrt{2p_T^\tau E_T^{\text{miss}}(1 - \cos \Delta\phi_{\tau, \text{miss}})}, \quad (7.4.1)$$

where $\Delta\phi_{\tau, \text{miss}}$ is the azimuthal angle between the τ_{had} and the direction of the missing transverse momentum.

The following requirements are then applied:

- at least one τ_{had} candidate with $p_T^\tau > 40$ GeV;
- no lepton (electron or muon) with E_T or p_T above 20 GeV, respectively;
- at least three jets with $p_T > 25$ GeV, of which at least one is b -tagged;
- $E_T^{\text{miss}} > 150$ GeV;
- $M_T > 50$ GeV.

A minimal requirement is placed on M_T at 50 GeV to reject events with mismeasured E_T^{miss} , where τ_{had} is nearly aligned with the direction of the missing transverse momentum.

The expected numbers of background events and the results from data, together with an expectation from the signal contribution at $m_{H^+} = 200$ GeV, are shown in table 7.1. Figure 7.4.1 show comparisons between predicted and measured distributions, for events after full selection. The $j \rightarrow \tau$ background includes all processes in which the selected τ_{had} candidate is from a quark- or gluon-initiated jet, the $l \rightarrow \tau$ background includes all processes in which a lepton (electron or muon) is reconstructed and identified as the τ_{had} object, and all other backgrounds correspond to events where the τ_{had} object matches a hadronic τ decay at the generator level. The latter two backgrounds are derived from simulation, while the former is estimated from data using the Fake Factor (FF) method (see Section 7.5.2).

Selection	top	$W \rightarrow \tau\nu$	$Z \rightarrow \tau\tau$	Diboson	$l \rightarrow \tau$
Trigger and skim	134368	140456	22593	4710	10205
Medium tau, $p_T^\tau > 40$ GeV	67797	73912	12371	2703	3109
Lepton veto	60680	73895	11318	2492	2879
$E_T^{\text{miss}} > 150$ GeV	26739	33127	3395	1374	841
≥ 1 b-jet	21511	3753	485	195	405
$m_T > 50$ GeV	7660 ± 1747	1047 ± 188	84 ± 50	63 ± 7	265 ± 35
Selection	$j \rightarrow \tau$	Total bkg	$H^+(200)$	$H^+(1000)$	data (36.1 fb^{-1})
Trigger and skim	2016098	2328431	2268	9676	2404104
Medium tau, $p_T^\tau > 40$ GeV	145716	305608	1455	6756	256668
Lepton veto	139352	290616	1353	6085	240067
$E_T^{\text{miss}} > 150$ GeV	7033	72509	680	5759	67673
≥ 1 b-jet	2884	29234	499	4257	27461
$m_T > 50$ GeV (SR)	2372 ± 257	11491 ± 1777	427 ± 55	4220 ± 319	11021

Table 7.1: Expected event yields after cumulative selection cuts and comparison with 36.1 fb^{-1} of data for $\tau_{\text{had-vis}} + \text{jets}$ channel. The values shown for the signal correspond to $\sigma(pp \rightarrow [b]tH^+) \times \text{Br}(H^+ \rightarrow \tau\nu) = 1 \text{ pb}$. Both the statistical and systematic uncertainties (Section 7.6) are shown for the final selection cut in the last row.

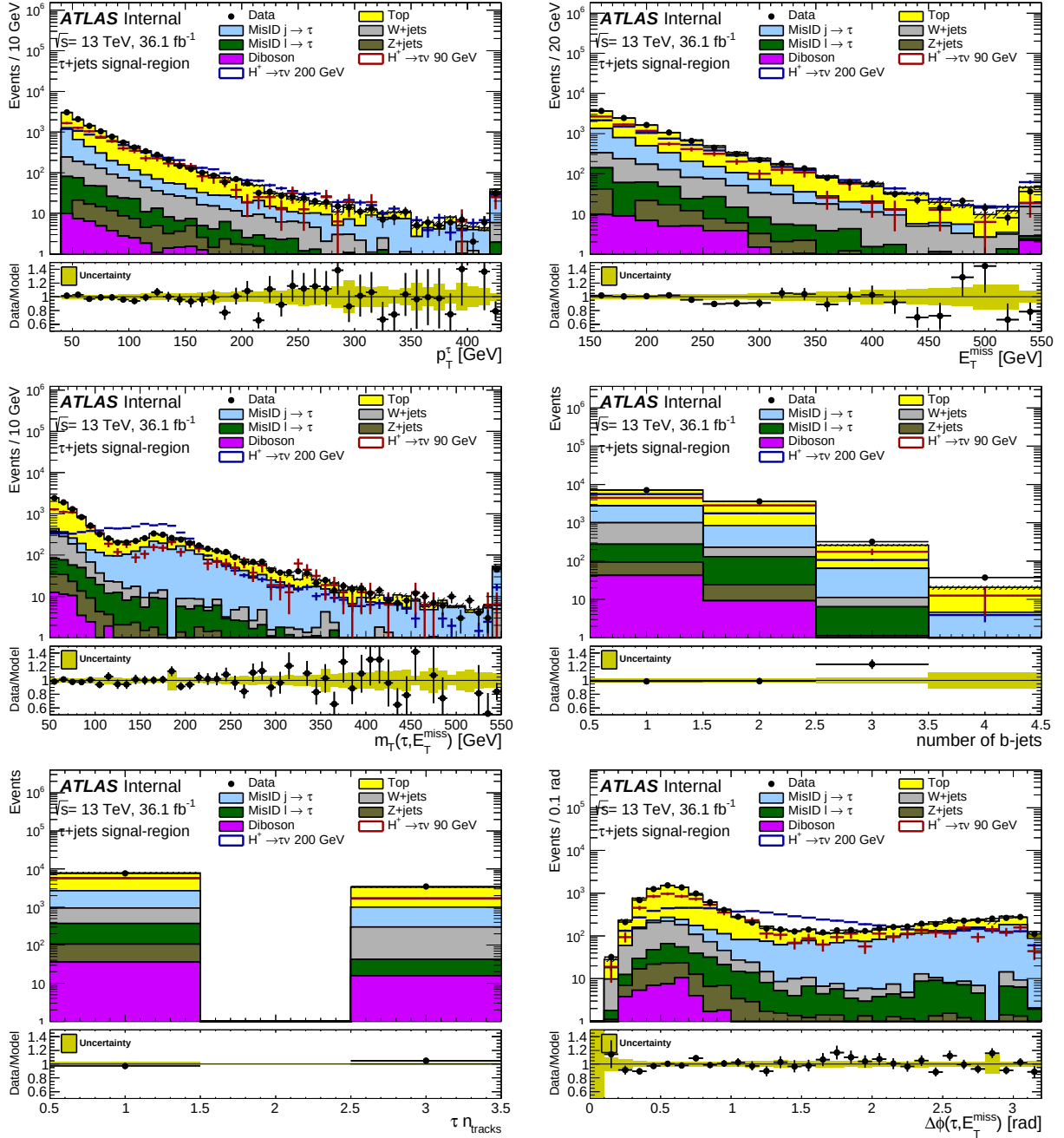


Figure 7.4.1: Comparison of the data with the predicted electroweak, top and multi-jet backgrounds, along with a few simulated signal samples (with $m_{H^+} = 90, 200$ GeV), after full event selection in $\tau_{\text{had}}+\text{jets}$ channel. Shown are (top left) the τ_{had} candidate p_T , (top right) the E_T^{miss} , (middle left) the reconstructed transverse mass of the τ_{had} and E_T^{miss} (middle right) the number of b-jets, (bottom left) the τ_{had} number of charged tracks and (bottom right) the angle between the τ_{had} candidate and the E_T^{miss} . The background is stacked, while the signal is overlaid. When plotting transverse momenta, the last bin contains overflow. The $j \rightarrow \tau$ background is estimated using the FF method. The uncertainty band in the ratio plots is statistical systematic uncertainty. The signal distributions are all scaled to the integral of the total background.

7.4.2 Event selection in the $\tau_{\text{had}}+\text{lep}$ channel

This second channel is based on events firing single-lepton triggers. Triggers with low p_T thresholds (24–26 GeV depending on the data-taking period, for both electrons and muons) and isolation re-

quirements are combined in a logical OR with triggers having higher p_T thresholds (60–140 GeV for electrons, 50 GeV for muons) and looser isolation or identification requirements to maximise the efficiency. Following the same data-quality requirements as in the $\tau_{\text{had}}+\text{jets}$ channel, events are selected with the requirements listed below:

- exactly one lepton (electron or muon) matched to the single-lepton trigger object, with E_T or p_T above 30 GeV, respectively;
- exactly one τ_{had} candidate with $p_T^\tau > 30$ GeV and an opposite electric charge with respect to the lepton;
- at least one jet with $p_T > 25$ GeV, of which at least one is b -tagged;
- $E_T^{\text{miss}} > 50$ GeV.

The expected numbers of events in the signal region coming from different backgrounds, together with an expectation for signal at $m_{H^+} = 200$ GeV and 1 TeV, as well as the number of events in data, are shown in Tables 7.2–7.3. Figure 7.4.2 show comparisons between predicted and measured distributions, for events after full selection.

Selection	top	$W \rightarrow \tau\nu$	$Z \rightarrow \tau\tau$	Diboson	$l \rightarrow \tau$
Trigger and skim	121539	646	100005	7131	91029
Medium tau, $p_T^\tau > 30$ GeV	85607	480	71243	5094	47779
Tight electron, $p_T^e > 30$ GeV	34197	39	21386	1767	30501
Electron and tau with OS	31598	22	18510	1431	26128
$E_T^{\text{miss}} > 50$ GeV	21290	9	5358	849	2493
≥ 1 b-jet (SR)	17271 ± 2529	0.3 ± 0.5	433 ± 94	39 ± 5	626 ± 66
Selection	$j \rightarrow \tau$	Total bkg	$H^+(200)$	$H^+(1000)$	data (36.1 fb^{-1})
Trigger and skim	392612	712962	1458	2043	5081123
Medium tau, $p_T^\tau > 30$ GeV	392612	602815	1087	1501	594680
Tight electron, $p_T^e > 30$ GeV	132413	220303	409	525	212426
Electron and tau with OS	72867	150555	357	485	147463
$E_T^{\text{miss}} > 50$ GeV	22024	52024	289	481	49610
≥ 1 b-jet (SR)	5642 ± 452	24013 ± 2571	202 ± 16	336 ± 28	22645

Table 7.2: Expected event yields after cumulative selection cuts and comparison with 36.1 fb^{-1} of data for $\tau_{\text{had-vis}} + e$ channel. The values shown for the signal correspond to $\sigma(pp \rightarrow [b]tH^+) \times \text{Br}(H^+ \rightarrow \tau\nu) = 1 \text{ pb}$. Both the statistical and systematic uncertainties (Section 7.6) are shown for the final selection cut in the last row.

Selection	top	$W \rightarrow \tau\nu$	$Z \rightarrow \tau\tau$	Diboson	$l \rightarrow \tau$
Trigger and skim	121539	646	100005	7131	91029
Medium tau, $p_T^\tau > 30$ GeV	85607	480	71243	5094	47779
Tight muon, $p_T^\mu > 30$ GeV	37231	19	24472	2132	8005
Muon and tau with OS	29536	12	19539	1493	6439
$E_T^{\text{miss}} > 50$ GeV	19652	5	4968	854	1065
≥ 1 b-jet	15860 ± 2458	0.2 ± 0.2	352 ± 68	32 ± 4	454 ± 31
Selection	$j \rightarrow \tau$	Total bkg	$H^+(200)$	$H^+(1000)$	data (36.1 fb^{-1})
Trigger and skim	392612	712962	1458	2043	5081123
Medium tau, $p_T^\tau > 30$ GeV	392612	602815	1087	1501	594680
Tight muon, $p_T^\mu > 30$ GeV	114607	186465	461	750	176457
Electron and tau with OS	67411	124430	357	592	125486
$E_T^{\text{miss}} > 50$ GeV	23677	50221	286	586	48669
≥ 1 b-jet (SR)	5462 ± 411	22160 ± 2493	204 ± 17	430 ± 37	21419

Table 7.3: Expected event yields after cumulative selection cuts and comparison with 36.1 fb^{-1} of data for $\tau_{\text{had-vis}} + \mu$ channel. The values shown for the signal correspond to $\sigma(pp \rightarrow [b]tH^+) \times \text{Br}(H^+ \rightarrow \tau\nu) = 1 \text{ pb}$. Both the statistical and systematic uncertainties (Section 7.6) are shown for the final selection cut in the last row.

7.4.3 Multi-variate discriminant

In the published results based on the proton-proton collision data recorded by the ATLAS experiment in 2015 [9], the analysis used the transverse mass (m_T) defined in equation 7.4.1 as a final discriminating variable. During the 2016 data taking period, a new discriminating variable was introduced, based on the Multi-Variable Analysis (MVA) approach – the Boosted Decision Tree (BDT) method. The output score of the BDT is used to separate the H^+ signal from the SM background processes and served as a discriminating variable. The MVA part of the analysis was done by others and is brought here for completeness.

The training of the BDTs is performed using the FastBDT [121] library via the TMVA toolkit [122]. Using the whole available set (or sample) in the training of the classifier (the BDT algorithm) leads to overfitting/overtraining as the classifier learns fluctuation in the dataset and performs worse on the actual “unseen” data. Usually, the sample is divided into two subsets – the training set and validation (or test) set. The classifier is trained against the training subset, and then the accuracy of the model is evaluated by validating the predicted results against the validation (test) subset. In this case, only a part of the available set (or sample) is used for the training, resulting in a weaker learning process. To overcome this limitation a k -fold cross validation method is used. In the k -fold approach, the events are divided into k subsets (each subset is called a **fold**). For each fold, the classifier is trained against the other $k - 1$ subsets and validated (tested) with the remaining fold. This procedure is repeated k times when each one of the events in the whole sample is used exactly once in the validation sample, and the whole set (sample) is ultimately used in the training of the classifier. The k results from the folds can then be averaged to produce a single estimation. The advantage of this approach is of using the whole dataset for testing and training, which reduces the overfitting/overtraining of the classifier. In the analysis $k = 5$ is used.

The signal samples are divided into five mass bins, in which the kinematic distributions of the input variables and the event topology are found to be similar enough to ensure that the higher statistics from inclusive training improves performance. The H^+ mass bins used in both channels are 90–120 GeV, 130–160 GeV (using the low-mass 160 GeV sample), 160–180 GeV (using the intermediate-mass 160 GeV sample), 200–400 GeV and 500–2000 GeV. All available H^+ signal samples corresponding to a given mass bin are combined into one inclusive signal sample. The BDTs are trained separately for events where the leading τ_{had} candidate has one or three associated tracks. The variables entering the BDT training differ for the two channels considered in this search, and they are summarised in Table 7.4. Among the τ_{had} candidates and b -tagged jets, the object that has the largest p_T is considered in the BDT input variables.

At low H^+ masses (i.e., between the W -boson and top-quark masses, typically), the kinematics of the $t \rightarrow bH^+$ and $t \rightarrow bW$ decay products can be very similar. In that case, the polarisation of the τ -lepton can serve as a discriminating variable: in all SM background processes, the τ_{had} object originates from a vector-boson decay, whereas it is generated in the decay of a scalar particle in the case of H^+ signal [123]. The τ -lepton decay mode with the highest branching fraction is via an intermediate ρ resonance (about half of all hadronic 1-prong τ -lepton decays). The polarization of the τ_{had} candidates in this decay mode can be measured by the asymmetry of energies carried by the charged and neutral pions from the τ -lepton decay, measured in the laboratory frame. For this purpose, the variable Υ is introduced [124]:

$$\Upsilon = \frac{E_{\text{T}}^{\pi^{\pm}} - E_{\text{T}}^{\pi^0}}{E_{\text{T}}^{\pi^{\pm}} + E_{\text{T}}^{\pi^0}} = 2 \frac{p_T^{\tau-\text{track}}}{p_T^{\tau}} - 1. \quad (7.4.2)$$

It is defined for τ_{had} candidates with only one associated track, with a transverse momentum $p_T^{\tau-\text{track}}$. In the absence of neutral τ -lepton decay products (i.e., when the τ_{had} object corresponds to a single charged meson), Υ is equal to unity and does not contribute to the BDT learning process. Hence the benefit is greater when Υ is used inclusively for all 1-prong τ_{had} candidates instead of splitting

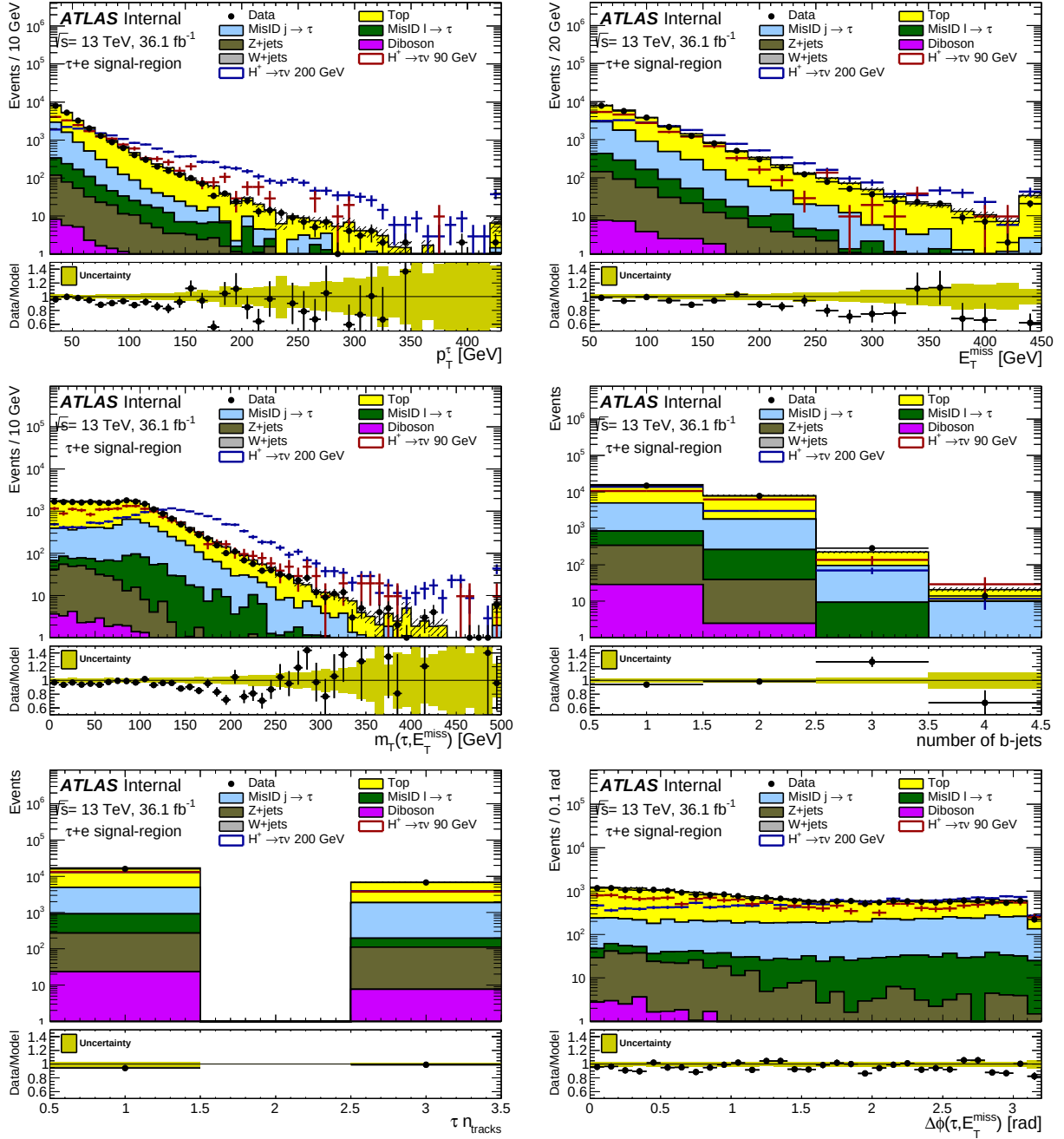


Figure 7.4.2: Predicted total background distributions including electroweak, top and multi-jet backgrounds, along with a few simulated signal samples (with $m_{H^+} = 90, 200$ GeV), after full $\tau_{\text{had}} + e$ event selection. Shown are (top left) the τ_{had} candidate p_T , (top right) the E_T^{miss} , (middle left) the reconstructed transverse mass of the τ_{had} and E_T^{miss} (middle right) the number of b-jets, (bottom left) the τ_{had} number of charged tracks and (bottom right) the angle between the τ_{had} candidate and the E_T^{miss} . The background is stacked, while the signal is overlaid. When plotting transverse momenta, the last bin contains overflow. The $j \rightarrow \tau$ background is estimated using the FF method. The uncertainty band in the ratio plots is statistical systematic uncertainty. The signal distributions are all scaled to the integral of the total background.

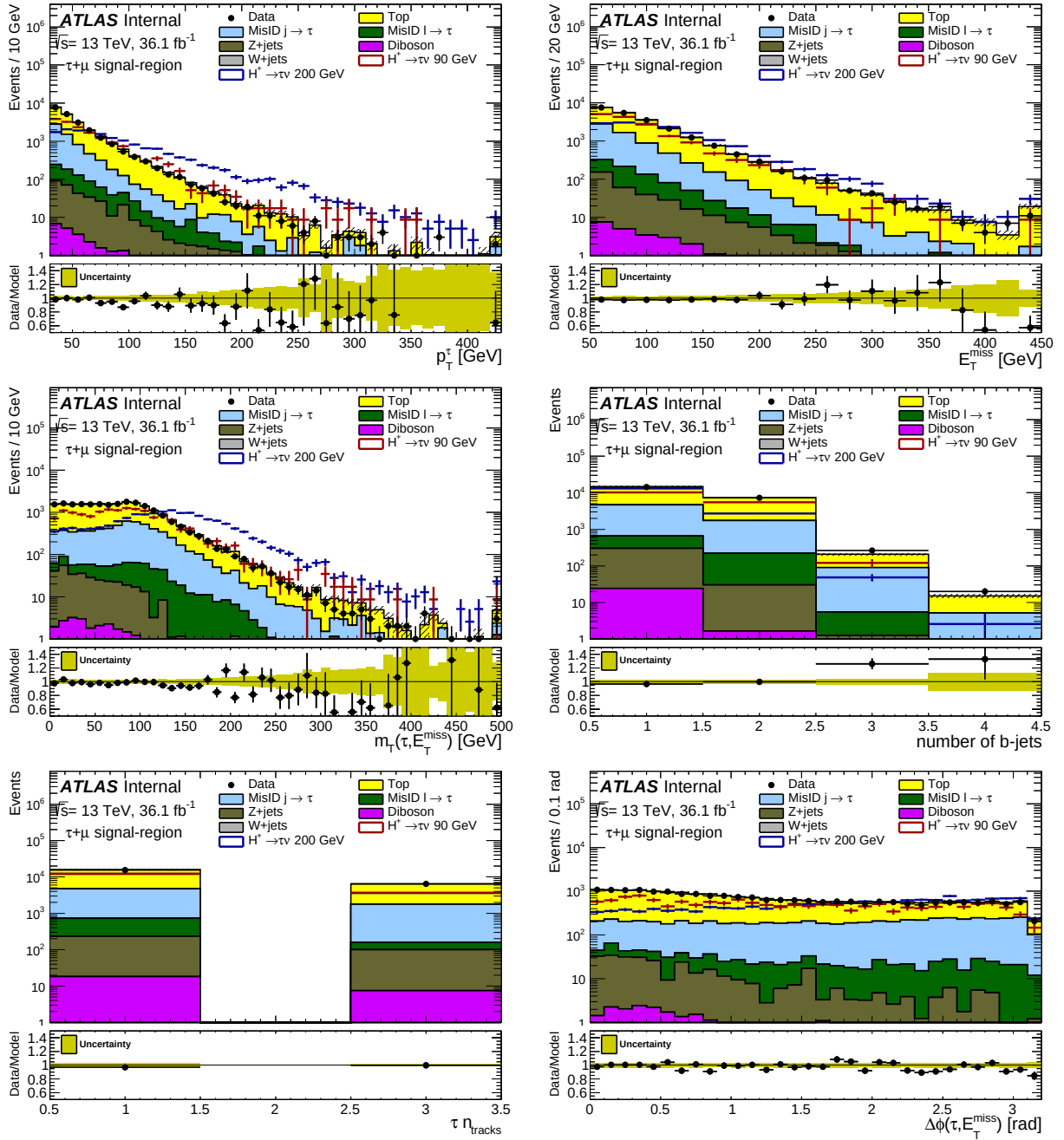


Figure 7.4.3: Predicted total background distributions including electroweak, top and multi-jet backgrounds, along with a few simulated signal samples (with $m_{H^+} = 90, 200, 1000$ GeV), after full $\tau_{\text{had}} + \mu$ event selection. Shown are (top left) the τ_{had} candidate p_T , (top right) the E_T^{miss} , (middle left) the reconstructed transverse mass of the τ_{had} and E_T^{miss} (middle right) the number of b-jets, (bottom left) the τ_{had} number of charged tracks and (bottom right) the angle between the τ_{had} candidate and the E_T^{miss} . The background is stacked, while the signal is overlaid. When plotting transverse momenta, the last bin contains overflow. The $j \rightarrow \tau$ background is estimated using the FF method. The uncertainty band in the ratio plots is statistical systematic uncertainty. The signal distributions are all scaled to the integral of the total background.

events according to decay modes with different reconstructed charged and neutral components. For H^+ masses in the range 90–400 GeV, the BDT training is performed separately for events with a selected 1- or 3-prong τ_{had} object, and Υ is included in the final BDT discriminant for events where τ_{had} has only one associated track. The importance of other kinematic variables in the BDT training becomes much greater at large H^+ masses, in which case the BDT discriminant is inclusive in the number of tracks associated to the τ_{had} candidate and does not contain the variable Υ .

BDT input variable	$\tau_{\text{had}}+\text{jets}$	$\tau_{\text{had}}+\text{lepton}$
$E_{\text{T}}^{\text{miss}}$	✓	✓
p_T^{τ}	✓	✓
$p_T^{b\text{-jet}}$	✓	✓
p_{T}^{ℓ}		✓
$\Delta\phi_{\tau, \text{miss}}$	✓	✓
$\Delta\phi_{b\text{-jet}, \text{miss}}$	✓	✓
$\Delta\phi_{\ell, \text{miss}}$		✓
$\Delta R_{\tau, \ell}$		✓
$\Delta R_{b\text{-jet}, \ell}$		✓
$\Delta R_{b\text{-jet}, \tau}$	✓	
$\Upsilon = 2 \frac{p_T^{\tau\text{-track}}}{p_T^{\tau}} - 1$	✓	✓

Table 7.4: List of kinematic variables used as input to the BDT in the $\tau_{\text{had}}+\text{jets}$ and/or $\tau_{\text{had}}+\text{lepton}$ channels. Here, ℓ refers to the selected lepton (electron or muon). $\Delta\phi_{X, \text{miss}}$ denotes the difference in azimuthal angle between a detector object X and the direction of the missing transverse momentum. Note that Υ is only defined for 1-prong τ_{had} candidates. Hence, for H^+ masses in the range 90–400 GeV, where the variable Υ is used, the BDT training is performed separately for events with a selected 1- or 3-prong τ_{had} candidate. In the mass range 500–2000 GeV, Υ is not used.

7.5 Background modelling

The background processes in the search for $H^+ \rightarrow \tau\nu$ are $t\bar{t}$, single-top-quark, W +jets, Z/γ^* +jets, diboson and multi-jet (MJ) events. The individual contributions from several of these backgrounds can be determined from the data.

Backgrounds are categorised based on the object that is selected as the reconstructed and identified τ_{had} : a true hadronically decaying τ lepton, a light lepton (e/μ), or a quark/gluon jet. This section describes the modelling of those background components. The estimation of the latter background is performed using a data-driven technique called the Fake Factor (FF) method (see Section 7.5.2).

7.5.1 Electron faking τ_{had} candidates

Electrons faking τ_{had} candidates are not guaranteed to be well modelled in simulation. In order to study this background component, a dedicated control region enriched in $Z \rightarrow ee$ events is defined, using the following event selection:

- single-electron trigger, the same as used in the τ_{had} +lepton signal region;
- exactly one *tight* electron with $E_T > 30$ GeV matched to the trigger;
- exactly one *medium* τ_{had} candidate with $p_T^\tau > 40$ GeV and an electric charge opposite to that of the selected electron;
- no b -tagged jets or muons;
- at least one jet with $p_T > 25$ GeV.

The topology of the selected events has a prompt electron that is reconstructed and identified as a *medium* τ_{had} candidate, but not as an electron. The distribution of the e - τ_{had} visible mass, as well as the transverse mass of the $\tau_{\text{had}} + E_T^{\text{miss}}$ system and other kinematic variables, as obtained with the event selection described above, are shown in figure 7.5.1. The modelling of electrons faking a τ_{had} candidate is found to be satisfactory in the SHERPA $Z \rightarrow ee$ samples. Therefore, no additional scale factors are applied, beyond the recommended $e \rightarrow \tau_{\text{had}}$ scale factors.

7.5.2 Fake-factor method (jet $\rightarrow \tau_{\text{had}}$ background)

Events that contain quark- or gluon-initiated jets can enter the signal region when one of these jets is reconstructed and identified as a τ_{had} candidate. These backgrounds are poorly modelled due to statistical limitations in the sample of simulated events (e.g. multi-jet processes) and due to the absence of a good understanding of systematic uncertainties related to those objects. Therefore, a data-driven approach is used to estimate this background.

7.5.2.1 Basics of the method

The fake-factor (FF) method relies on the measured rate of fake τ_{had} objects (quark- or gluon-initiated jets that reconstructed as τ_{had} candidates) passing the τ_{had} identification criteria. The identification criteria is based on the BDT output (see section 7.4) of a τ_{had} candidate, where the BDT output is used to distinguish τ_{had} candidates from jets not initiated by hadronically decaying τ leptons. In this method, weights are applied to a specific subset of the τ_{had} candidates that fail the identification criteria in the signal region.

First, an “anti- τ ” control region is defined as a subset of τ_{had} candidates that fail the loosest identification criteria. This control region is required to be populated with only fake objects and it

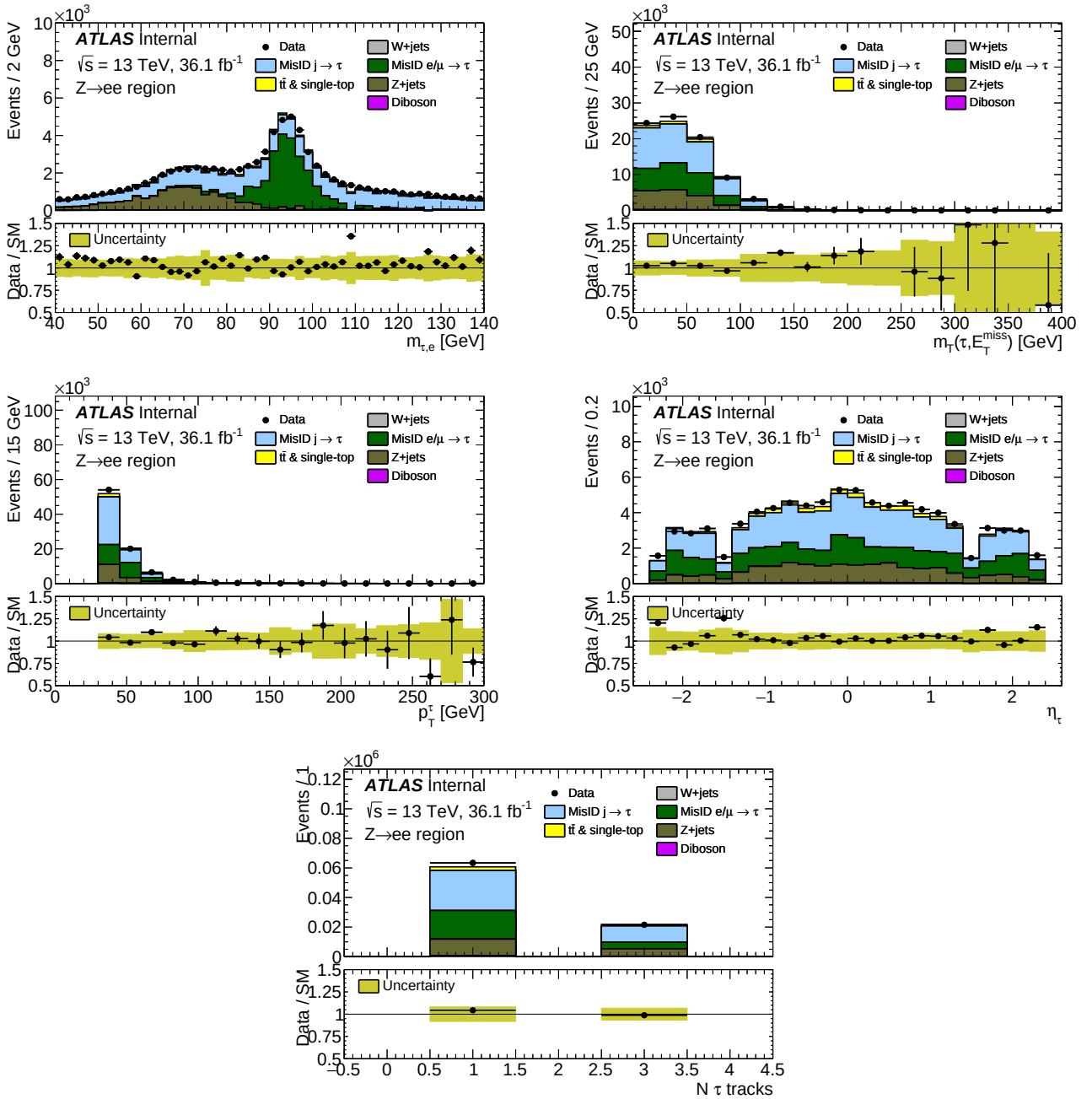


Figure 7.5.1: Distribution of the e - τ_{had} visible mass and transverse mass of the $\tau_{\text{had}} + E_T^{\text{miss}}$ system, as well as p_T , η and track multiplicity of the τ_{had} candidate in the $Z \rightarrow ee$ control region. The recommended $e \rightarrow \tau_{\text{had}}$ scale factors are applied. Jets misidentified as τ_{had} are estimated from data using the FF method. The uncertainty band in the ratio plots includes the total statistical and systematic uncertainty of the simulated events.

needs to have an event topology similar to the jets faking τ_{had} objects in the signal region. Additionally, a lower cut on the non-loose τ_{had} BDTJetSigTrans³ score at 0.02 is applied in order to keep the event topology similar to the signal region. The anti- τ selection criteria are thus: non-LooseID τ_{had} (τ candidates that fail the “Loose” identification criteria) with BDTJetSigTrans score greater than 0.02. Then, corresponding weights, also known as fake factors, are defined as the ratio of the number of fake τ_{had} candidates passing the nominal identification criteria to the number of fake τ_{had}

³BDTJetSigTrans is flattened τ BDT score in p_T and η

candidates satisfying the “anti- τ ” control region criteria. The FF and the number of events with misidentified τ_{had} objects in the SR are:

$$\text{FF} = \frac{N_{\tau\text{-id}}}{N_{\text{anti-}\tau\text{-id}}}, \quad (7.5.1)$$

$$N_{\text{fakes}}^{\tau} = N_{\text{fakes}}^{\text{anti-}\tau} \times \text{FF}, \quad (7.5.2)$$

where N_{fakes} refers to the number of misidentified objects in the signal or in control (anti- τ) regions, and FF is the fake factor defined above. In the previous equations, $N_{\text{fakes}}^{\text{anti-}\tau}$ is corrected for τ_{had} candidates not fulfilling the identification criteria but matching a true hadronic τ decay at generator level.

7.5.2.2 Regions for fake-factor measurements

The jet $\rightarrow \tau_{\text{had}}$ background in the signal region comes mainly from $t\bar{t}$ and multi-jet processes. In $t\bar{t}$ processes, the dominant fake τ_{had} sources are quark-initiated jets, whereas in multi-jet events both quark- and gluon-initiated jets contribute. A low τ_{had} BDTJetSigTrans score is associated with gluon-initiated jets, while quark-initiated jets (both light and heavy quarks) typically have a higher BDTJetSigTrans score.

Two control regions with different jet compositions are used to estimate the rates of the fake τ_{had} objects. The first one is the multi-jet CR, which is defined by keeping events that pass all τ +jets selection cuts except that one has a b -veto and $E_{\text{T}}^{\text{miss}} < 80$ GeV. The second control region is the W +jets CR, in which the fake τ_{had} composition is dominated by light-quark jets. The W +jets CR has the following requirements, in addition to the basic event cleaning cuts:

- exactly one electron that fires the single-lepton trigger (similarly to the trigger requirement of the τ_{had} +lepton channel);
- zero b -tagged jets;
- at least one reconstructed τ_{had} candidate;
- $60 \text{ GeV} < M_T(\ell, E_{\text{T}}^{\text{miss}}) < 160 \text{ GeV}$.

	τ +jets SR		τ +lepton SR		multi-jet CR		$W(\ell\nu)$ +jets CR	
	τ	anti- τ	τ	anti- τ	τ	anti- τ	τ	anti- τ
electron	2.9	2.1	2.4	0.9	—	—	2.7	—
light-quark	6.7	43.6	12.6	49.3	56.3	50.7	54.5	61.0
c -quark	2.0	13.4	3.7	15.4	7.3	9.7	11.1	13.1
b -quark	1.5	17.3	2.7	20.2	1.4	1.2	2.2	4.1
gluon	0.4	3.6	0.5	4.1	22.9	32.6	7.9	14.0
other	0.2	0.7	0.3	1.0	6.2	5.6	8.6	7.4
fraction of fakes	13.7	80.7	22.2	90.9	94.4	99.8	87.0	99.6

Table 7.5: Fraction (ordered by sources and total in the last row) of fake τ_{had} objects (in %) for various event selections. The row “other” represents jets that are not matched to any of the sources above. For the signal regions, a sample of $t\bar{t}$ events with at least one leptonically decaying top quark is used. For the multi-jet and W +jets control regions, the corresponding simulated samples (di-jet and $W \rightarrow \ell\nu$) are used to identify the sources of fake τ_{had} objects.

In the multi-jet CR, the contamination arising from correctly reconstructed and identified τ_{had} is small (5%), and in the W +jets CR, this contamination is about 10%. During the computation of

the Fake-factors, contamination of the truth τ_{had} is subtracted using MC prediction. Table 7.5 shows the fraction of different sources faking τ_{had} objects in τ and anti- τ regions, as well as the fraction of fake τ_{had} candidates in the Signal-Regions. The table also provides the fraction of different fake τ_{had} sources estimated from the corresponding MC samples for W +jets and multi-jet control regions. Transverse mass distributions in the two control regions described above are shown in figure 7.5.2.

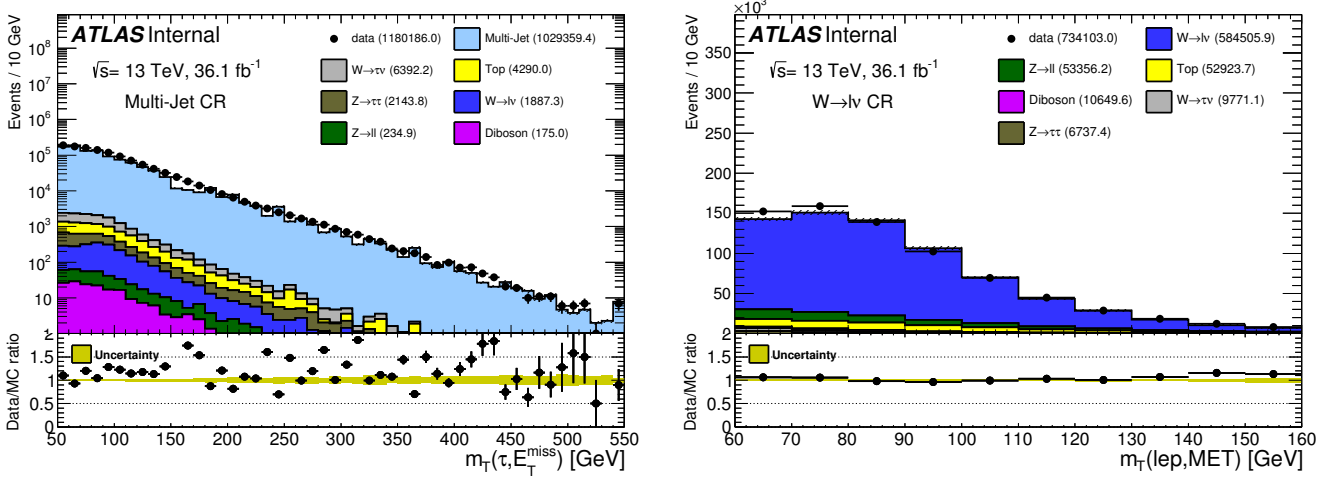


Figure 7.5.2: Transverse mass distributions in the multi-jet CR (left) and the W +jets CR (right).

The fake factors computed from these two control regions are shown in the left-hand side of Figure 7.5.3. FFs were estimated separately for 1-prong and 3-prong τ_{had} objects. The p_T binning of the FFs was optimized to follow the fake rate variation as a function of the τ_{had} transverse momentum, and to have a minimal statistical uncertainty for a single bin (the impact of the statistical uncertainty is discussed in Section 7.6.1.1).

7.5.2.3 Estimation of the combined fake factors

The multi-jet CR contains similar fractions of quark- and gluon-initiated jets, while the W +jets CR is dominated by quark-initiated jets. The SR is expected to have contributions from both types, but with different fractions. A template-fit method is used, to estimate the fraction of gluon-initiated jets in the signal region. The method is based on discriminating variables that are sensitive to the source of the jet. Later, these fractions are used to estimate combined fake factors, which are linear combinations of the fake factors measured in the multi-jet and W +jets CRs.

Method: Consider two populations of jets with different fake factors such that the total fake factor in the multi-jet CR (FF_{MJ}) or the W +jets CR ($\text{FF}_{W+\text{jets}}$) can be expressed as:

$$\text{FF}_{\text{MJ}} = f_g^{\text{MJ}} \times \text{FF}_g + (1 - f_g^{\text{MJ}}) \times \text{FF}_q, \quad (7.5.3)$$

$$\text{FF}_{W+\text{jets}} = f_g^{W+\text{jets}} \times \text{FF}_g + (1 - f_g^{W+\text{jets}}) \times \text{FF}_q, \quad (7.5.4)$$

where f_g^{MJ} and $f_g^{W+\text{jets}}$ are the fractions of gluon-initiated jets in the multi-jet and W +jets CRs, respectively, and FF_g and FF_q are the fake factors of these two populations (denoted by g for gluon-initiated jets and q for quark-initiated jets). Similarly, the fake factors in the signal region can be expressed by:

$$\text{FF}_{\text{SR}} = f_g^{\text{SR}} \times \text{FF}_g + (1 - f_g^{\text{SR}}) \times \text{FF}_q, \quad (7.5.5)$$

where f_g^{SR} is the fraction of gluon-initiated jets in the signal region. One can define

$$\alpha_{\text{MJ}} := \frac{f_g^{\text{SR}} - f_g^{W+\text{jets}}}{f_g^{\text{MJ}} - f_g^{W+\text{jets}}}. \quad (7.5.6)$$

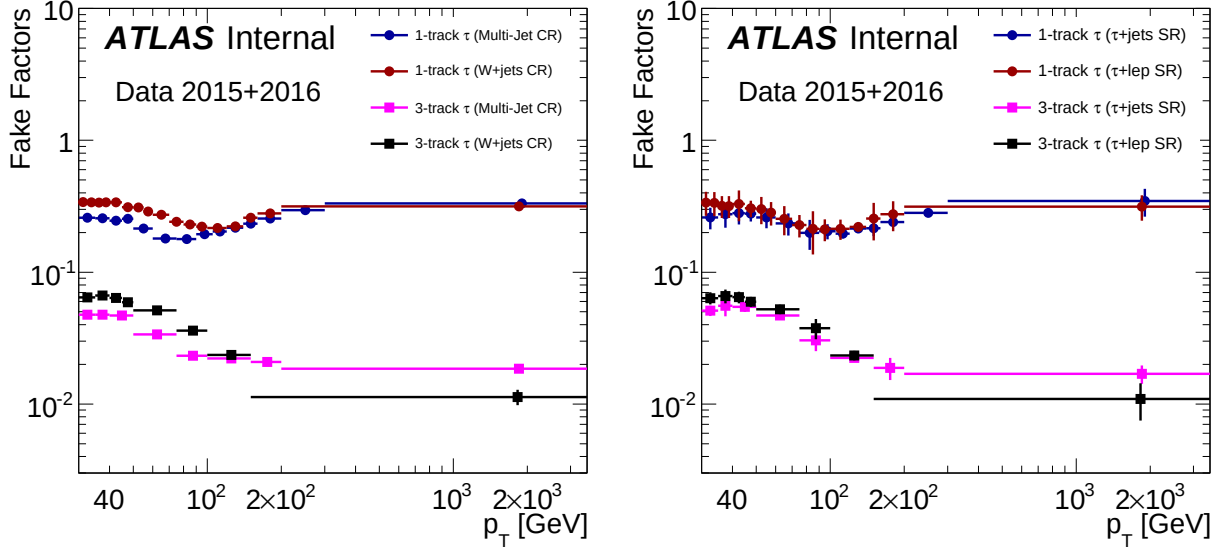


Figure 7.5.3: Fake factors (FF) parametrized as a function of p_T^τ and the number of charged τ decay products (two categories: 1-prong and 3-prong). The FFs are obtained in the multi-jet and W +jets CRs (left), as well as after reweighting by α_{MJ} in the τ_{had} +jets and τ_{had} +lepton channels (right). See section 7.5.2.3 for details about the computation of fake factors in the different control and signal regions. The errors shown come from the statistical uncertainty in a given p_T^τ bin (left) and with additional systematical uncertainties obtained from the combination in a given p_T^τ bin (right).

Then, Eq. (7.5.5) can be rearranged as a function of α_{MJ} and the fake factors extracted from the multi-jet and W +jets CRs:

$$\text{FF}_{\text{SR}} = \alpha_{\text{MJ}} \times \text{FF}_{\text{MJ}} + (1 - \alpha_{\text{MJ}}) \times \text{FF}_{W+\text{jets}}. \quad (7.5.7)$$

Note that α_{MJ} can get negative values when the signal region has a larger fraction of quark-initiated jets than in the W +jets CR ($f_g^{\text{SR}} \leq f_g^{W+\text{jets}}$), and values greater than one when the signal region has a larger fraction of gluon-initiated jets than the multi-jet CR ($f_g^{\text{SR}} \geq f_g^{\text{MJ}}$). Also note that $f_g^{\text{MJ}} \geq f_g^{W+\text{jets}}$.

Estimation of α_{MJ} : The parameter α_{MJ} is estimated by using a template-fit approach (described below) based on the distribution of the variables that are sensitive to the fraction of gluon-initiated jets in the selected regions. It is parametrized as a function of the p_T of the fake τ_{had} object and the number of associated tracks. The variables that are chosen for the templates are the TAU_JETBDT output score for 3-prong τ_{had} candidates, while for 1-prong τ_{had} candidates, the τ_{had} width is used, defined as:

$$w_\tau = \frac{\sum [p_T^{\text{track}} \times \Delta R(\tau_{\text{had}}, \text{track})]}{\sum p_T^{\text{track}}} \quad (7.5.8)$$

for tracks satisfying $\Delta R(\tau_{\text{had}}, \text{track}) < 0.4$.

The templates, i.e. the normalised distributions of TAU_JETBDT output score or the τ_{had} width, for anti- τ_{had} candidates are obtained in the multi-jet and W +jets CRs, for different bins of p_T and number of associated tracks of the fake τ_{had} ($P_{\text{bin}}^{\text{multi-jet}}(x)$ and $P_{\text{bin}}^{W+\text{jets}}(x)$). The weighted combination of the two shapes is:

$$P_{\text{bin}}^{\alpha_{\text{MJ}}}(x) = \alpha_{\text{MJ}} \times P_{\text{bin}}^{\text{multi-jet}}(x) + (1 - \alpha_{\text{MJ}}) \times P_{\text{bin}}^{W+\text{jets}}(x). \quad (7.5.9)$$

It is fitted to the shape measured for anti- τ_{had} candidates in the region of interest $P_{\text{bin}}^{\text{ROI}}(x)$, e.g. the

signal region, by minimising the χ^2 as a function of α_{MJ} :

$$\chi_{\text{bin}}^2(\alpha_{\text{MJ}}) = \sum_{x=0}^{K+1} \frac{(P_{\text{bin}}^{\alpha_{\text{MJ}}}(x) - P_{\text{bin}}^{\text{ROI}}(x))^2}{(\sigma_{\text{bin}}^{\text{template}}(x))^2 + (\sigma_{\text{bin}}^{\text{ROI}}(x))^2}, \quad (7.5.10)$$

where $\sigma_{\text{bin}}(x)$ is the statistical uncertainty and $K + 1$ is the number of bins in the `TAU_JETBDT` output score or the τ_{had} width in the template distribution (later denoted as number of degrees of freedom, or ndf). The distribution of χ_{bin}^2 can be described by a χ^2 -function with K degrees of freedom, which has a mean and a variance of K and $2K$, respectively.

The template shapes obtained in the fake-factor control regions, $P_{\text{bin}}^{\text{multi-jet}}(x)$ and $P_{\text{bin}}^{W+\text{jets}}(x)$, the template shape in the region of interest $P_{\text{bin}}^{\text{ROI}}(x)$ together with the fitted shape $P_{\text{bin}}^{\alpha_{\text{MJ}}}(x)$ that minimises $\chi^2(\alpha_{\text{MJ}})$, and the distribution of χ^2/ndf as a function of the varying parameter α_{MJ} are all shown in Figs. 7.5.4–7.5.7 for the $\tau_{\text{had}}+\text{jets}$ signal region and in Figs. 7.5.8–7.5.11 for the $\tau_{\text{had}}+\text{lepton}$ signal regions. An uncertainty on the fit is considered by taking a band within $\sqrt{2/\text{ndf}}$ from $\chi_{\text{min}}^2/\text{ndf}$ (the smallest value of the χ^2 -function). For α_{MJ} values where the combined template has an unphysical shape (negative bins), the value of α_{MJ} corresponding to the maximal χ^2 value (χ_{max}^2 , i.e., the worse physical fit) is used instead.

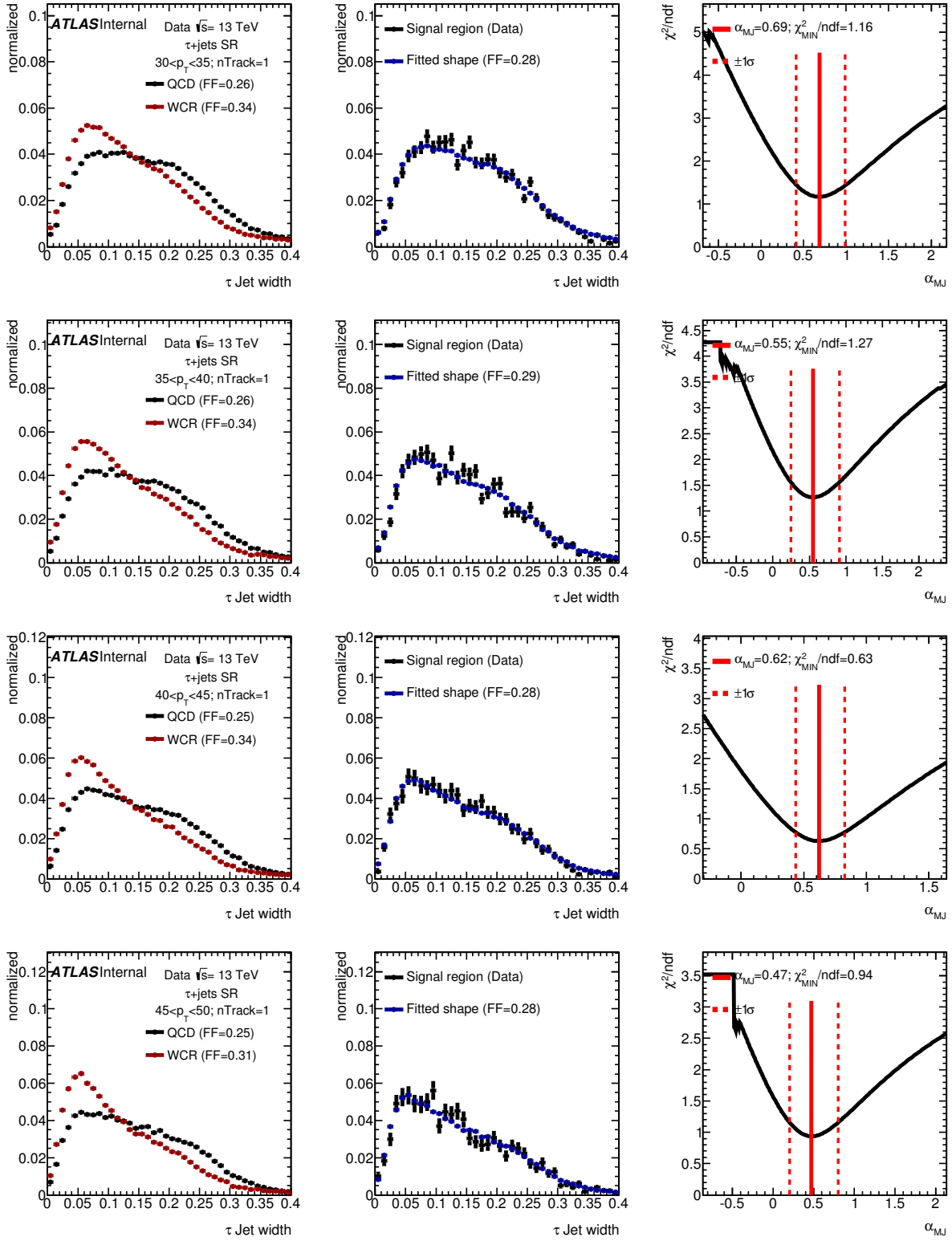


Figure 7.5.4: Estimation of α_{MJ} in the $\tau_{\text{had}} + \text{jets}$ signal region for $p_T \leq 50$ GeV 1-prong τ_{had} candidates. Left: templates of discriminating variables for different τ_{had} p_T and n-prong slices. Middle: shape of the discriminating variable obtained in the signal region and fitted shape using the templates measured in the control regions. Right: χ^2/ndf of the fit as a function of α_{MJ} , the error on α_{MJ} is defined by the band at $\chi^2_{\text{min}}/\text{ndf} + \sqrt{\frac{2}{\text{ndf}}}$.

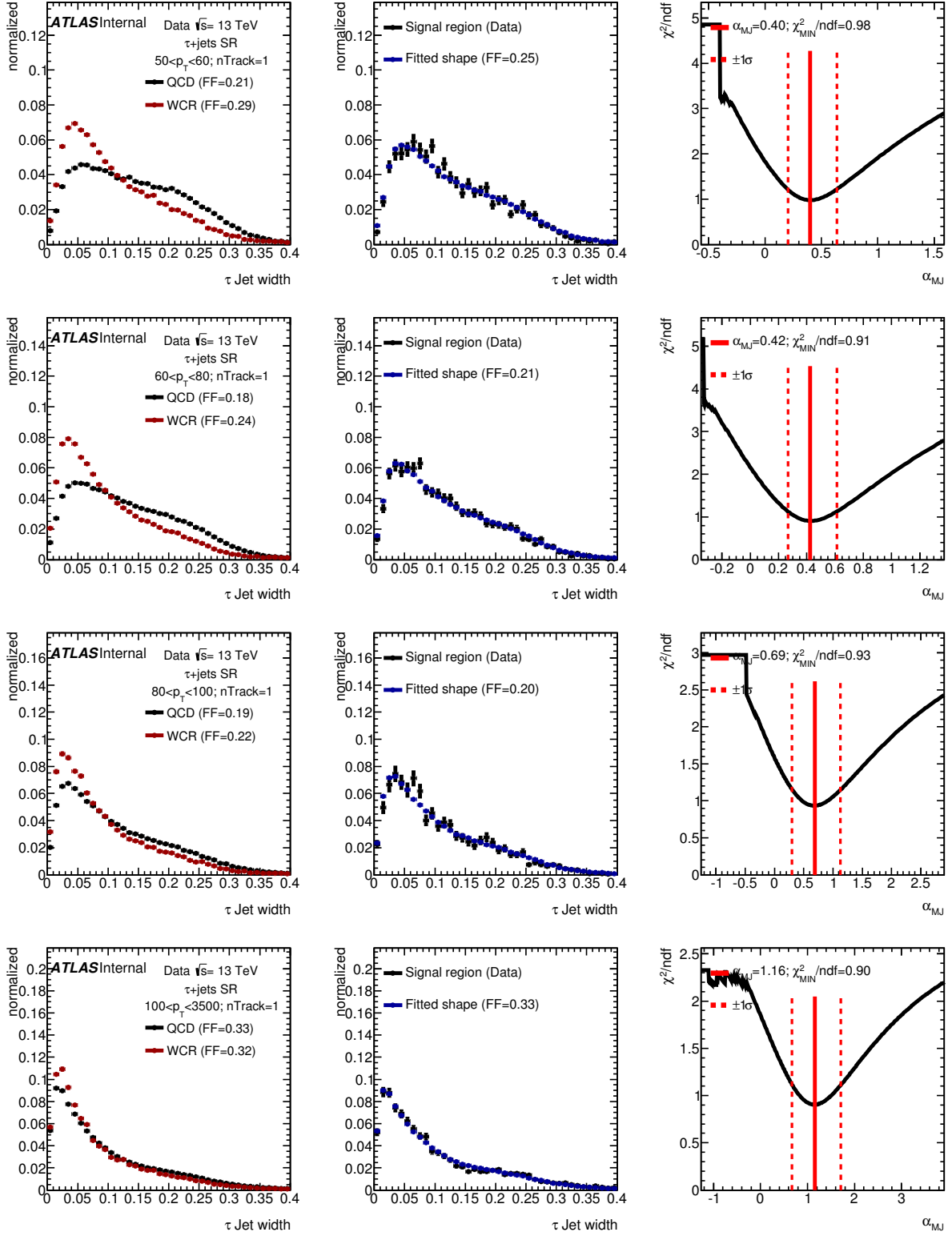


Figure 7.5.5: Estimation of α_{MJ} in the $\tau_{\text{had}} + \text{jets}$ signal region for $p_T \geq 50$ GeV 1-prong τ_{had} candidates. Left: templates of discriminating variables for different τ_{had} p_T and n -prong slices. Middle: shape of the discriminating variable obtained in the signal region and fitted shape using the templates measured in the control regions. Right: χ^2/ndf of the fit as a function of α_{MJ} , the error on α_{MJ} is defined by the band at $\chi^2_{\text{min}}/\text{ndf} + \sqrt{\frac{2}{\text{ndf}}}$.

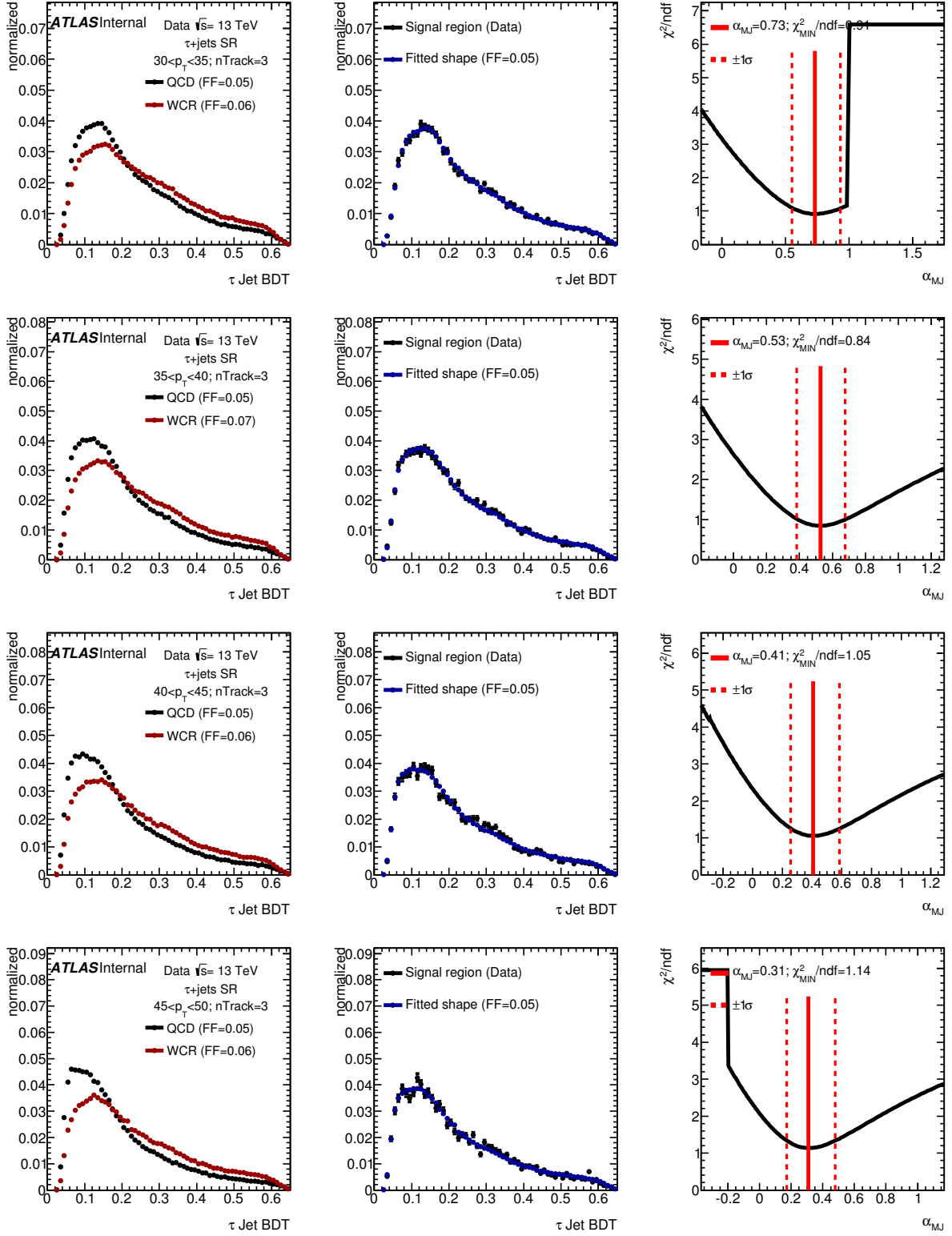


Figure 7.5.6: Estimation of α_{MJ} in the $\tau_{\text{had}}+\text{jets}$ signal region for $p_T \leq 50$ GeV 3-prong τ_{had} candidates. Left: templates of discriminating variables for different τ_{had} p_T and n-prong slices. Middle: shape of the discriminating variable obtained in the signal region and fitted shape using the templates measured in the control regions. Right: χ^2/ndf of the fit as a function of α_{MJ} , the error on α_{MJ} is defined by the band at $\chi^2_{\text{min}}/\text{ndf} + \sqrt{\frac{2}{\text{ndf}}}$.

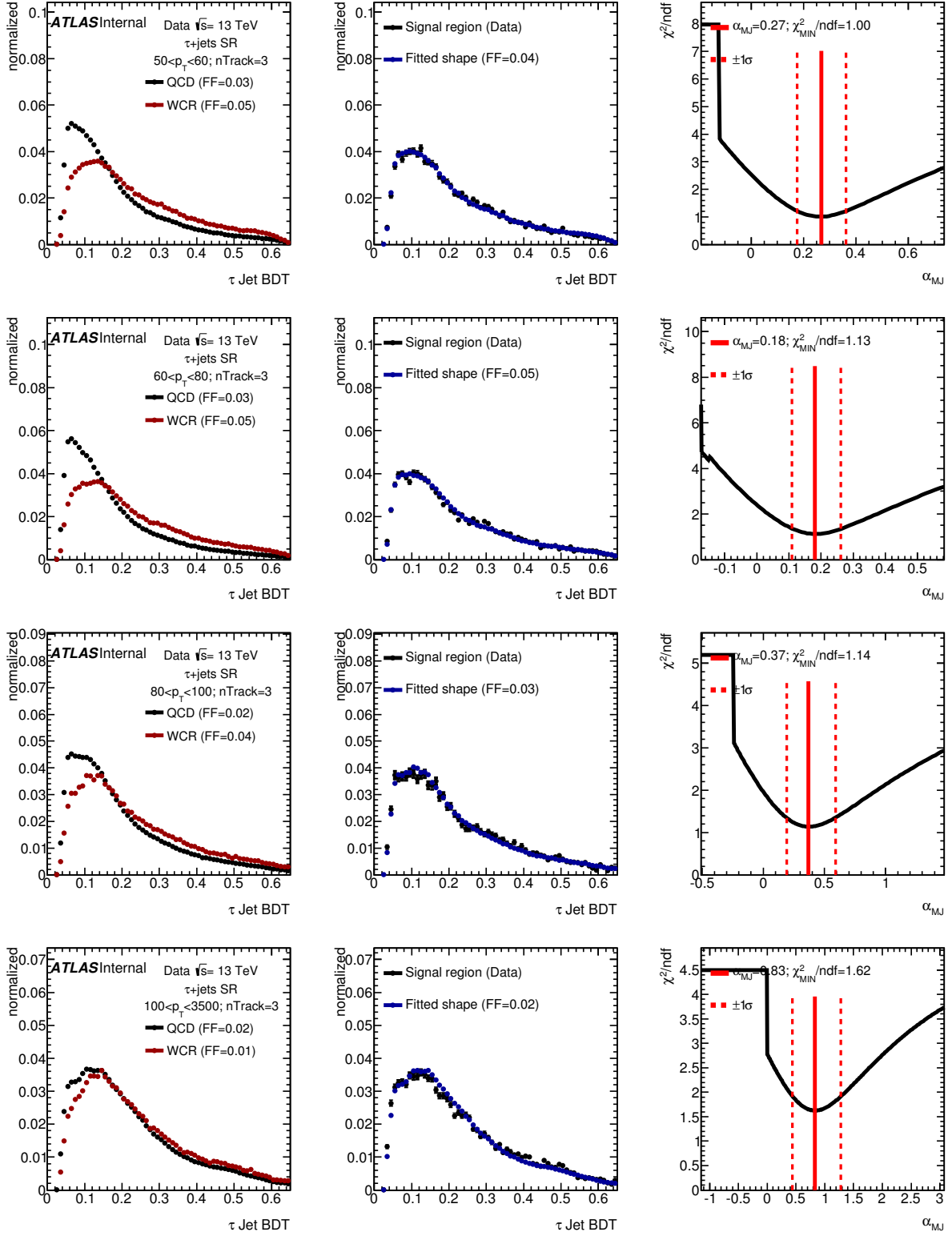


Figure 7.5.7: Estimation of α_{MJ} in the $\tau_{\text{had}} + \text{jets}$ signal region for $p_T \geq 50$ GeV 3-prong τ_{had} candidates. Left: templates of discriminating variables for different τ_{had} p_T and n-prong slices. Middle: shape of the discriminating variable obtained in the signal region and fitted shape using the templates measured in the control regions. Right: χ^2/ndf of the fit as a function of α_{MJ} , the error on α_{MJ} is defined by the band at $\chi^2_{\text{min}}/\text{ndf} + \sqrt{\frac{2}{\text{ndf}}}$.

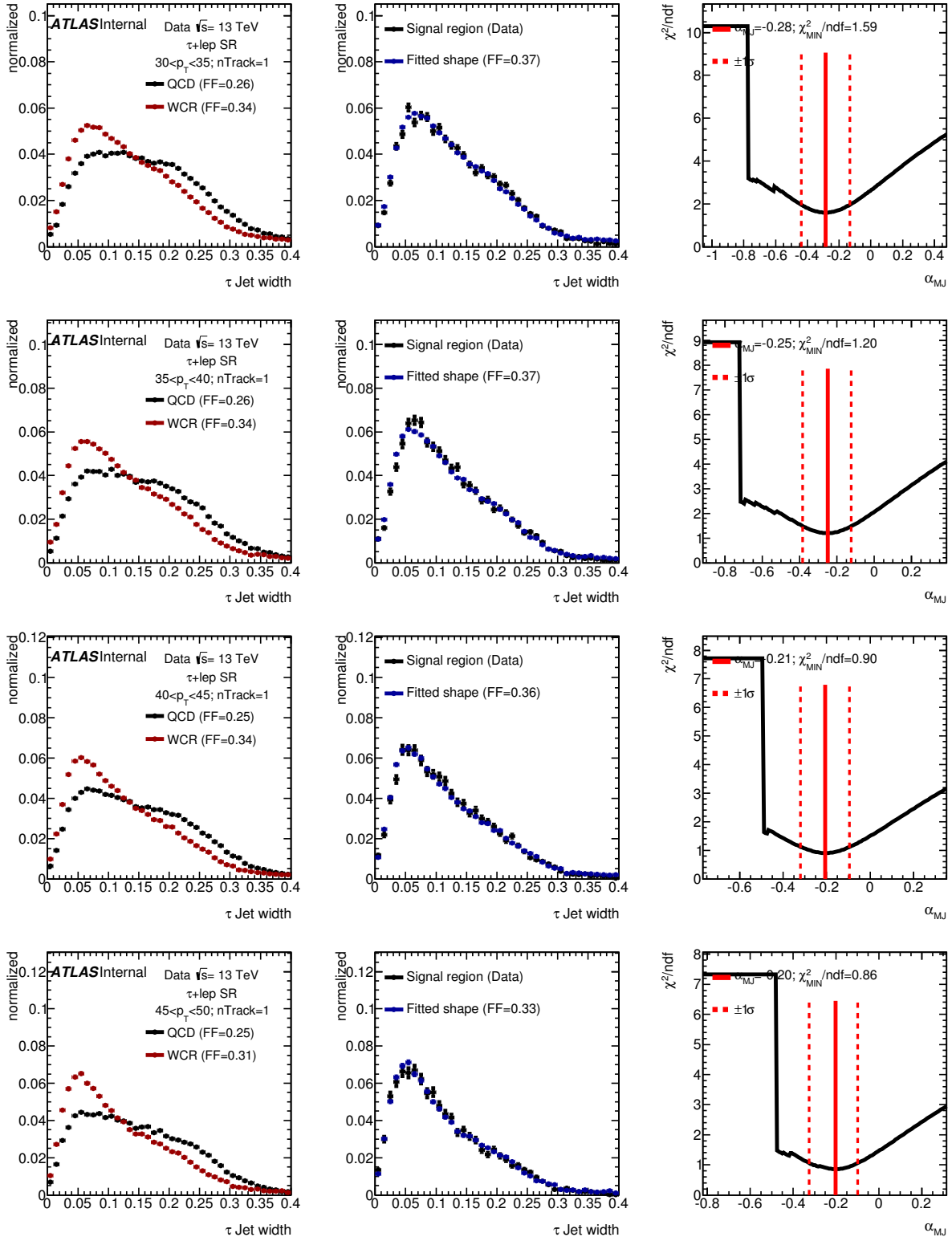


Figure 7.5.8: Estimation of α_{MJ} in the $\tau_{\text{had}} + \text{lepton}$ signal region for $p_T \leq 50$ GeV 1-prong τ_{had} candidates. Left: templates of discriminating variables for different τ_{had} p_T and n-prong slices. Middle: shape of the discriminating variable obtained in the signal region and fitted shape using the templates measured in the control regions. Right: χ^2/ndf of the fit as a function of α_{MJ} , the error on α_{MJ} is defined by the band at $\chi^2_{\text{min}}/\text{ndf} + \sqrt{\frac{2}{\text{ndf}}}$.

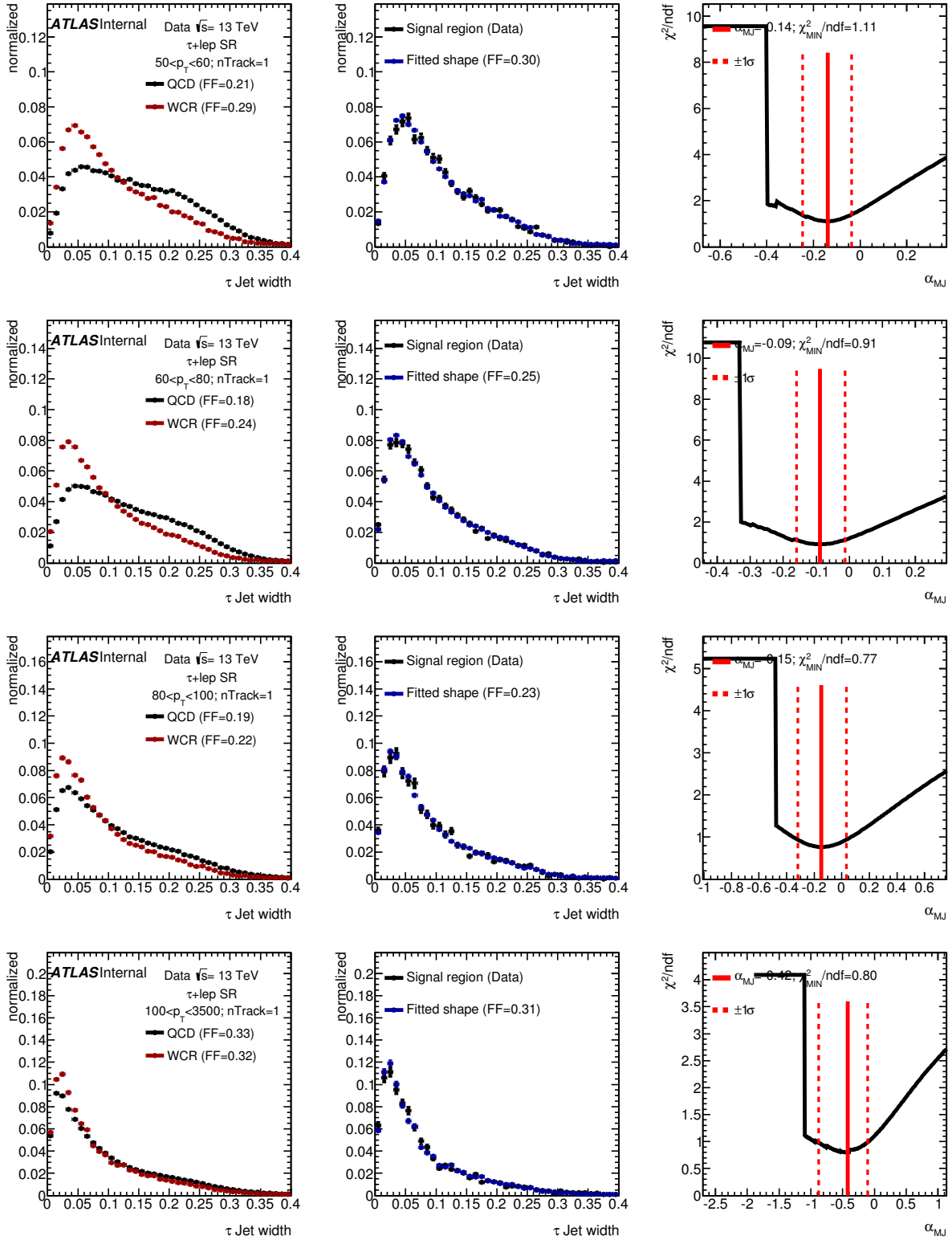


Figure 7.5.9: Estimation of α_{MJ} in the $\tau_{\text{had}} + \text{lepton}$ signal region for $p_T \geq 50$ GeV 1-prong τ_{had} candidates. Left: templates of discriminating variables for different τ_{had} p_T and n-prong slices. Middle: shape of the discriminating variable obtained in the signal region and fitted shape using the templates measured in the control regions. Right: χ^2/ndf of the fit as a function of α_{MJ} , the error on α_{MJ} is defined by the band at $\chi^2_{\text{min}}/\text{ndf} + \sqrt{\frac{2}{\text{ndf}}}$.

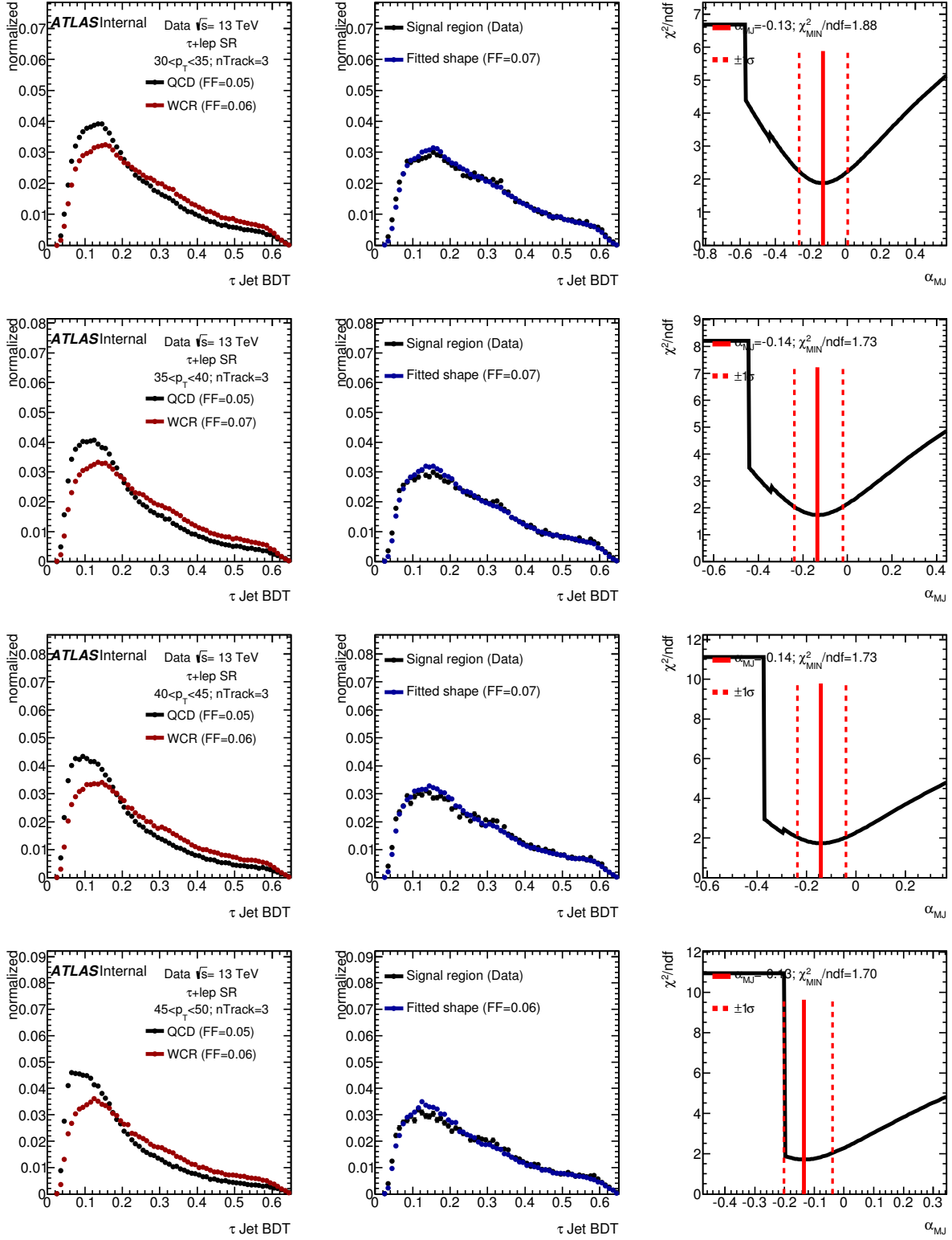


Figure 7.5.10: Estimation of α_{MJ} in the $\tau_{\text{had}} + \text{lepton}$ signal region for $p_T \leq 50$ GeV 3-prong τ_{had} candidates. Left: templates of discriminating variables for different τ_{had} p_T and n-prong slices. Middle: shape of the discriminating variable obtained in the signal region and fitted shape using the templates measured in the control regions. Right: χ^2/ndf of the fit as a function of α_{MJ} , the error on α_{MJ} is defined by the band at $\chi^2_{\text{min}}/\text{ndf} + \sqrt{\frac{2}{\text{ndf}}}$.

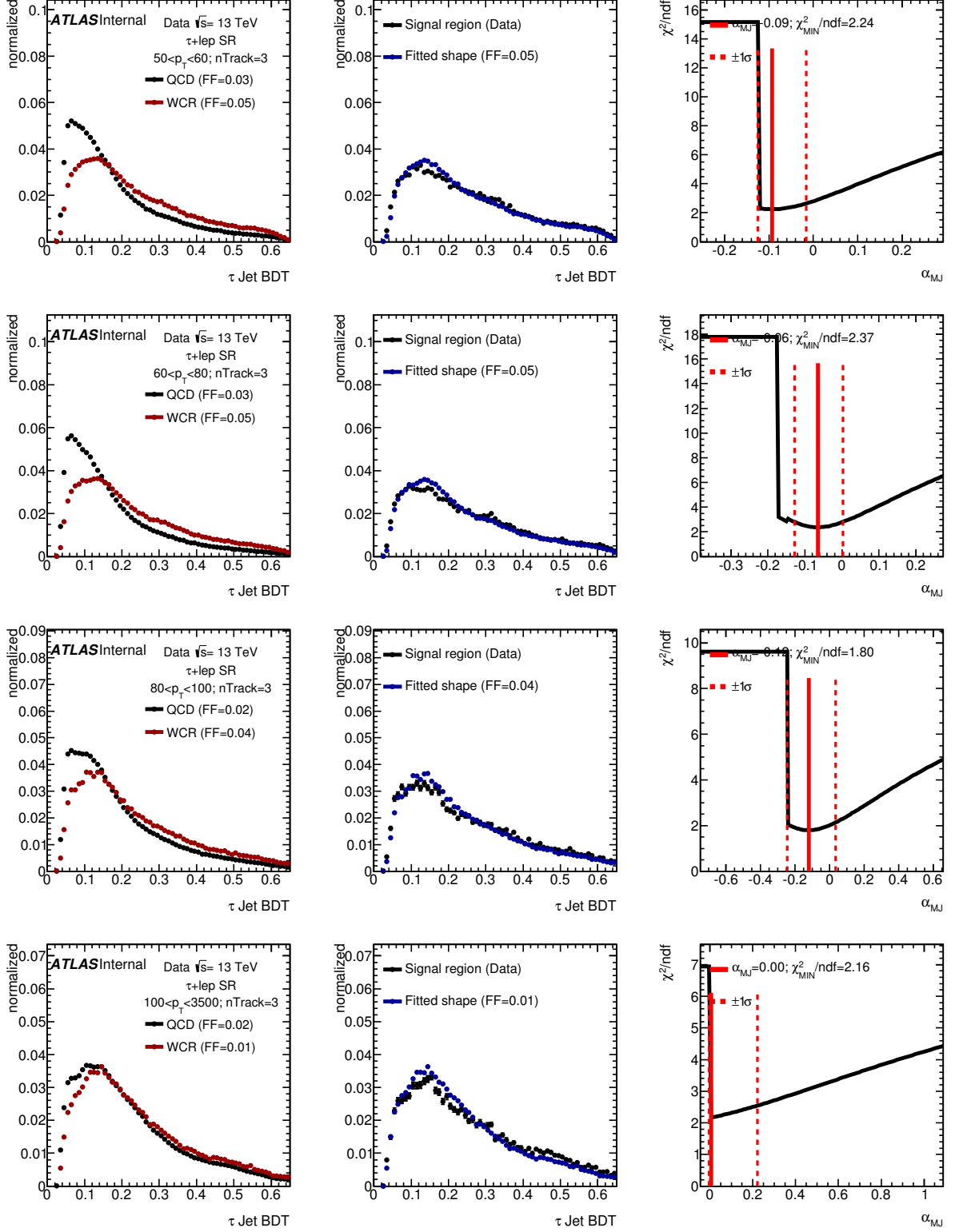


Figure 7.5.11: Estimation of α_{MJ} in the $\tau_{\text{had}} + \text{lepton}$ signal region for $p_T \geq 50$ GeV 3-prong τ_{had} candidates. Left: templates of discriminating variables for different τ_{had} p_T and n-prong slices. Middle: shape of the discriminating variable obtained in the signal region and fitted shape using the templates measured in the control regions. Right: χ^2/ndf of the fit as a function of α_{MJ} , the error on α_{MJ} is defined by the band at $\chi^2_{\text{min}}/\text{ndf} + \sqrt{\frac{2}{\text{ndf}}}$.

The anti- τ_{had} region used to obtain the template fits is defined with *non-loose* candidates, while the anti- τ_{had} region to obtain the fake factors is defined with *non-loose* candidates that also have a lower cut on the BDTJetSigTrans score. Therefore, the parameter α_{MJ} measured using the template fits gives the gluon-initiated jet fraction for a looser selection. This looser selection was chosen to have a better separation between gluon- and quark-initiated jets and the error on the fit is minimized. To correct for the gluon- and quark-initiated jet fractions of the actual anti- τ_{had} region used for the fake-factor estimation, a corrected α_{MJ} is used, defined as:

$$\alpha_{\text{MJ}}^{\text{Corr}} = \frac{\zeta_{\text{MJ}} \times \alpha_{\text{MJ}}}{(\zeta_{\text{MJ}} \times \alpha_{\text{MJ}} + \zeta_{W+\text{jets}} \times (1 - \alpha_{\text{MJ}}))}, \quad (7.5.11)$$

where ζ_{MJ} and $\zeta_{W+\text{jets}}$ are fractions of events in the *non-loose* multi-jet and $W+\text{jets}$ control regions, respectively, that pass the lower cut on the BDTJetSigTrans score.

To validate the estimation of the differences in fractions between gluon- and quark-initiated jets, two additional validation regions are used: a $\tau_{\text{had}}+\text{jets}$ signal-like region with b -veto cut and a $\tau_{\text{had}}+\text{lepton}$ signal-like region with same-sign charges. The α_{MJ} values used for the combined fake factors for the $\tau_{\text{had}}+\text{jets}$ b -veto control and signal regions, as well as for the $\tau_{\text{had}}+\text{lepton}$ same-sign control and signal regions are shown in figure 7.5.12. The validation plots obtained in the two additional regions described above are shown in figure 7.5.13, where a good modelling of the fake τ_{had} objects is observed.

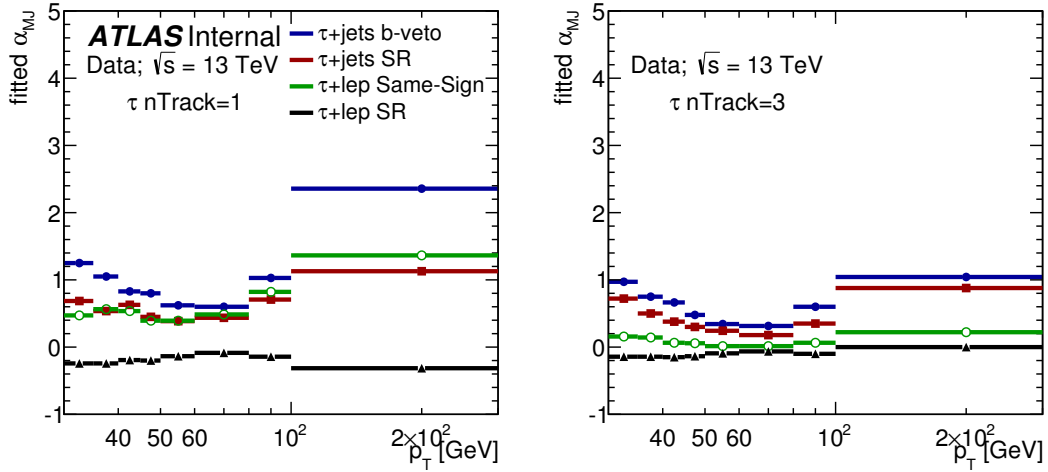


Figure 7.5.12: Corrected α_{MJ} values for the $\tau_{\text{had}}+\text{jets}$ b -veto, $\tau_{\text{had}}+\text{jets}$ signal region, $\tau_{\text{had}}+\text{lepton}$ signal region with same-sign control region and the $\tau_{\text{had}}+\text{lepton}$ signal region.

7.5.2.4 τ_{had} fake factors from heavy flavor jets

Fake factors are usually strongly dependent on the type of jets. During the computation of the combined fake-factors, described in section 7.5.2.3, the α_{MJ} is extracted from the fit of fake- τ_{had} templates in the signal region. Fake factors are computed in the regions where gluon- or light-quark-initiated jets are misidentified as τ_{had} . These regions may, however, have a small fraction of heavy-quark-initiated jets. Therefore, this might lead to an additional uncertainty on the evaluation of the fake factors in the signal regions. The signal region typically has about 30–40% of heavy-flavor jets, as shown in table 7.5. The impact of heavy-flavor jet contamination on the fake-factor method is studied here.

The dependence of the fake-factors on the type of jet faking the τ_{had} object was studied using $t\bar{t}$ MC sample, where the highest energy parton matched to reconstructed jet is used to identify from

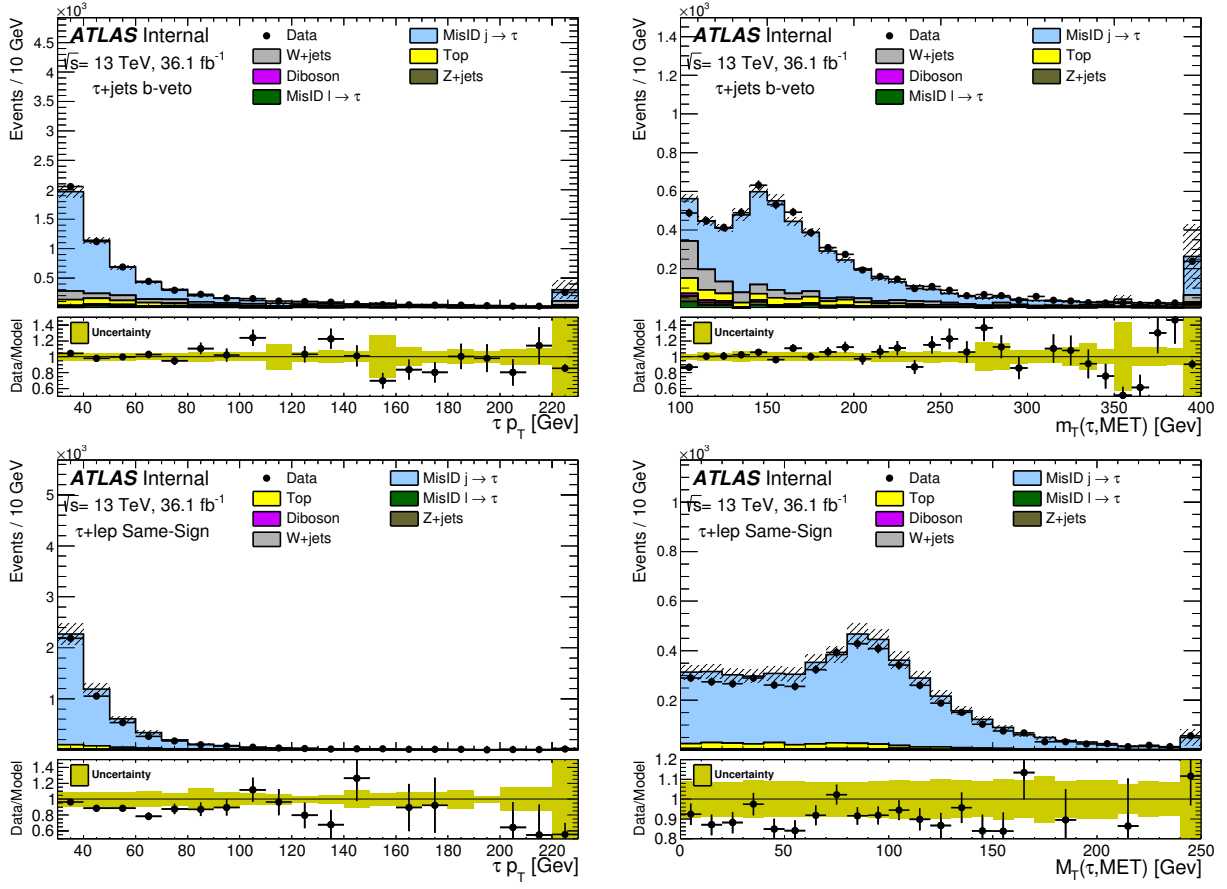


Figure 7.5.13: $j \rightarrow \tau_{\text{had}}$ background validation plots: τ_{had} +jets signal-like region with a b -jet veto (top) and same-sign τ_{had} +lepton signal-like region (bottom).

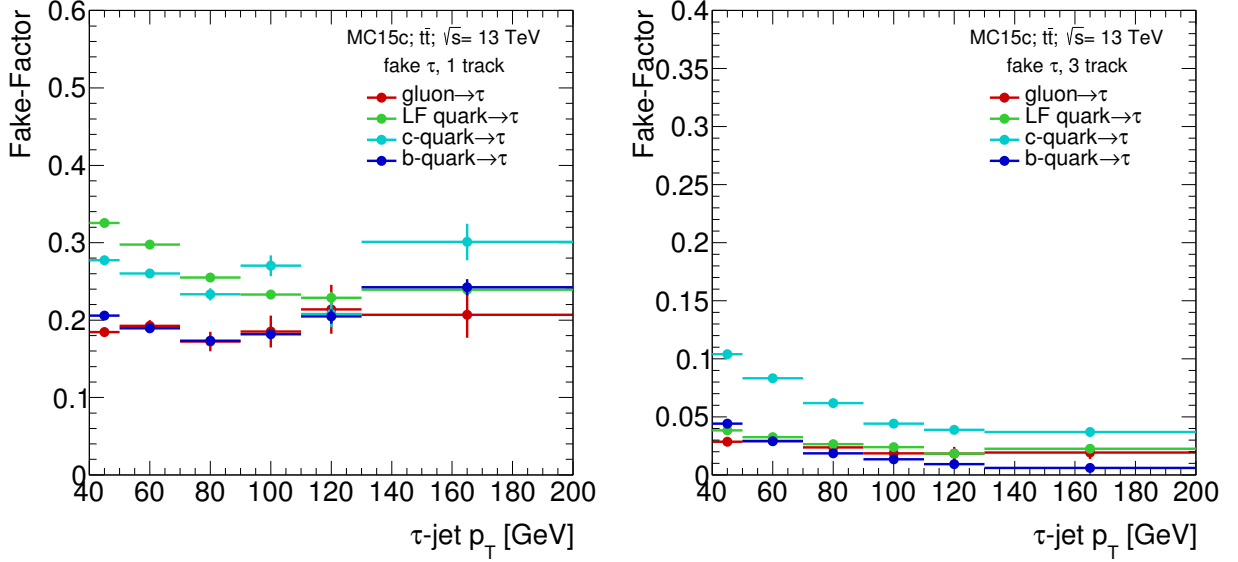


Figure 7.5.14: Fake-Factors of $j \rightarrow \tau_{\text{had}}$ background for different selection of τ initiated jet. The association between the jet and the initial quark was calculated using *PartonTruthLabelID* variable of jet container. In the plots Fake-Factors shown for 1-track (left) and 3-track (right) $j \rightarrow \tau_{\text{had}}$ separately.

which quark the jet is coming from. The result of this study is illustrated by figure 7.5.14, separately for 1-prong and 3-prong τ_{had} objects. Note that, for 3-prong $\tau_{\text{had-vis}}$ candidates, c -jets have a high probability to mimic $\tau_{\text{had-vis}}$ objects, due to the proximity of the D -meson lifetime to that of the τ -lepton.

The impact of the heavy-flavor jets in the signal regions on the $j \rightarrow \tau_{\text{had}}$ background was tested using the following method: The fake factors are calculated separately for different types of jets misidentified as a τ_{had} candidate in the control regions. Three (four) orthogonal control regions for 1-track (3-track) τ_{had} objects are selected, based on the weight of the associated heavy-flavor jet-tagger for the τ_{had} object – $MV2c20$ which is the b-jet weight or $MV2cl100$ which is the c-jet weight (both weight are the outcome of the MVA-based discriminant trained to separate jets initiated by b- or c-quarks from jet initiated by light-quarks):

1 **b-tag** region: $MV2c20 > 0.8$

2 **c-tag** region: $MV2c20 \leq 0.8 \ \&\& \ MV2cl100 > 0.8$

3+4 **light quark** region: $MV2c20 \leq 0.8 \ \&\& \ MV2cl100 \leq 0.8$

The last region is further divided into $MV2c20 \leq -0.95$ or $MV2c20 > -0.95$ for 1-track τ_{had} candidates in order to best cover the pure light-flavor region, which has a large fake factor. The composition of the selected control regions and the corresponding “extended” fake factors, i.e. $\text{FF}(p_T, \text{trk}, \text{flavor})$, are shown in figures 7.5.15 and 7.5.16, respectively.

The prediction using the nominal fake factors or the “extended” fake factors (which cover differences in the composition of the $j \rightarrow \tau_{\text{had}}$ background) are compared in figure 7.5.17. The differences in the predicted yields are 2% and 5% for the $\tau_{\text{had}}+\text{jets}$ and $\tau_{\text{had}}+\text{lepton}$ channels, respectively, and the most substantial deviation (set as a systematic uncertainty) is about 5% for both final states.

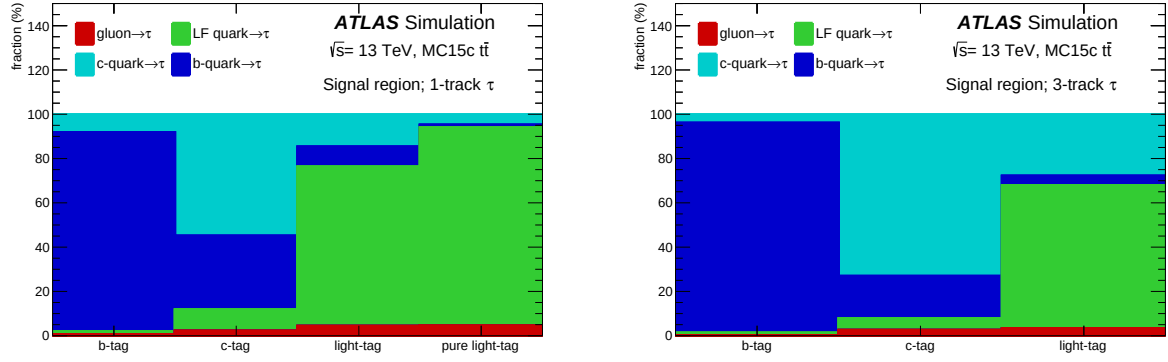


Figure 7.5.15: Composition of $j \rightarrow \tau_{\text{had}}$ background for different selection based on the flavor tagger weights. Selection shown for τ +jets signal region selection for 1-track (left) and 3-track (right) $j \rightarrow \tau_{\text{had}}$ separately.

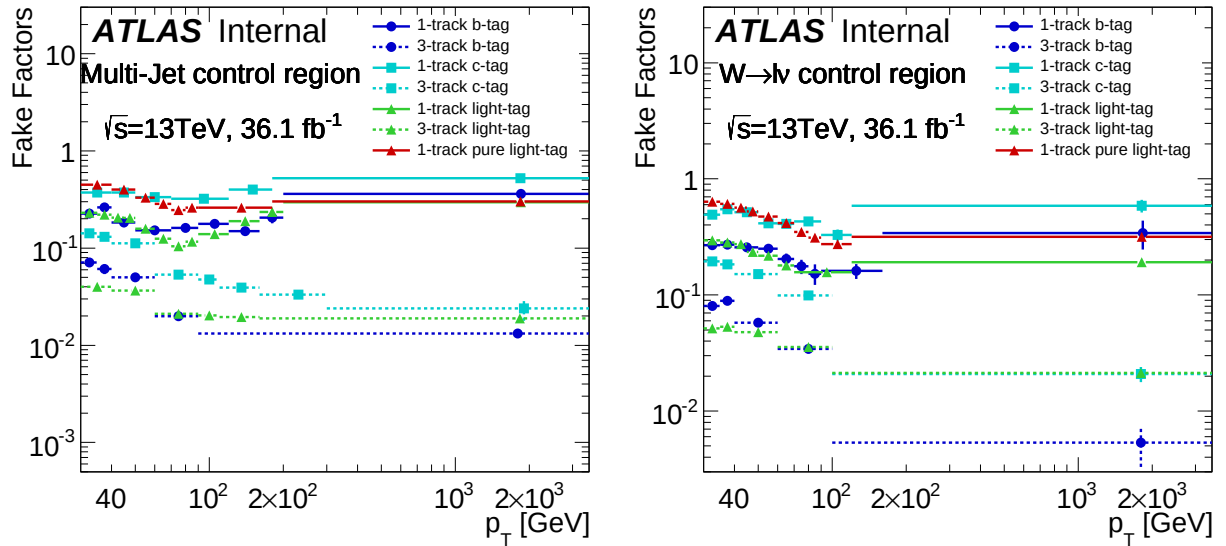


Figure 7.5.16: Fake factors parameterised as a function of p_T^τ and the number of charged τ decay products (two categories: 1-prong and 3-prong), as obtained in the multi-jet (left) and W +jets CRs (right).

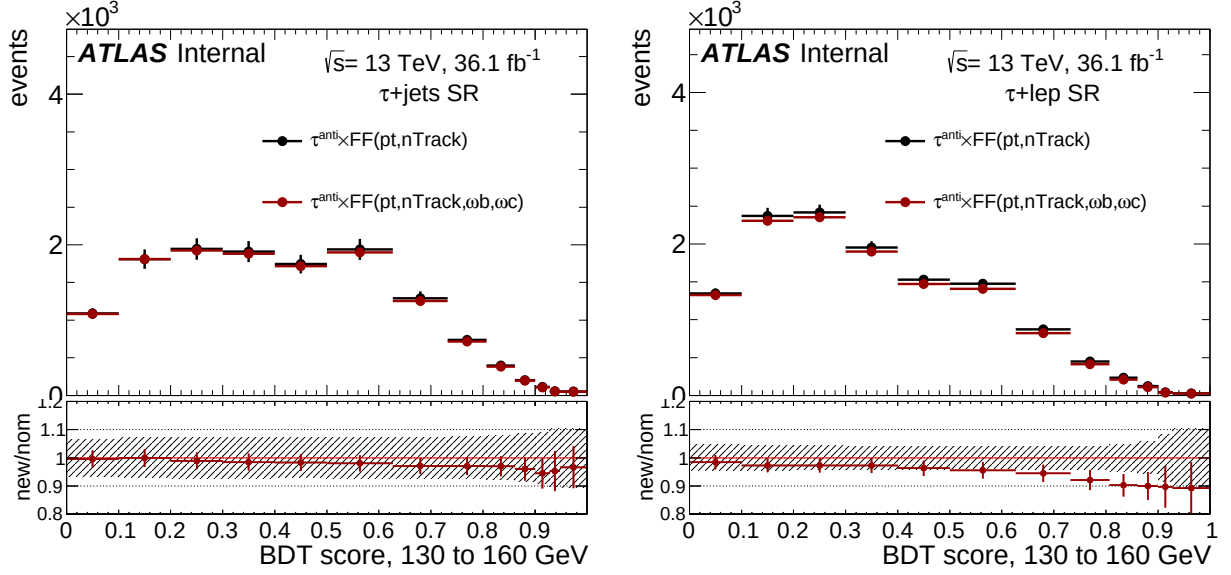


Figure 7.5.17: Composition of $j \rightarrow \tau_{\text{had}}$ background modelling in τ +jets (left) and τ +lep (right) signal region using nominal and “extended” Fake-Factors.

7.5.2.5 Υ correction of fake- τ_{had} candidates

Hadronic τ decays are identified using a BDT, which is based on several input variables [118], where one of them, the leading-track momentum fraction, is strongly correlated with the Υ . As a result, the distribution of the Υ variable significantly differs between τ_{had} and anti- τ_{had} candidates. Since the Υ variable is used as an input to the final BDT discriminant of the analysis, its shape should be appropriately modeled for the τ_{had} candidates in the signal region. The Υ variable shows no correlation with any of the other variables that are used as input to the final BDT. Hence, its shape is corrected using a Smirnov transformation [125]. The Smirnov transformation works as follows: shapes of the Υ variable are obtained for τ_{had} and anti- τ_{had} in the control region, then a cumulative distribution function (CDF) is calculated from these shapes ($F(\Upsilon)$). Using an inverse transformation of F , the corrected value is obtained:

$$\Upsilon_{\text{corr}} = F_{\tau}^{-1}((F_{\text{anti-}\tau}(\Upsilon))), \quad (7.5.12)$$

where $F_{\tau}^{-1}(x)$ is the inverse of the cumulative distribution function of τ_{had} candidates and $F_{\text{anti-}\tau}(x)$ is the cumulative distribution function of anti- τ_{had} candidates.

Figure 7.5.18 shows the distribution and the CDF of the Υ variable in the W +jets control region for 1-prong objects (Υ is not used in the training of the final BDT discriminant for 3-prong τ_{had} candidates).

The distributions of Υ before and after Smirnov transformation in the τ_{had} +jets b -veto and τ_{had} +lepton same-sign control regions are shown in figure 7.5.19.

The systematic uncertainty on the Smirnov transformation is taken as the difference between the resulting Υ_{corr} obtained in the multi-jet and W +jets control regions.

7.5.3 Validation of the background modelling

The background modelling is validated in signal-depleted regions, as illustrated here for the τ_{had} +lepton channel. A validation region enriched in $t\bar{t}$ events is defined with the same event selection as the signal region, but with the requirement of having an $e\mu$ pair (with E_T or p_T above 30 GeV for the electron or muon, respectively) instead of the $e/\mu + \tau_{\text{had}}$ pair. Another validation region of the τ_{had} +lepton

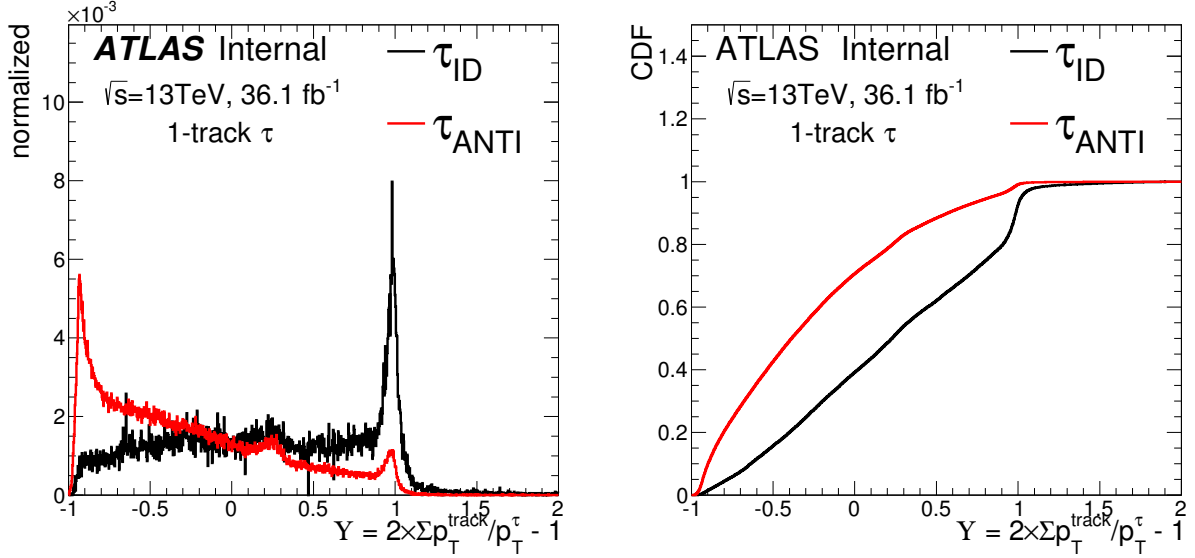


Figure 7.5.18: Left: Distribution of the Υ variable for τ_{had} (black) and anti- τ_{had} (red) candidates in the W +jets control region. Right: CDF of Υ for τ_{had} (black) and anti- τ_{had} (red) candidates in the W +jets control region.

channel is defined with the same selection criteria as the signal region, but with a veto on b -tagged jets, thereby ensuring that the dominant background consists of processes with a jet misidentified as the selected τ_{had} candidate. Comparisons of predicted and measured BDT score distributions for the two validation regions discussed above are shown in figures 7.5.20 and 7.5.21.

7.6 Systematic uncertainties

Several sources of systematic uncertainty, affecting the normalisation of signal and SM background processes or the shape of their distributions, are considered. The individual sources of systematic uncertainty are assumed to be uncorrelated. However, when applicable, correlations of a given systematic uncertainty are maintained across all processes. All systematic uncertainties are symmetrised with respect to the nominal value.

7.6.1 Experimental uncertainties

To assess the impact of most detector-related systematic sources, the selection cuts are re-applied after shifting a particular parameter to its ± 1 standard deviation value. The luminosity uncertainties of 2.1% serve directly as a scale factor on the event yield of all simulated samples. In general, the dominant instrumental systematic uncertainties arise from the jet reconstruction, the jet/ τ_{had} energy scale and τ_{had} misidentification probability. The effect of the main sources of uncertainties on the event yield for the $t\bar{t}$ and an example H^+ sample ($m_{H^+} = 200$ GeV) can be found in table 7.6 for τ_{had} +jets channel and in tables 7.7–7.8 for τ_{had} +lep channel (only sources with an effect of more than 1% are quoted).

7.6.1.1 Fake Factor uncertainties

In the estimation of backgrounds with jets misidentified as τ_{had} , discussed in section 7.5.2, the dominant systematic uncertainties are the statistical uncertainty due to the control sample size (figure 7.5.3) and the uncertainty due to the selection of the lower BDT cut in the “anti- τ ” control

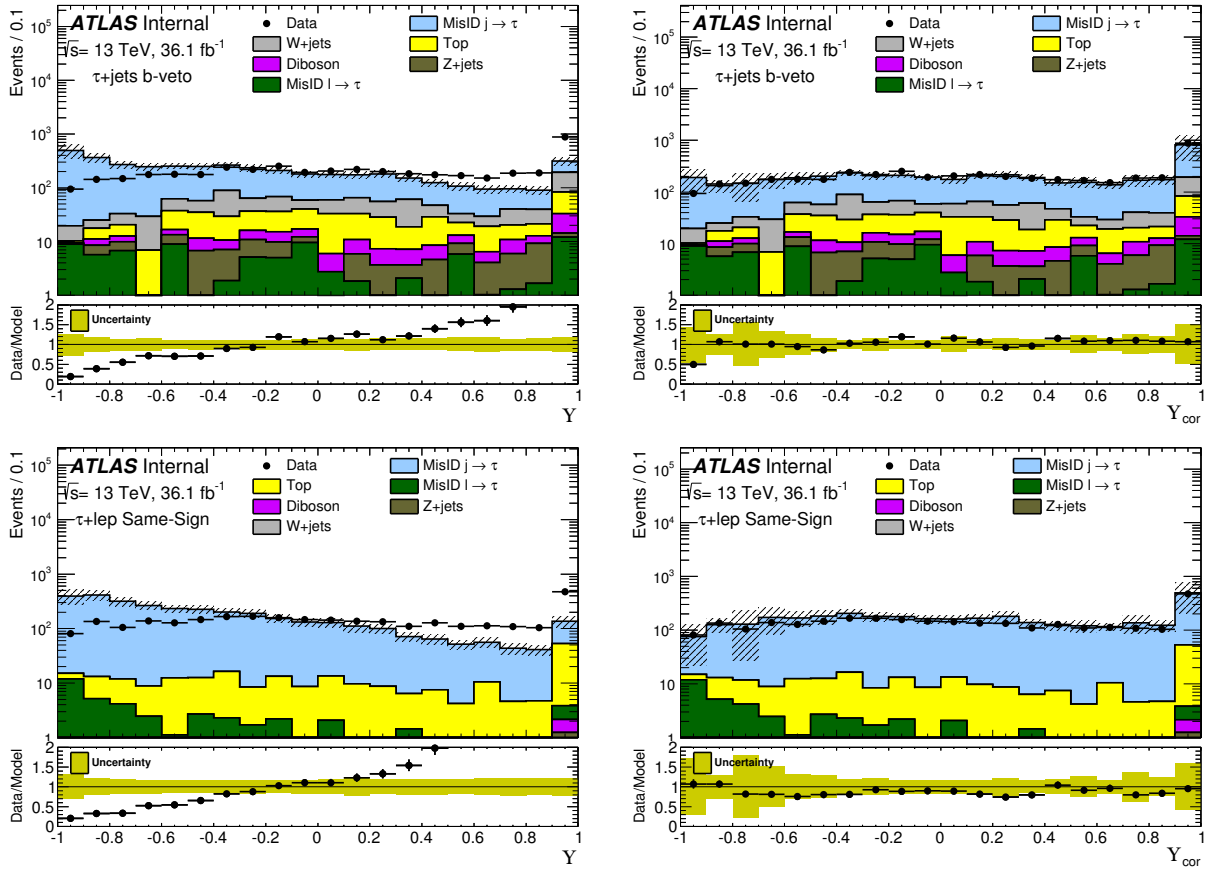


Figure 7.5.19: Distribution of Υ variable before (left) and after (right) Smirnov transformation in the τ_{had} +jets signal-like region with a b -jet veto (top) and in the same-sign τ_{had} +lepton signal-like region (bottom).

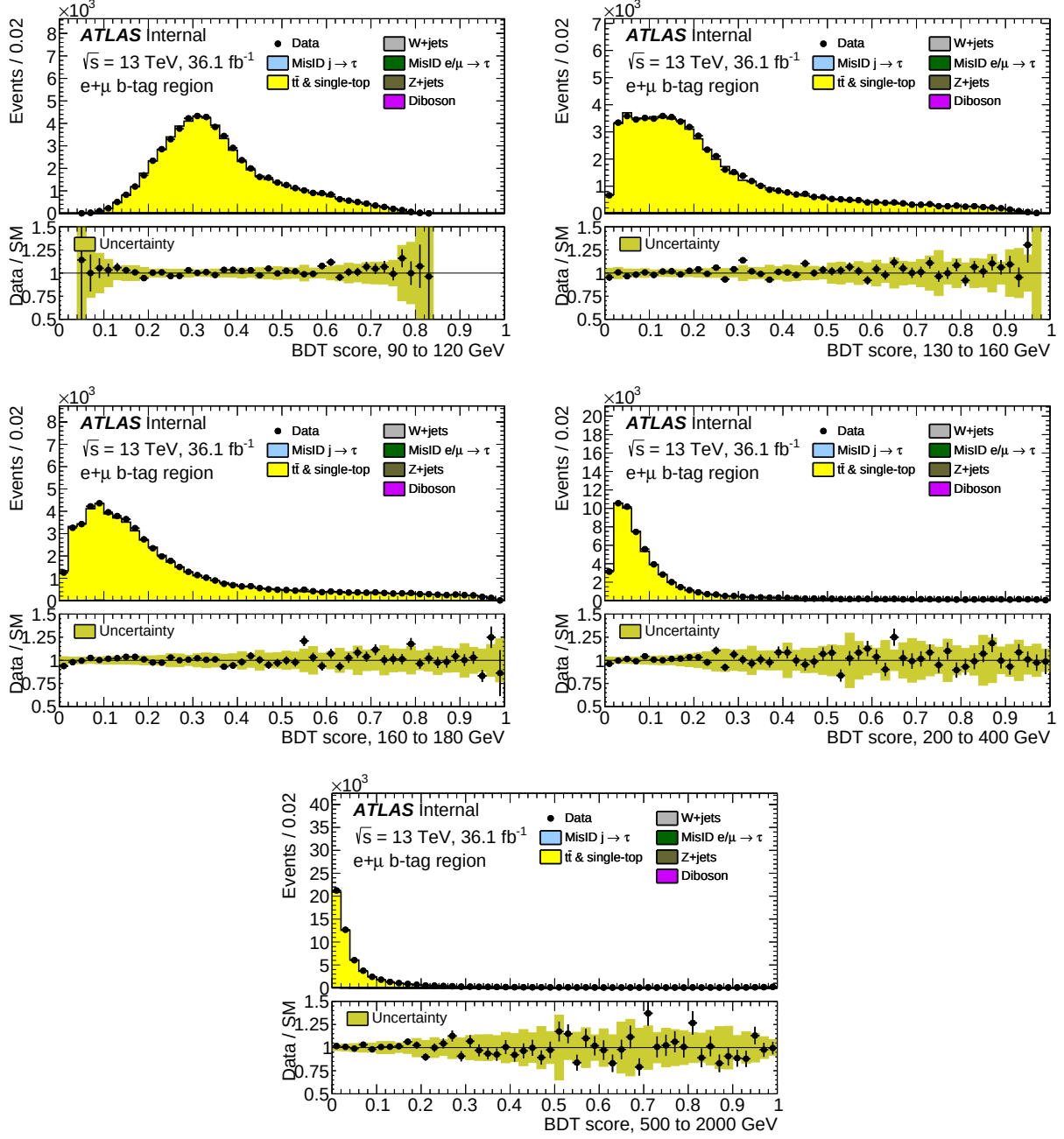


Figure 7.5.20: BDT score distribution for the predicted backgrounds and data in the validation region of the $\tau_{\text{had}} + \text{lepton}$ channel with an $e\mu$ pair instead of the $e/\mu + \tau_{\text{had}}$ pair (see text for details). The five $H^\pm$ mass range trainings are shown. The uncertainty bands in the lower plots include all statistical and systematic uncertainties.

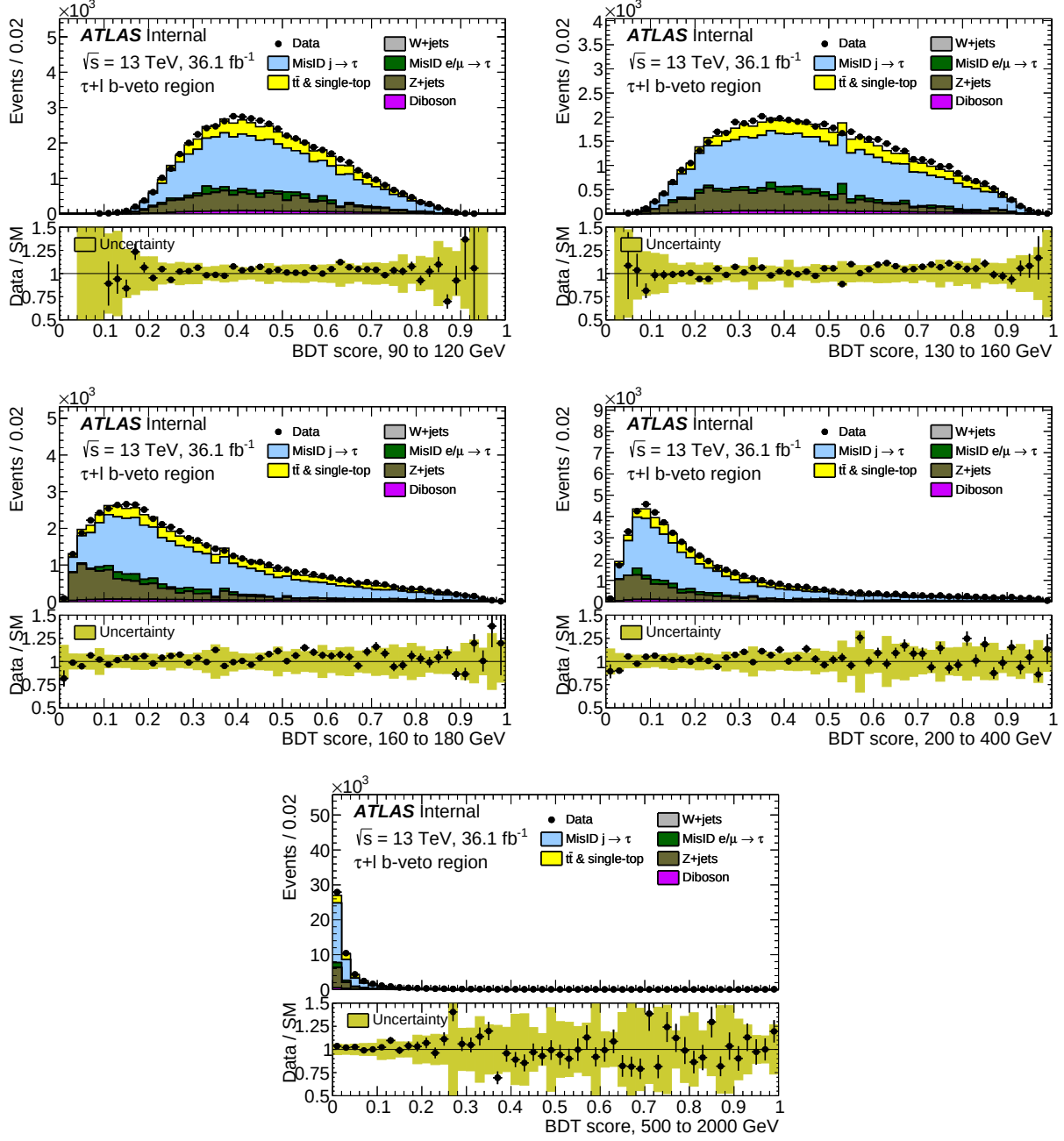


Figure 7.5.21: BDT score distribution for the predicted backgrounds and data in the validation region of the $\tau_{\text{had}}+\text{lepton}$ channel ($\tau_{\text{had}}+\text{electron}$ and $\tau_{\text{had}}+\text{muon}$ combined) with exactly zero b -tagged jet (see text for details). The five $H^\pm$ mass range trainings are shown. The uncertainty bands in the lower plots include both statistical and systematic uncertainties of simulated events.

Source	Impact on the event yield (%)	
	$t\bar{t}$	$H^+ 200 \text{ GeV}$
τ_{had} reconstruction efficiency	± 2.8	± 2.8
τ_{had} -id uncertainty	± 5.9	± 5.8
τ_{had} energy scale	± 5.1	± 4.9
jet energy scale	± 11.3	± 9.7
b -jet tag efficiency	± 2.1	± 2.7
$E_{\text{T}}^{\text{miss}}$ soft term scale/resolution	± 2.6	± 1.1

Table 7.6: Effect of the main systematic uncertainties on the event yield for $t\bar{t}$ and signal events ($m_{H^+} = 200 \text{ GeV}$) passing the nominal event selection of the $\tau_{\text{had}} + \text{jets}$ channel. The three components of the τ_{had} energy scale uncertainty are shown in the table.

Source	Impact on the event yield (%)	
	$t\bar{t}$	$H^+ 200 \text{ GeV}$
τ_{had} reconstruction efficiency	± 3.4	± 3.3
τ_{had} -id uncertainty	± 5.8	± 5.8
τ_{had} energy scale	± 4.1	± 3.6
jet energy scale	± 2.6	± 2.2
b -jet tag efficiency	± 2.1	± 3.4

Table 7.7: Effect of the main systematic uncertainties on the event yield for $t\bar{t}$ and signal events ($m_{H^+} = 200 \text{ GeV}$) passing the nominal event selection of the $\tau_{\text{had}} + e$ channel. The three components of the τ_{had} energy scale uncertainty are shown in the table.

sample. For different choices of the lower BDT cut, different fraction of gluon- and quark-initiated jets populate the “anti- τ ” control region. In order to assess the systematic uncertainty related to this choice, the lower cut on non-loose τ_{had} BDT weight was varied between 0.01 and 0.03, and the variation of the shape was selected as a shape uncertainty on the final BDT distribution. To account for an additional uncertainty from a possible bias resulting from different contaminations of heavy-flavor jets between control and signal regions, a 5% uncertainty on the normalisation of the fake- τ background is applied. An additional (conservative) uncertainty of 50% is applied on the amount of τ_{had} candidates from a true hadronic τ decay that must be subtracted when computing $N_{\text{fakes}}^{\text{anti-}\tau}$:

$$N_{\text{fakes}}^{\text{anti-}\tau} = N_{\text{fakes}}^{\text{anti-}\tau}(\text{data}) - [0.5, 1.5] \times N_{\text{fakes}}^{\text{anti-}\tau}(\text{MC}). \quad (7.6.1)$$

A summary is given in table 7.9.

7.6.1.2 Uncertainties on the $t\bar{t}$ background

The dominant background with a τ_{had} candidate matched to a true τ_{had} object at the generator level is the production of $t\bar{t}$ pairs and single-top-quark events. No cross-section uncertainty is included as the normalization of this background is computed in a simultaneous fit, in which the validation region of the $\tau_{\text{had}} + \text{lepton}$ channel with an $e\mu$ pair and at least two b -jets is included. Other $t\bar{t}$ modelling uncertainties are considered though. Systematic uncertainties due to the choice of parton shower and hadronisation models are derived by comparing $t\bar{t}$ events generated with POWHEG-BOX interfaced to either PYTHIA v6.428 or HERWIG++ v2.7.1 [126]. The systematic uncertainties arising from initial- and final-state parton radiation, which modifies the jet production rate, are computed with the same packages as for the baseline $t\bar{t}$ event generation, by setting the corresponding parameters in PYTHIA to a range of values not excluded by the experimental data. The uncertainty

Source	Impact on the event yield (%)	
	$t\bar{t}$	H^+ 200 GeV
τ_{had} reconstruction efficiency	± 3.4	± 3.2
τ_{had} -id uncertainty	± 5.8	± 5.8
τ_{had} energy scale	± 4.0	± 3.8
μ -id uncertainty	± 1.2	± 1.2
jet energy scale	± 2.1	± 2.4
b -jet tag efficiency	± 2.2	± 3.1
trigger	± 1.1	± 1.1

Table 7.8: Effect of the main systematic uncertainties on the event yield for $t\bar{t}$ and signal events ($m_{H^+} = 200$ GeV) passing the nominal event selection of the $\tau_{\text{had}} + \mu$ channel. The three components of the τ_{had} energy scale uncertainty are shown in the table.

Source of uncertainty	$\tau_{\text{had-vis}} + \text{jets}$		$\tau_{\text{had-vis}} + \text{lepton}$	
	Effect on yield	Shape	Effect on yield	Shape
Fake factors: jet composition	1.6%	✓	0.6%	✓
Fake factors: statistical uncertainties	1.6%	✗	1.7%	✗
Fake factors: prompt $\tau_{\text{had-vis}}$ in the anti- τ CR	+5.6%	✗	+4.8%	✗
	-8.3%		-7.2%	
Fake factors: α_{MJ} uncertainty	7%	✗	6.2%	✗
Fake factors: Smirnov transform.	0%	✓	0%	✓
Fake factors: heavy flavor jet fraction.	5%	✓	5%	✓

Table 7.9: Effect on the shape variation and the yields of systematic uncertainties associated with the data-driven fake factor method, used to estimate the $j \rightarrow \tau$ background in the $\tau_{\text{had-vis}} + \text{jets}$ and $\tau_{\text{had-vis}} + \text{lepton}$ channel.

due to the choice of a matrix-element generator is evaluated by comparing $t\bar{t}$ samples generated with MADGRAPH5_AMC@NLO or POWHEG-BOX. The impacts of the three systematic uncertainties listed above on the event yield of the $t\bar{t}$ background are, respectively, 12%, 3%, 13% in the $\tau_{\text{had}} + \text{jets}$ channel and 13%, 8%, 9% in the $\tau_{\text{had}} + \text{lepton}$ channel.

7.6.2 Smoothing procedure for MC-MC shape uncertainties

Several systematic uncertainties are estimated by comparing different MC samples, for example, the $t\bar{t}$ theory uncertainties described above. Uncertainties derived from MC-to-MC comparison (comparison between two statistically independent samples), can lead to an unpredicted bias of the shape variation when one of the samples is statistically limited, or when MC shape estimation is strongly affected by negative weights. To overcome this limitation, a dedicated smoothing procedure is applied to the derived shape variations. The smoothing procedure integrates the information about the statistical uncertainty of the sample and reduces possible bias due to a lack of MC statistics. In the standard approach, a bin-by-bin variation between the alternative and the nominal samples is taken as the systematic uncertainty for that specific background. In the case when some bins are statistically limited, the shape variation in that bins is mostly formed by statistical fluctuation rather than by the real difference in the modelling. Next smoothing is applied – the input histograms are rebinned in such way that the relative statistical uncertainty of each bin range is smaller than a given value

of δ for both input histograms (the nominal and the alternative). The δ given by:

$$\delta = \sigma_{\text{stat}}(\text{bin})/N(\text{bin}) \quad (7.6.2)$$

where $\sigma_{\text{stat}}(\text{bin})$ is the statistical uncertainty and $N(\text{bin})$ is the expected number of events in a given bin respectively. Then the shape variation is obtained as a function of the BDT score – $\Delta(\text{bdt})$. This shape variations is depend on the rebinning procedure, and it is different for different thresholds δ (denoted as $\Delta_{\delta}(\text{bdt})$). Next, a new threshold δ' is chosen, and a new shape variation $\Delta_{\delta'}(\text{bdt})$ is extracted again from the input histograms. Such procedure is repeated for different thresholds in the range between 10% to 25% ($\delta \in [0.1, 0.25]$). Finally, the shape variation for a given BDT-bin is chosen to be the weighted average variation defined by:

$$\Delta(\text{bdt}) = \frac{\sum_{\delta} \Delta_{\delta}(\text{bdt}) \times 1/\delta}{\sum_{\delta} 1/\delta} \quad (7.6.3)$$

7.6.2.1 Toy model study

The robustness of the method was tested using MC toys. A nominal and alternative sample were generated from an analytical distribution function (Landau convoluted with a Gaussian). The analytical shapes used in the toy model are shown on the right-hand side of figure 7.6.1. From the analytical function, two histograms were randomly generated with 10^4 events each (right-hand side of figure 7.6.1).

The smoothing procedure is then applied, and the weighted shape variations are obtained. Figure 7.6.2 show comparison between the nominal and the alternative samples, with (right) and without (left) the smoothing procedure.

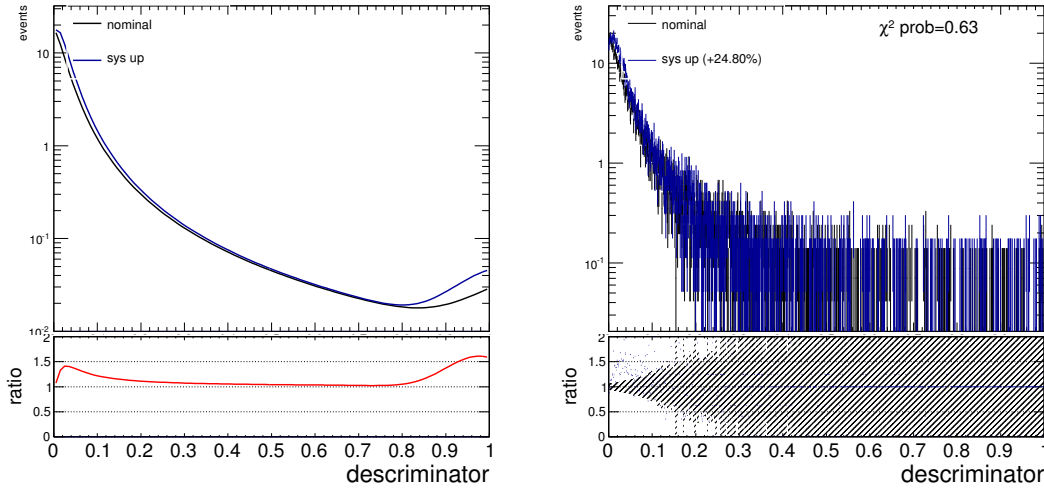


Figure 7.6.1: Left: Analytical function used in the toy MC study for nominal and the alternative shape model, the red curve in the bottom plot shows the actual systematic shift. Right: Distribution from 10000 generated events from the analytical function for the nominal and the alternative shape model. the black dashed band in the ratio plot is the statistical uncertainty of the nominal background.

One can note, that on the left-hand side of figure 7.6.2, the high BDT bins, are statistically limited, resulting in substantial shape variations. Such large shape variations can potentially bias the obtained results in the signal region.

The results are shown in figures 7.6.1–7.6.2 are obtained for a single toy MC. To validate the robustness of the method, a large set of toys were simulated, and the differences between estimated

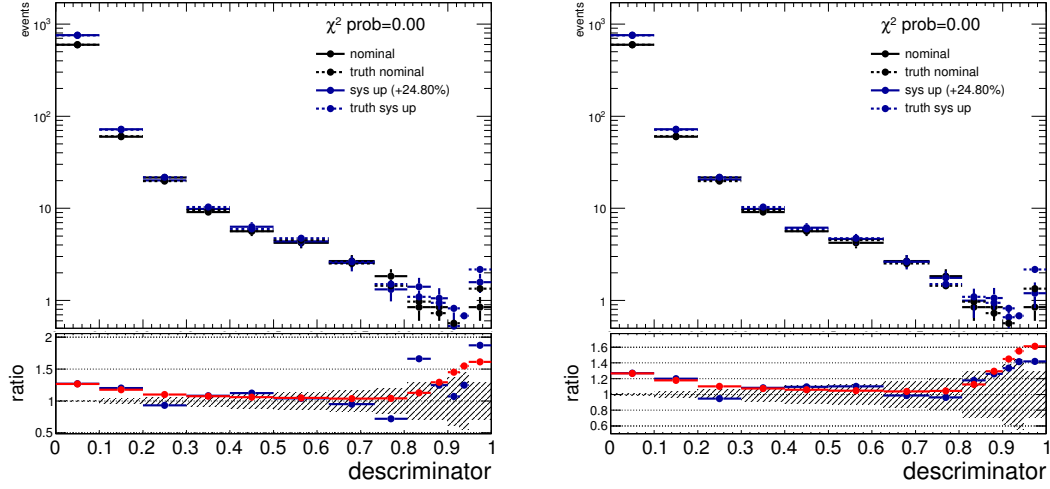


Figure 7.6.2: Distribution using the final binning of the $\tau_{\text{had}}+\text{jet}$ channel, for the nominal and the alternative background shape obtained from the toy model. The left plot shows the alternative model obtained from the toy MC, while the right plot shows the smoothed alternative shape. Both distributions are shown – the shape distribution according to the analytical function, obtained by integrating in a given bin range the analytical function that is depicted in left-hand side of figure 7.6.1 (dashed line, labelled as *truth*), and the distribution obtained from randomly generated events using a toy MC, obtained by integrating in a given bin range the generated shapes that are depicted in right-hand side of figure 7.6.1 (solid line). The bottom ratio plot shows the actual shape variations (red) and the estimated shape variations from a given toy MC (blue).

shift (blue line in ratio plot of figure 7.6.2) and the real systematic shift (red line in the ratio plot of figure 7.6.2) for each one of the last 4 bins was calculated and are depicted in figure 7.6.3.

The results show that with the smoothing procedure, the obtained shape variations, are less sensitive to statistical fluctuations. Therefore this approach is used for the shape systematic uncertainty when it was derived in MC-MC comparison.

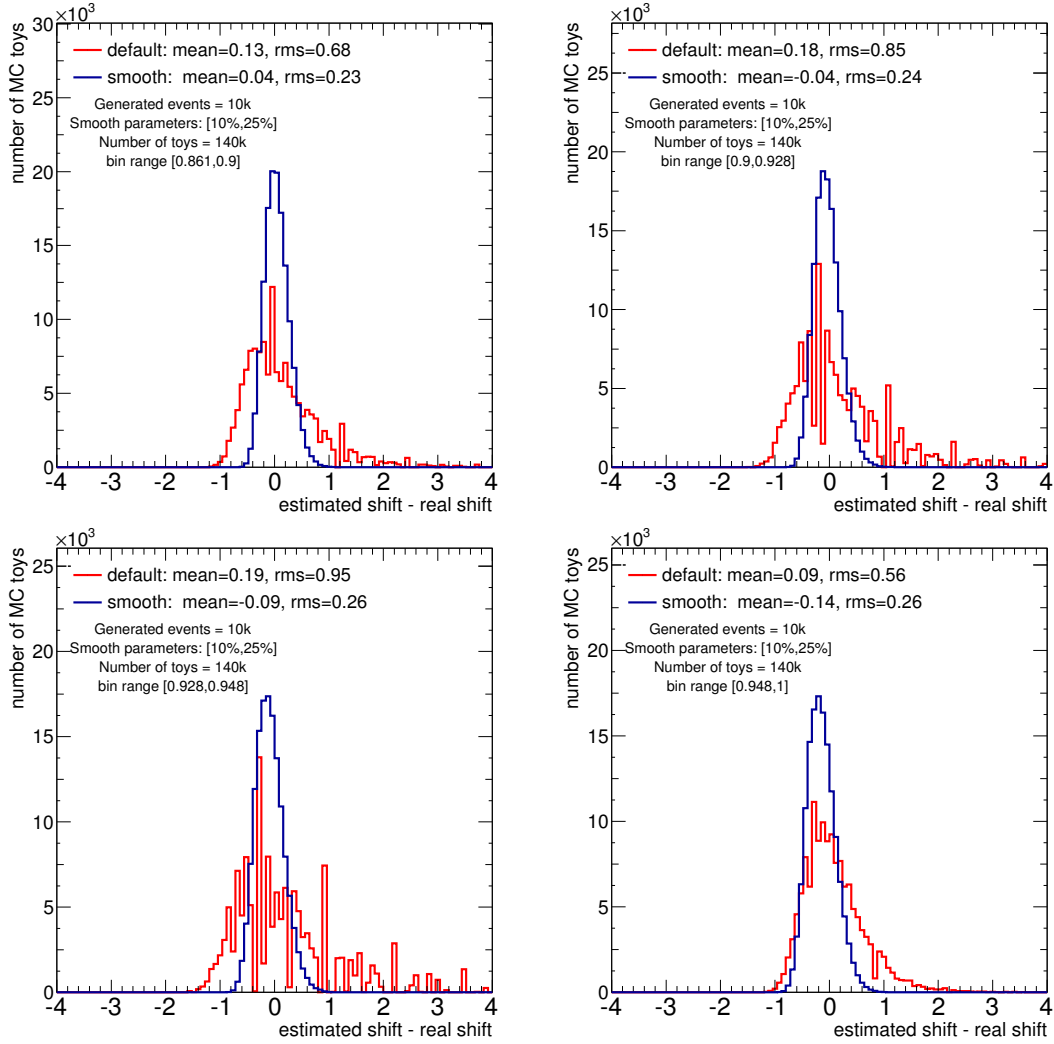


Figure 7.6.3: The residuals between the estimated shift to the actual shape variation, for the last four bins of the BDT distribution, obtained using toy MC for the standard approach (red) or the smoothing procedure (blue). The mean and the RMS of each distribution are shown in the legend.

7.7 Results

The expected number of events for all SM processes and the measured event yields in the three signal regions are shown in Tables 7.10 and 7.11, together with the contribution expected from a hypothetical charged Higgs boson with a mass of 200 or 1000 GeV, and with $\sigma(pp \rightarrow [b]tH^+) \times \text{Br}(H^+ \rightarrow \tau\nu)$ set to the prediction from the hMSSM scenario for $\tan\beta = 40$, as computed using Refs. [86, 92, 114, 127, 128] for the production cross-section and HDECAY [129] for the branching fractions. The signal acceptances, as evaluated with respect to a sample of simulated events where both the τ -lepton and the top-quark decay inclusively, are 1.2%, 0.6% and 0.6% (11.6%, 0.9% and 1.3%) in the signal regions of the $\tau_{\text{had}}+\text{jets}$, $\tau_{\text{had}}+\text{electron}$ and $\tau_{\text{had}}+\text{muon}$ channels, respectively, for a charged Higgs boson mass of 200 (1000) GeV. The event yields observed in 36.1 fb^{-1} of data collected at 13 TeV are found to be consistent with the expectation for the background-only hypothesis.

Sample	Event yields $\tau_{\text{had-vis}}+\text{jets}$			
True τ_{had}				
$t\bar{t}$ & single-top-quark	7700	± 60	± 1800	
$W \rightarrow \tau\nu$	1050	± 30	± 180	
$Z \rightarrow \tau\tau$	84	± 42	± 28	
Diboson (WW, WZ, ZZ)	63	± 5	± 7	
Misidentified $e, \mu \rightarrow \tau_{\text{had-vis}}$	265	± 12	± 35	
Misidentified jet $\rightarrow \tau_{\text{had-vis}}$	2370	± 20	± 260	
All backgrounds	11500	± 80	± 1800	
H^+ (200 GeV), hMSSM $\tan\beta = 40$	710	± 6	± 94	
H^+ (1000 GeV), hMSSM $\tan\beta = 40$	9.6 ± 0.1	± 0.7		
Data	11021			

Table 7.10: Expected event yields for the backgrounds and a hypothetical H^+ signal after all $\tau_{\text{had-vis}}+\text{jets}$ selection criteria, and comparison with 36.1 fb^{-1} of data. All yields are evaluated prior to using the multi-variate discriminant and applying the statistical fitting procedure. The values shown for the signal assume a charged Higgs boson mass of 200 or 1000 GeV, with a cross-section times branching fraction $\sigma(pp \rightarrow [b]tH^+) \times \text{BR}(H^+ \rightarrow \tau\nu)$ corresponding to $\tan\beta = 40$ in the hMSSM benchmark scenario. Statistical and systematic uncertainties are quoted, respectively.

Having described in detail the event selection used in the search for Charged Higgs bosons in the $H^+ \rightarrow \tau\nu$ decay mode and having discussed the background and signal models, with their uncertainties, a statistical analysis is performed in order to test the compatibility of the data with the background-only and signal+background hypotheses.

For the statistical analysis described here, a profile likelihood ratio [130] is used, with BDT as the discriminant. The one-sided profile likelihood ratio, $\tilde{q}_\mu$, is used as the test statistic. The compatibility of the data with the background-only hypothesis is measured by p_0 -values, which correspond to the test statistic q_0 . The q_0 test statistic assesses the compatibility with the background-only hypothesis, while the $\tilde{q}_\mu$ test statistic assesses the compatibility with background plus signal. All systematic uncertainties from theoretical or experimental sources are implemented as nuisance parameters. The parameter of interest (or signal strength) μ is $\sigma(pp \rightarrow [b]tH^\pm) \times \text{BR}(H^\pm \rightarrow \tau\nu)$. Expected limits are derived using the asymptotic approximation [131].

Three signal regions and one validation region enriched in $t\bar{t}$ events are considered in the simultaneous fit:

- A binned likelihood function is used for the BDT score in the three signal regions of the $\tau_{\text{had}}+\text{jets}$, $\tau_{\text{had}}+\text{electron}$ and $\tau_{\text{had}}+\text{muon}$ channels, respectively (different BDT distributions are used depending on the H^+ mass hypothesis).

Sample	Event yields $\tau_{\text{had-vis}} + \text{electron}$			Event yields $\tau_{\text{had-vis}} + \text{muon}$		
True τ_{had}						
$t\bar{t}$ & single-top-quark	17300	± 90	± 2500	15900	± 80	± 2500
$Z \rightarrow \tau\tau$	433	± 27	± 80	352	± 48	± 43
Diboson (WW, WZ, ZZ)	39	± 2	± 5	32	± 2	± 4
Misidentified $e, \mu \rightarrow \tau_{\text{had-vis}}$	626	± 27	± 59	454	± 16	± 27
Misidentified jet $\rightarrow \tau_{\text{had-vis}}$	5640	± 40	± 450	5460	± 40	± 410
All backgrounds	24000	± 100	± 2600	22200	± 100	± 2500
H^+ (200 GeV), hMSSM $\tan\beta = 40$	337	± 5	± 27	339	± 4	± 28
H^+ (1000 GeV), hMSSM $\tan\beta = 40$	$0.76 \pm$	$0.02 \pm$	0.06	$0.97 \pm$	$0.02 \pm$	0.08
Data	22645			21419		

Table 7.11: Expected event yields for the backgrounds and a hypothetical H^+ signal after all $\tau_{\text{had-vis}} + \text{lepton}$ selection criteria, and comparison with 36.1 fb^{-1} of data. All yields are evaluated prior to using the multi-variate discriminant and applying the statistical fitting procedure. The values shown for the signal assume a charged Higgs boson mass of 200 or 1000 GeV, with a cross-section times branching fraction $\sigma(pp \rightarrow [b]tH^+) \times \text{BR}(H^+ \rightarrow \tau\nu)$ corresponding to $\tan\beta = 40$ in the hMSSM benchmark scenario. Statistical and systematic uncertainties are quoted, respectively.

- A one-bin likelihood is used in the validation region of the $\tau_{\text{had}} + \text{lepton}$ channel enriched in $t\bar{t}$ events, defined with the same event selection as the signal region, but with the requirement of an e/μ pair instead of the $e/\mu + \tau_{\text{had}}$ pair.

The data are found to be consistent with the expected SM predictions, hence the exclusion limits are computed on $\text{BR}(t \rightarrow bH^+) \times \text{BR}(H^+ \rightarrow \tau\nu)$ for low H^+ mass range and on $\sigma(pp \rightarrow [b]tH^+) \times \text{Br}(H^+ \rightarrow \tau\nu)$ for full mass range investigated at the 95% confidence level using the CL_s procedure [132, 133].

7.7.1 Post-fit distributions and final limits

The BDT score distributions in the five charged Higgs boson mass ranges considered in the analysis are shown in figure 7.7.1 for the signal region of the $\tau_{\text{had-vis}} + \text{jets}$ channel, as well as in figures 7.7.2 and 7.7.3 for the $\tau_{\text{had-vis}} + \text{electron}$ and $\tau_{\text{had-vis}} + \text{muon}$ channels, respectively. All plots are obtained after the statistical fitting procedure with the background-only hypothesis. The binning shown in the figures is also used in the statistical analysis.

Figure 7.7.4 shows the observed and the expected limits as a function of the H^+ mass hypothesis. All SM backgrounds are considered, along with the multi-jet estimate with the fake factor method (Section 7.5.2). There is no significant deviation from the expected limits. The solid line in the figure is used to denote the observed 95% confidence levels, while the dashed line represents the expected exclusion limits. The outer edges of the green and yellow shaded regions are used to show the 1σ and 2σ error bands.

Figure 7.7.5 shows the 95% CL exclusion limits on $\tan\beta$ as a function of the charged Higgs boson mass in the context of the hMSSM and in the $m_h^{\text{mod-}}$ scenario of the MSSM. For hMSSM scenario, the values of $\tan\beta$ in the range 14–60 are excluded for $m_{H^+} = 200 \text{ GeV}$. At $\tan\beta = 60$, above which no reliable theoretical calculations exist, the charged Higgs boson mass range from 200 to 1100 GeV is excluded, hence significantly improving the results based on the dataset collected in 2015 and corresponding to an integrated luminosity of 3.2 fb^{-1} [9].

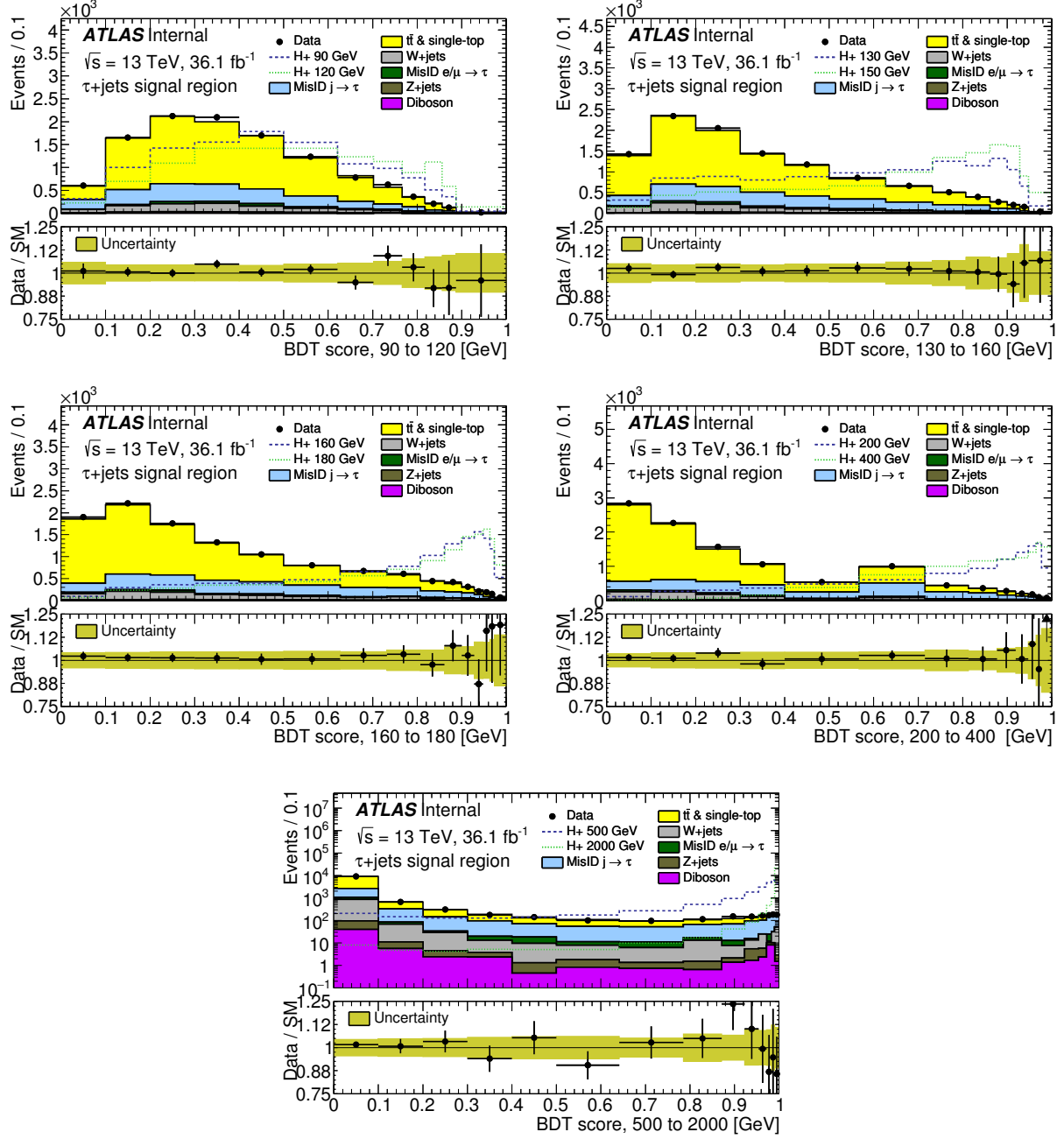


Figure 7.7.1: BDT score distributions in the signal region of the $\tau_{\text{had-vis}}+\text{jets}$ channel, in the five mass ranges used for the BDT trainings, after a fit to the data with the background-only hypothesis. The uncertainty bands in the ratio plots include both the statistical and systematic uncertainties. The normalisation of the signal (shown for illustration) corresponds to the integral of the background.

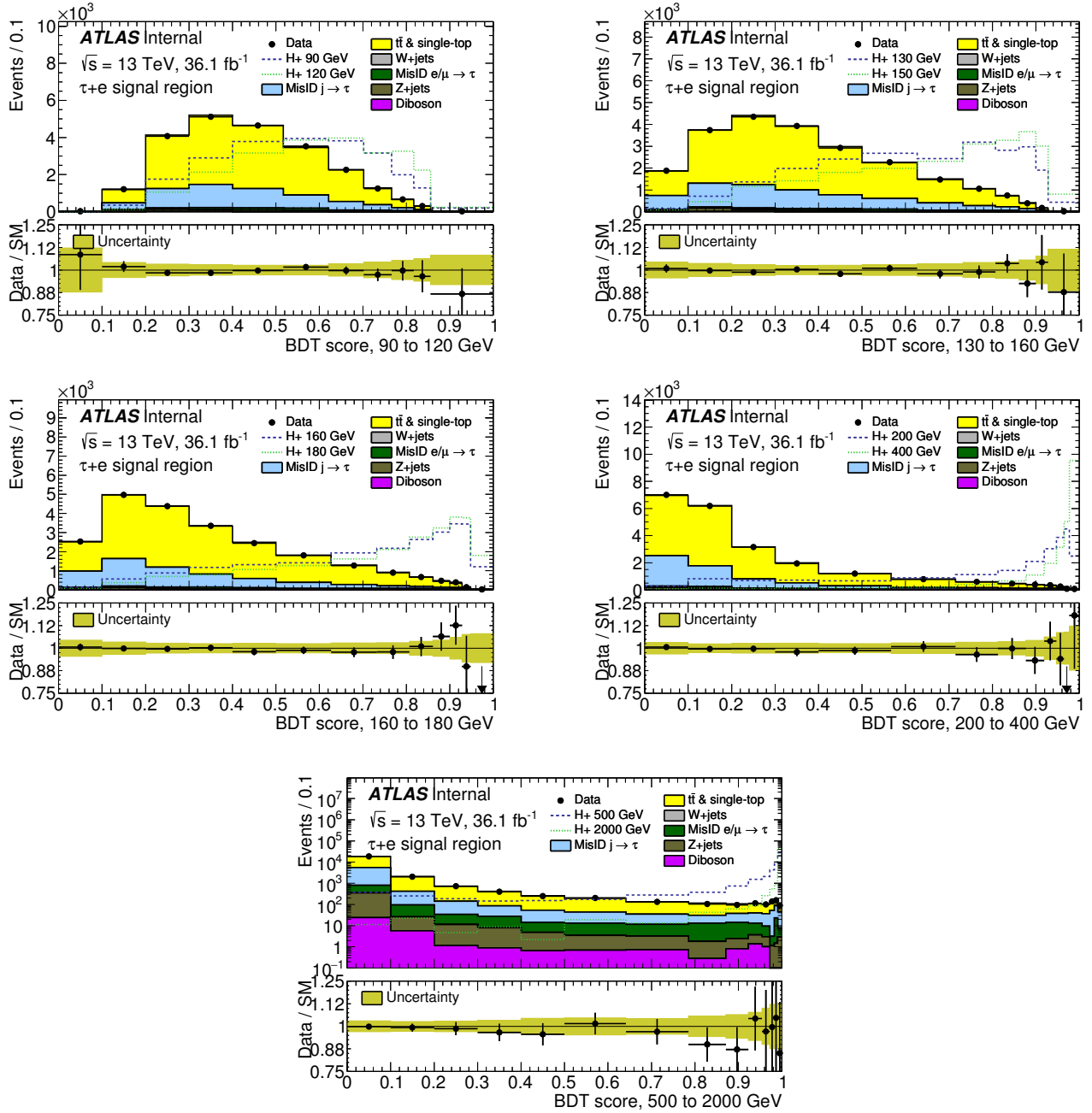


Figure 7.7.2: BDT score distributions in the signal region of the $\tau_{\text{had-vis}} + \text{electron}$ channel, in the five mass ranges used for the BDT trainings, after a fit to the data with the background-only hypothesis. The uncertainty bands in the ratio plots include both the statistical and systematic uncertainties. The normalisation of the signal (shown for illustration) corresponds to the integral of the background.

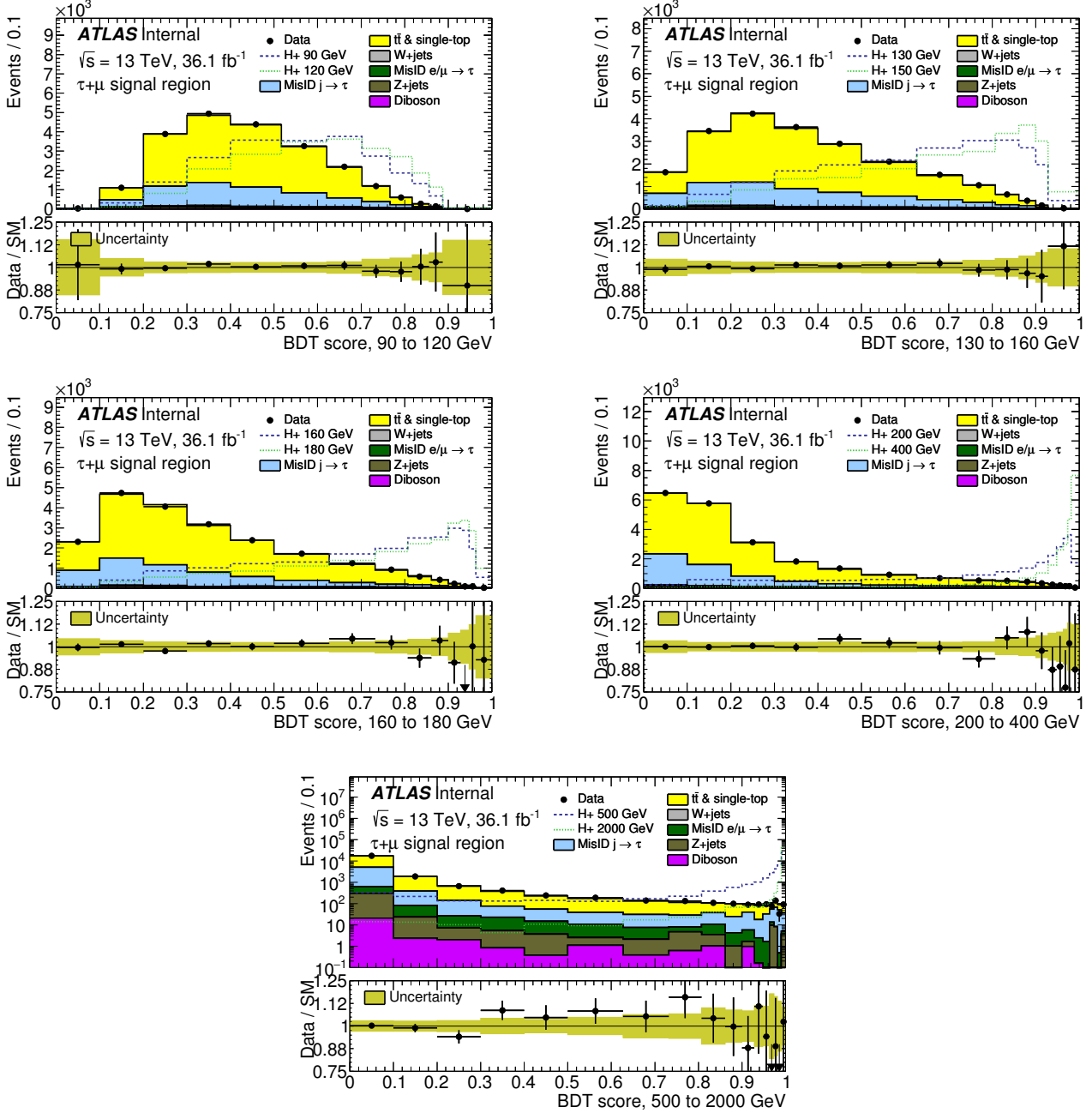


Figure 7.7.3: BDT score distributions in the signal region of the $\tau_{\text{had-vis}} + \mu$ channel, in the five mass ranges used for the BDT trainings, after a fit to the data with the background-only hypothesis. The uncertainty bands in the ratio plots include both the statistical and systematic uncertainties. The normalisation of the signal (shown for illustration) corresponds to the integral of the background.

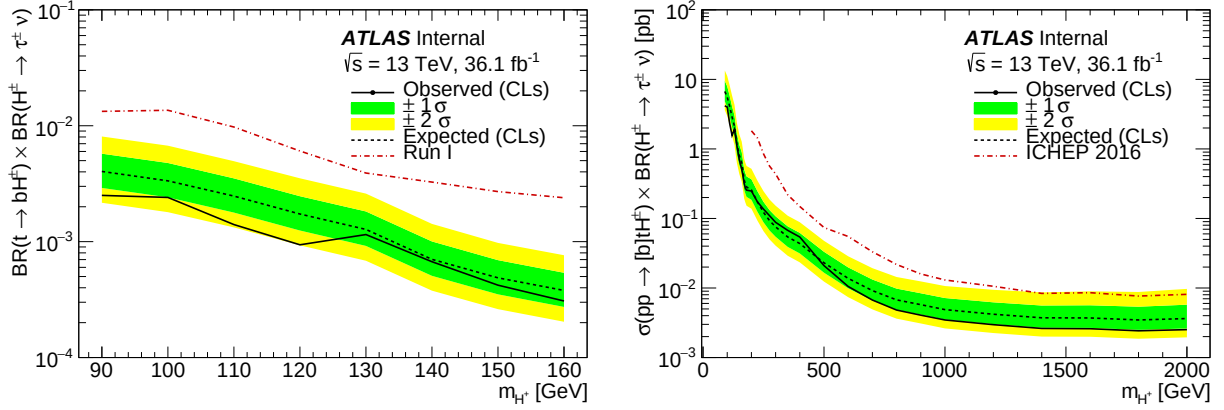


Figure 7.7.4: Observed and expected 95% CL exclusion combined limits on $\text{BR}(t \rightarrow bH^+) \times \text{BR}(H^+ \rightarrow \tau\nu)$ (left) and $\sigma(pp \rightarrow [b]tH^+) \times \text{BR}(H^+ \rightarrow \tau\nu)$ (right) for charged Higgs boson production as a function of $m_{H^\pm}$ in 36.1 fb^{-1} of pp collision data at $\sqrt{s} = 13 \text{ TeV}$. The limits are compared with previous public results [10, 100].

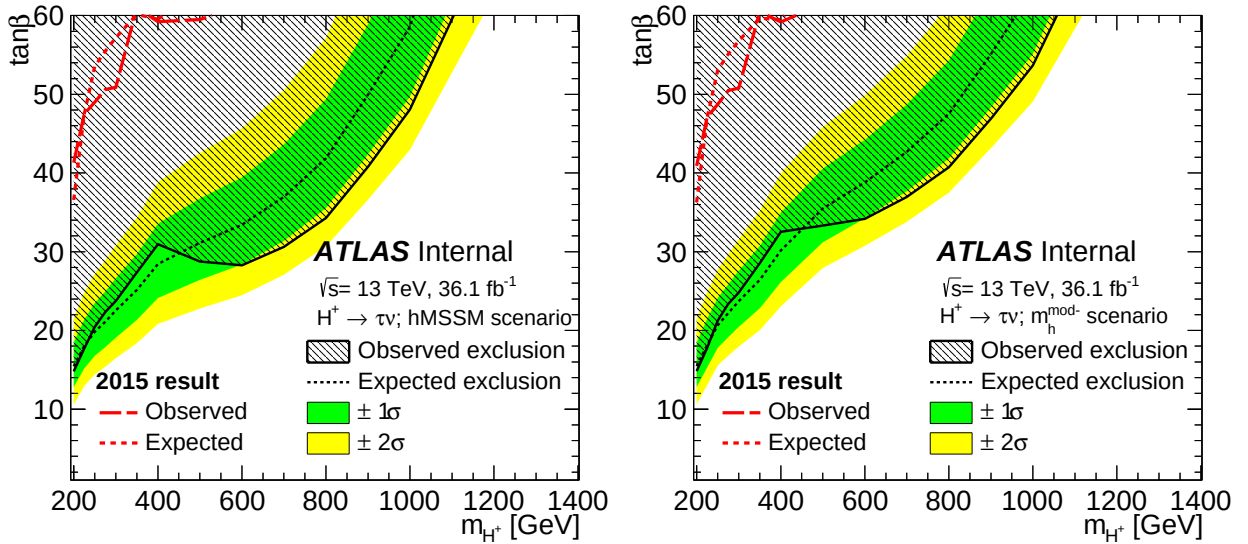


Figure 7.7.5: 95% CL exclusion limits on $\tan\beta$ as a function of m_{H^+} , shown in the context of the hMSSM, for the regions in which reliable theoretical predictions exist ($\tan\beta \leq 60$). As a comparison, the red curves show the observed and expected exclusion limits based on the dataset collected in 2015 at $\sqrt{s} = 13 \text{ TeV}$ [9].

7.8 Summary

A search for charged Higgs bosons produced either in top-quark decays or in association with a top-quark, subsequently decaying via $H^+ \rightarrow \tau\nu$ is performed, based on $\tau_{\text{had}}+\text{jets}$ and $\tau_{\text{had}}+\text{lepton}$ final states. The dataset used for this analysis contains 36.1 fb^{-1} of pp collisions at $\sqrt{s} = 13 \text{ TeV}$, recorded in 2015 and 2016 by the ATLAS detector at the LHC. The data are found to be in agreement with the background-only hypothesis. Upper limits are set on the production cross-section times branching fraction $\sigma(pp \rightarrow [b]tH^+) \times \text{BR}(H^+ \rightarrow \tau\nu)$ between 4.2 pb and 2.5 fb for a charged Higgs boson mass range of 90–2000 GeV, corresponding to upper limits between 0.25% and 0.031% for the branching fraction $\text{BR}(t \rightarrow bH^+) \times \text{BR}(H^+ \rightarrow \tau\nu)$ in the mass range 90–160 GeV. In the context of the hMSSM scenario, all $\tan\beta$ values are excluded for the H^+ mass hypothesis below 160 GeV. The H^+ mass range up to 1100 GeV is excluded at $\tan\beta = 60$.

8 Conclusions

The thesis comprises of three independent parts: R&D on particle detectors, ATLAS detector-performance studies and Data analysis part. In this chapter we conclude separately on each of them.

Part I: R&D of particle detectors – study of charging-up processes affecting gain stability in THGEM gas-avalanche particle detectors

Detectors, incorporating insulating surfaces usually exhibit some gain variations, caused by electrical-charge attachment to the insulating surfaces. The charging-up phenomenon is usually associated with detector’s gain instabilities occurring during its initial operation period. In this work, the charging up phenomenon in Thick Gas Electron Multiplier (THGEM) -based detectors was studied using a phenomenological model, followed by an experimental set of measurements. It has been shown by the experimental studies, that the phenomenological model qualitatively describes the gain stabilization phenomenon. Furthermore, the model guided us to address several detector features related to its structure, e.g. the presence of hole-rims; it precisely predicts the detector’s gain evolution. Differently to Gas Electron Multiplier (GEM) detectors with single-conical or double-conical hole geometry, where the gain stabilization exhibits an increase over time, THGEM electrodes with cylindrical holes exhibit a decrease of the detector gain due to a different charge distribution along the hole’s surface. It was found that charging-up processes can be quantitatively modeled through basic parameters such as “characteristic time” – the time it takes the gain to reach half of its total variation, or “characteristic charge” – the total amount of charge passing through the THGEM holes during the relaxation period. The latter could also indicate the rate of gain stabilization. The effect of geometrical parameters of the THGEM electrode on detector’s gain stabilization was studied and resulted in several observations. Thicker electrodes are usually undergoing faster stabilization, due to a broader diffusion of the electron-avalanche within the holes. The “characteristic charge” of the stabilization phenomenon is proportional to THGEM operational voltages: longer stabilization time observed in gas mixtures under higher operating voltages. A typical characteristic charging-up time in THGEM electrodes is found to be equivalent to a total irradiated charge of hundreds of pC, similarly to the values reported for GEM electrodes with double-conical geometry.

The effect of the etched hole-rims was systematically investigated. This effect is reflected by an increase in the detector’s gain. It was found that the “top-rim” is manifested with a long-term stabilization time of a detector. In the case of a detector with etched hole-rims, a short-term decrease of the gain is followed by a slow increase – typically two-fold longer compared than the short-term one.

This study suggests that the charging-up transients relate only to the initial detector’s operation period, and should not affect the detector’s long-term operation.

The measurements were performed in noble gas mixtures, therefore after an initial gain stabilization, the performance of the detector is expected to be stable. In gas mixtures with electro-negative compounds, a charge evacuation from the insulating surfaces may occur; it can result in gain recovery after a long interruption of detector irradiation, or in detector’s gain dependence on the irradiation rate (when the rate of charge accumulation on the insulating surfaces is comparative to the rate of

charge evacuation from these surfaces). Further studies in compound gas mixtures are required to address such effects. It was also observed that under detector operation at high gains (close to the maximal stable value); occasional discharges are usually assisting in the evacuation of accumulated charges; their evacuation leads to an increase of the detector's gain. In THGEM-based detectors incorporating discharge-quenching substrates (such as resistive anodes), operating in a micro-discharge mode (with occasional discharges being quenched), a rapid increase of the gain may be followed by additional discharges – since the detector's gain rises above its maximal stable value. This limitation can be resolved by either suppressing the high initial gain variation – e.g. by introducing hole-rims, or by reducing detector's effective capacitance – reducing the discharge duration. The observations made here could be valuable for a deeper understanding of gain instabilities in other gas-avalanche detectors incorporating insulating materials; they are relevant for the conception of stable detectors for future particle-physics experiments.

Part II: Performance studies – photon identification efficiency measurement

Photon identification efficiency, of the cut-based identification algorithms used in the ATLAS experiment, was measured during the 2012 data taking period, with 20.3fb^{-1} of pp collision data recorded at $\sqrt{s} = 8$ TeV. The identification efficiency was measured using the matrix-method, and applied to photons with $20 < E_T < 1500$ GeV. The measured efficiencies in the data, are compared to those obtained from Monte Carlo predictions and are found to agree within 2-4% in a E_T range between 30-40 GeV, and typically below 1% for $E_T > 40$. For the low E_T range, since this region is dominated by the non-prompt photons that are contributing to higher background systematic uncertainty, the poor agreement between the data and the simulation is associated with relatively large errors of the tight identification efficiency obtained with the matrix method. These results were combined with two other data-driven methods, and compared to the MC simulation. The simulation describes well in the entire E_T and η range accessible by the data-driven methods. The residual difference between the efficiencies in data and MC are taken into account by computing data-to-MC efficiency scale factors. It is to be noted that the obtained scale-factors were used in the 2012 Higgs boson discovery with the $H \rightarrow \gamma\gamma$ channel.

Part III: Data analysis – searches for SM and BSM Higgs bosons

The analysis consists of two different searches: a search for $H \rightarrow \tau\tau$ via the associated production of the Standard Model Higgs boson with a pair of top-quarks ($t\bar{t}H$) at $\sqrt{s} = 8$ TeV pp collision data recorded by the ATLAS experiment in 2012, and a search for Beyond the Standard Model charged Higgs bosons via the $H^\pm \rightarrow \tau\nu$ decay mode at $\sqrt{s} = 13$ TeV pp collision data recorded by the ATLAS experiment during the 2015-2016 data taking periods.

The observed upper limit of $(\sigma(t\bar{t}H) \times BR(H \rightarrow \tau\tau)) / (\sigma_{\text{SM}}(t\bar{t}H) \times BR_{\text{SM}}(H \rightarrow \tau\tau)) < 13$ was derived in the $1\ell 2\tau_{\text{had}}$ channel. The upper limit combined with all other channels in the multi-lepton search, was found to be 4.7. Assuming a SM $BR(H \rightarrow \tau\tau)$, this measurement result in an observed upper limit on the signal strength value $\mu = \sigma_{\text{obs}}^{t\bar{t}H} / \sigma_{\text{SM}}^{t\bar{t}H} < 4.7$, the MLE of μ is found to be $\mu = 2.1_{-1.2}^{+1.4}$. It is important to mention that with the 2015-2016 data recorded by the ATLAS experiment, at $\sqrt{s} = 13$ TeV, evidence for the associated production of the SM Higgs boson with a top quark pair was provided.

Charged Higgs bosons produced in association with a single top quark and decaying via $H^\pm \rightarrow \tau\nu$ were searched for with the ATLAS experiment at the LHC, using proton-proton collision data at

$\sqrt{s} = 13$ TeV with an integrated luminosity of 14.7 fb^{-1} . A 95% confidence-level upper limits on the production cross section times branching fraction $\sigma(pp \rightarrow [b]tH^\pm) \times \text{BR}(H^\pm \rightarrow \tau\nu)$ of 1.9 pb to 15 fb, were obtained for charged Higgs boson masses ranging from 200 to 2000 GeV. The analysis with the full 2015-2016 dataset corresponding to an integrated luminosity of 36.1 fb^{-1} , explored the intermediate-mass region (160–200 GeV) for the first time. It was also the first time that the low-mass region (90–160 GeV) was probed using the pp collision data at $\sqrt{s} = 13$ TeV. The data are found to agree with the background-only hypothesis. An upper limit on the production cross-section times the branching fraction, $\sigma(pp \rightarrow [b]tH^\pm) \times \text{BR}(H^\pm \rightarrow \tau\nu)$, at 95% confidence-level was obtained between 4.2 pb and 2.5 fb for charged Higgs boson masses ranging from 90 to 2000 GeV. For low-mass range (90-160 GeV) a 95% confidence-level upper limits on the product of branching ratios $B(t \rightarrow bH^\pm) \times B(H^\pm \rightarrow \tau\nu)$, between 0.03% and 0.25% for charged Higgs boson masses in the range 90–160 GeV were obtained.

Although no excess in this search is observed, further studies should be carried out with new data. Furthermore, new analysis techniques, such as probing the lepton universality can provide a better probing for this rare hypothetical process.

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A Matrix-Method based fake estimation in 1 lepton and 2 τ_{had} channel

The general purpose of the Matrix-Method (MM) is to estimate the contamination of fake objects in a signal region. The method is based on the measured efficiencies for both real and fake objects, which are in the 1 lepton and 2 τ s is the hadronically reconstructed τ s (τ_{had}), here we describe the evolution of the matrix-method into a simplified approach similar to the ABCD method.

In this appendix, first we consider the case of one fake τ_{had} , and then the case of two hadronic τ s. We simplify the general MM to the ABCD method for the case that one of the taus is always a fake. Denote by N^t the number of reconstructed *Medium* τ_{had} and by N^l the number of reconstructed *Loose* τ_{had} . First, we consider the simple case of events with one reconstructed hadronic τ_{had} . We can express the number of reconstructed *Medium* and *Loose* τ_{had} s in the following way:

$$N^t = N_{\text{pass}}^r + N_{\text{pass}}^f \quad (\text{A.1})$$

$$N^l = N^r + N^f, \quad (\text{A.2})$$

where $N_{\text{pass}}^r(N_{\text{pass}}^f)$ and $N^r(N^f)$ are real (fake) reconstructed τ_{had} that pass *Medium* and *Loose* selection ID, respectively.

Denoting $r = \frac{N_{\text{pass}}^r}{N^r}$ to be the efficiency of real τ to pass *Medium* selection and $f = \frac{N_{\text{pass}}^f}{N^f}$ to be the efficiency of a fake τ to pass the *Medium* selection, we can express the number of reconstructed events that pass *Loose* or *Medium* τ ID using the efficiency matrix:

$$\begin{pmatrix} N^t \\ N^l \end{pmatrix} = \begin{pmatrix} r & f \\ 1 & 1 \end{pmatrix} \begin{pmatrix} N^r \\ N^f \end{pmatrix} \quad (\text{A.3})$$

By inverting the efficiency matrix, the number of fakes passing our *Medium* selection can be expressed as follows:

$$N_{\text{fakes}}^t = f N^f = \frac{f}{r-f} (r N^l - N^t) = \frac{f}{r-f} (r N^j - (1-r) N^t), \quad (\text{A.4})$$

where $N^j = N^l - N^t$ is the number of reconstructed *Loose* τ_{had} that fail the *Medium* selection criteria. In case of no real τ contamination in this control region (“anti- τ ” control region - N^j) from the selection or by subtraction, i.e. if $r = 1$ or $N^r = 0$, then Equation A.4 reduces to a simpler form:

$$N_f^t = FF \times N^j, \quad (\text{A.5})$$

where $FF = \frac{f}{1-f}$ is called the fake factor. This approach is commonly called the “fake-factor” method, which is based only on the estimation of the fake τ_{had} efficiencies.

In case of two τ candidates, we define four orthogonal regions with hadronic τ s that pass (*t*) or fail (*j*) *Medium* ID selection. In addition (as it will be shown latter in the text) since both hadronic τ s in the our selection have an opposite charge to each other, then we can separate them according to their charge sign with respect to reconstructed lepton: one that have an opposite charge to reconstructed lepton, and one that have a same sign to the reconstructed lepton. Then one can use a 4×4 efficiency matrix to obtain the number of reconstructed events:

$$\begin{pmatrix} N^{tt} \\ N^{tj} \\ N^{jt} \\ N^{jj} \end{pmatrix} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{pmatrix} \begin{pmatrix} N^{rr} \\ N^{rf} \\ N^{fr} \\ N^{ff} \end{pmatrix}, \quad (\text{A.6})$$

where the first (second) index refers to a τ_{had} with OS (SS) to the reconstructed lepton. Again, by inverting the efficiency matrix, one can express the number of entries originating from events with at least one non-prompt τ_{had} in the following way:

$$N_{fakes}^{tt} = \left(1 - \frac{\alpha_1}{FF_1} \frac{\alpha_2}{FF_2}\right) N^{tt} + \frac{\alpha_1}{FF_1} FF_2 N^{tj} + FF_1 \frac{\alpha_2}{FF_2} N^{jt} - \alpha_1 \alpha_2 N^{jj}, \quad (\text{A.7})$$

where $\alpha_i = \frac{r_i f_i}{r_i - f_i}$. Equation is the general expression for the expected number of events that contains at least one fake τ . One can avoid estimation of the efficiency of a real τ_{had} in the same way as it have been shown for 1D case - by subtracting the contribution of the backgrounds with pair of prompt τ s, i.e. $N^{rr} = 0$, then $\alpha = FF$, and Equation A.7 reduces to a simple form:

$$N_{fakes}^{tt} = FF_2 \times N^{tj} + FF_1 \times N^{jt} - FF_1 \times FF_2 \times N^{jj} \quad (\text{A.8})$$

Now, once we have show that the estimation of the real efficiencies can be avoided from subtracting the contribution from the backgrounds with a pair of prompt hadronic τ s, we will show that even a simpler form of the fake estimation can be also obtained from the MM formalism.

In our channel, the main background that contributes to the fakes, is the $t\bar{t}$ background. For the $t\bar{t}$ process, the reconstructed lepton arises from leptonic top decay. Then, the reconstructed τ can be either from $W \rightarrow \tau$ decay or faked from jets. In this case, the prompt τ_{had} will have always opposite sign to the reconstructed lepton in case of charge of lepton/ τ_{had} is reconstructed correctly. Then the τ_{had} with the same sign as the selected lepton will always be a fake τ_{had} (originating from a jet). In this case $N^{fr} = 0$, and then by dividing the rows of Equation A.7 - (1)/(2) and (3)/(4) we obtain:

$$\begin{aligned} N^{tt}/N^{tj} &= \frac{(r_1 \cdot f_2 \cdot N^{rf} + f_1 \cdot f_2 N^{ff})}{(r_1 \cdot (1 - f_2) \cdot N^{rf} + f_1 \cdot (1 - f_2) \cdot N^{ff})} \\ &= f_2/(1 - f_2) \end{aligned} \quad (\text{A.9})$$

$$\begin{aligned} N^{jt}/N^{jj} &= \frac{((1 - r_1) \cdot f - 2 \cdot N^{rf} + (1 - f_1) \cdot f_2 N^{ff})}{((1 - r_1) \cdot (1 - f_2) \cdot N^{rf} + (1 - f_1) \cdot (1 - f_2) \cdot N^{ff})} \\ &= f_2/(1 - f_2). \end{aligned} \quad (\text{A.10})$$

which results in

$$N_{fakes}^{tt} = \theta \times N^{tj}, \quad (\text{A.11})$$

with $\theta = N^{jt}/N^{jj}$, and this approach is commonly called the ‘‘ABCD’’ method. This is the simplified case of the MM formalism that we finally use to estimate the amount of fakes in our signal region for the $1\ell 2\tau_{\text{had}}$ channel.