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Calibration of b -tagging efficiency and
search for Dark Matter production in association with
heavy flavour quarks with the ATLAS experiment

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Sammanfattning

Den subatomära världen kan beskrivas väldigt väl med den så kallade Standardmodellen för partikelfysik. I Standardmodellen ingår materiapartiklar av typen kvarkar och leptoner som kan bygga upp vanlig materia, samt partiklar som förmedlar de fundamentala naturkrafterna. Det senaste tillskottet till Standardmodellen är Higgspartikeln som genererar elementarpartiklarnas massor.

Den stora hadronkollideraren LHC vid CERN är världens mest kraftfulla och komplexa partikelaccelerator. Här kollideras protoner med varandra vid nära ljusets hastighet, och i kollisionerna kan nya elementarpartiklar skapas från protonernas rörelseenergi. Vid LHC finns fyra stora experiment som registrerar kollisionerna: ATLAS, CMS, ALICE och LHCb. De två sistnämnda är mer specialiserade medan ATLAS och CMS är konstruerade för att kunna möjliggöra ett brett spektrum av mätningar. Den forskning som bedrivs här omfattar både precisionsmätningar av processer som ingår i Standardmodellen och sökandet efter förutsägelser från olika utvidgningar av Standardmodellen. Denna avhandling presenterar tre studier genomförda med proton-proton-kollisioner registrerade med ATLAS-experimentet.

En typ av elementarpartikel, den så kallade bottenkvarken, spelar en viktig roll i många mätningar vid LHC. Avhandlingen presenterar en ny metod för att kalibrera de algoritmer som används för att identifiera bottenkvarkar i detektorn. Metoden möjliggör att effektiviteten för identifikation av bottenkvarkar med mycket hög rörelsemängd kan mätas i data, något som tidigare inte varit möjligt.

Mörk materia är något som introducerats för att förklara en rad astrofysikaliska observationer. Vad som utgör den mörka materian är en av de viktigaste frågorna inom dagens fysikforskning, och ett intensivt sökande efter mörk materia pågår även vid LHC. Vid en kollisionsenergi av 8 TeV genomförde ATLAS-kollaborationen en sökning efter mörk materia producerad tillsammans med ett par av topp- eller bottenkvarkar, baserad på så kallad effektiv fältteori. Denna avhandling innehåller en omtolkning av dessa resultat för en grupp fenomenologiska modeller. I

dessa modeller sker kopplingen mellan vanlig materia och mörk materia via en förmedlarpartikel med spin 0. Modellerna spänner över en rad olika massor hos den hypotetiska mörka materian och förmedlarpartikeln, samt olika värden på styrkan hos kopplingen mellan förmedlarpartikeln och den mörka och vanliga materian. Utifrån resultaten i denna studie valdes en grupp av modeller ut för vidare studier vid högre kollisionsenergi.

Den sista delen av avhandlingen presenterar en sökning efter mörk materia producerad tillsammans med ett par av toppkvarkar vid en kollisionsenergi av 13 TeV. Analysen baseras på de modeller som tagits fram i den tidigare studien. De observerade resultaten stämmer väl överens med vad som förväntas från Standardmodellen, och används därmed för att sätta en övre gräns på tvärsnittet för produktion av mörk materia.

Abstract

The Large Hadron Collider (LHC) is the most powerful and complex particle accelerator ever built. The ATLAS and the CMS are the two multipurpose particle detectors at the LHC, designed to cover a wide range of physics measurements. Three physics studies performed using data of proton-proton collisions collected with the ATLAS detector are presented.

The identification of jets originating from b quarks, also known as b -tagging, is a crucial tool for many physics analyses at the LHC. This thesis presents a calibration of the b -tagging efficiency for high transverse momentum jets using a new calibration technique. This analysis is based on template fits and uses multi-jet events, which allows to perform the calibration for jets with transverse momenta up to 1200 GeV. This thesis also describes a completed and connected technical project on the development of the b -tagging ATLAS software.

Dark Matter (DM) is a new phenomenon introduced to explain astrophysical observations. The nature of DM is one of the most important subjects of investigations in the modern physics, and many of these investigations are carried out at the LHC. A search for DM production in association with a pair of heavy flavour quarks has been recently performed in ATLAS at a centre-of-mass energy $\sqrt{s} = 8$ TeV under the Effective Field Theory approach. A re-interpretation of the results of this search under assumption of the simplified models is presented. A set of simplified models is considered with various DM masses, masses of the spin-0 exchange particle, that mediates the interaction between DM and the regular matter, and various values of couplings. Benchmark models are chosen to be used in the DM searches at $\sqrt{s} = 13$ TeV.

The last part of the thesis presents a search for DM production in association with a pair of top quarks performed under assumption of the simplified models with spin-0 mediator, using the data collected at a centre-of-mass energy $\sqrt{s} = 13$ TeV. The observed data are shown to be in good agreement with the Standard Model predictions, and upper limits are set on a ratio between the observed DM production cross section and the value expected by the simplified model.

Acknowledgments

None of the results presented in this thesis had been possible without the help and advice from others. First of all, I would like to cordially thank all my colleagues in the wonderful ATLAS and IceCube groups at Stockholm University. You made AlbaNova and Stockholm my second home, and all of you now have a special place in my heart. I'm very grateful to the people I worked with in the Flavour Tagging group, in the Dark Matter plus Heavy Flavour analysis team, and in the Stop 1-Lepton analysis team.

I would especially like to thank my supervisors: Sara Strandberg, Kerstin Jon-And and Priscilla Pani for the continuous professional advice and guidance, as well as for their patience during proof-reading of multiple drafts of this thesis. Your feedback and suggestions were extremely helpful!

I am infinitely grateful to Sara Strandberg for the fantastic guidance, for all the detailed explanations and answering kindly my questions. Thank you, Sara, for your priceless advice, for the attempts to protect me from the pernicious multitasking, for giving me the freedom and means to learn, and for your moral support and encouragement in right moments. I would gladly be your student once again; and if I have my own students, I will try to be like you.

Finally, I acknowledge arXiv.org and Sci-Hub for providing free access to the scientific papers and resources for learning.

Index of Abbreviation and Acronyms

ANN	Artificial Neural Network
AOD	Analysis Object Data format
ATLAS	A Toroidal LHC ApparatuS
BR	Branching Ratio
BEH	Brout-Englert-Higgs mechanism
CERN	European Organization for Nuclear Research (from French “Conseil Européen pour la Recherche Nucléaire”)
CL	Confidence Level
CMS	Compact Muon Solenoid
CR	Control Region
CSC	Cathode Strip Chambers
CTP	Central Trigger Processor
DAQ	Data AcQuision system
DM	Dark Matter
D3PD	Derived Physics Data format
EDM	Event Data Model
EF	Event Filter (the third level, software-based trigger in ATLAS during LHC Run I)
EFT	Effective Field Theory
EM	ElectroMagnetic
ESD	Event Summary Data format
EWT	ElectroWeak Theory
FCal	Forward Calorimeter
FSR	Final State Radiation
HLT	High Level Trigger (the second level, software-based trigger in ATLAS during LHC Run II)
JER	Jet Energy Resolution
JES	Jet Energy Scale
JVF	Jet Vertex Fraction
JVT	Jet Vertex Tagger
IBL	Insertable B-layer, the innermost layer in the Pixel detector
ID	Inner Detector
IP	Impact Parameter
ISR	Initial State Radiation
JVF	Jet Vertex Fraction

L1Calo	Level-1 Calorimeter trigger
L1	Level-1 trigger
L2	Level-2 trigger
LAr	Liquid Argon
LEP	Large Electron-Positron collider
LHC	Large Hadron Collider
LO	Leading Order in perturbative calculations
MC	Monte Carlo
MDT	Monitored Drift Tubes
MS	Muon Spectrometer
MFV	Minimal Flavor Violating
NF	Normalization Factor (used to normalize the background prediction in data)
N(N)LO	Next-to-(Next-to) Leading Order in perturbative calculations
PDF	Probability Density Function, Parton Distribution Function
PV	Primary Vertex
RoI	Region of Interest
RPC	Resistive Plate Chambers
QCD	Quantum ChromoDynamics
SCT	SemiConductor Tracker
SM	Standard Model of particle physics
SUSY	SUperSYmmetry
SV	Secondary Vertex
SR	Signal Region
TDAQ	Trigger and Data Acquisition
TRT	Transition Radiation Tracker
TileCal	Tile Calorimeter
TF	Transfer Factor (used to extrapolate the background prediction from the CR into the SR and VRs)
TGC	Thin Gap Chamber
TRT	Transition Radiation Tracker
VR	Validation Region
WIMP	Weakly Interacting Massive Particle

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Preface

The goal of the field of particle physics is to explore the properties of the elementary constituents of matter and energy, the interactions between them, and the nature of space and time. For the past half-century humanity has made a tremendous step in understanding these issues. The persistent efforts in theoretical and experimental physics allowed us to develop a remarkably simple and elegant picture, called the Standard Model (SM) of particle physics, which provides a successful description of most of the current experimental data. However, the SM does not explain a number of observed phenomena and does not solve some theoretical problems, which establishes a motive to search for Beyond the SM physics.

Exploring the subatomic structure of the Universe requires probing the matter at extremely small distances, corresponding to high energies. Therefore, many modern experiments in particle physics find use of high-energy particle accelerators. The Large Hadron Collider (LHC) is the largest and the highest energy particle accelerator ever constructed. The aim of the LHC is to test the SM predictions, to search for the Higgs boson and to measure its properties, and to probe various possible extensions of the SM, e.g. models providing an explanation to the abundance of Dark Matter (DM) in the Universe.

The ATLAS and the CMS are the two multipurpose particle detectors at the LHC. The analyses presented in this thesis are based on the proton-proton collision data collected by ATLAS. I am sincerely glad to be part of the ATLAS Collaboration that uses the advanced technology of the world's largest particle detector, and to make my small contribution to the extension of the frontiers of physics knowledge.

In particle physics a specific convention of natural units is generally used: $\hbar = c = 1$, where $\hbar$ is the reduced Planck constant and c is the speed of light. Under this convention, mass, momentum and energy are expressed in the same units, which are the inverse of the units of time and length. These units are assumed throughout the thesis.

About this thesis

This Ph.D. thesis consists of four parts. Part I provides a theoretical overview of particle physics. Chapter 1 introduces the basic aspects of the Standard Model of particle physics, which currently is the most successful model describing the fundamental particles in nature and the interactions between them. Chapter 2 highlights the shortcomings of the Standard Model, one of which is the absence of an explanation for the existence of DM in nature. Various models suggesting candidates for a DM particle are studied by the ATLAS experiment at the LHC. The models relevant for the searches presented in Part IV of the thesis are discussed in Chapter 2.

Part II describes the experimental techniques and facilities used by the ATLAS experiment. The layout of the LHC and the design of the ATLAS detector and its subsystems are discussed in Chapter 3. Chapter 4 explains how particles and their properties are identified and reconstructed in ATLAS. In addition, the statistical methods and tools, utilized in the following parts, are given.

Part III is devoted to the identification of b jets, referred to as b -tagging. The concept of b -tagging is introduced in Chapter 5, which presents the main classes of b -tagging algorithms used in ATLAS. The JetProb algorithm is described in more detail, since the JetProb weight is tested as a discriminating variable in the additional study included in Appendix F.3. The implementation of b -tagging in the ATLAS software framework and the improvements that were done during the long LHC shutdown in 2013-2014 are also presented.

Chapter 6 presents a new method to calibrate the b -tagging efficiency for jets with high transverse momentum using a template fit to the transverse impact parameter significance. The event and object selection, the strategy of building the templates and the template fit model, validation of the fit, estimation of the systematic uncertainties, and the results of the analysis in form of data-to-simulation scale factors are presented.

Part IV of the thesis is devoted to the searches for DM production in association with a pair of heavy flavour quarks. Chapter 7 discusses the signal signatures and the dominant background processes, as well as the analysis strategy and the variables used to discriminate between the signal and the background. This chapter plays a role of a shared introduction to the studies presented in Chapters 8 and 9. Both studies use simplified models in which DM is pair-produced via a spin-0 mediator. Chapter 8 presents the re-interpretation in term of simplified models of the DM search which was performed at a centre-of-mass energy $\sqrt{s} = 8$ TeV under the Effective Field Theory assumption. DM

production in association with a pair of either top or bottom quarks is considered, and signal selections for both signatures are discussed. The procedure of the re-interpretation is explained in detail and the most promising models for the searches during LHC Run II are identified.

Chapter 9 presents the search for DM production in association with a pair of top quarks using the full data set of pp collisions collected in 2015 and 2016 with the ATLAS detector at a centre-of-mass energy $\sqrt{s} = 13$ TeV. Two new signal regions, DM_low and DM_high, are optimized for this analysis to probe models with low and high mediator masses. In addition, the analysis is carried out with the signal region DM_low_loose to monitor the excess previously observed in this signal region in the earlier search for the same final state that used the partial 2016 data set. The signal and background selections, along with the validation of the background predictions, are described. The configurations used for the likelihood fits in the discovery and exclusion formalism, as well as the evaluation of systematic uncertainties are discussed. The estimated Standard Model predictions are compared to the observations and the upper limits are set on the ratio of the DM production cross section over the expectation from the simplified models.

The appendices contain all the auxiliary material, such as the templates used in the fits in Chapter 6, pseudo-data experiments validating the fits, interim results, breakdown of systematic uncertainties and additional searches.

Some chapters of this Ph.D. thesis have been previously included in my licentiate thesis [1]. Chapters 1, 2 and 3 along with Chapters 5 and 6 are taken from Ref. [1] nearly without changes. Chapter 4 is based on the material included in Ref. [1], with some modifications and additional subsections. The descriptions of the signal and background processes and some of the discriminating variables given in Chapter 7 are partially taken from Ref. [1]. The DM study at $\sqrt{s} = 8$ TeV has been published in Ref. [1] but is described in more detail in Chapter 8. The DM search at $\sqrt{s} = 13$ TeV was carried out after the defense of my licentiate thesis, therefore Chapter 9 is completely new.

Main publications

The material in this Ph.D. thesis has also been included in the following publications:

ATLAS Collaboration, *Search for top squarks in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, ATLAS-CONF-2016-050, August 2016 [2].

ATLAS Collaboration, *Search for Dark Matter production associated with bottom quarks with 13.3 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC*, ATLAS-CONF-2016-086, August 2016 [3].

ATLAS Collaboration, *Search for top squark pair production in final states with one isolated lepton, jets, and missing transverse momentum using $\sqrt{s} = 13$ TeV pp collision data with the ATLAS detector*, ATLAS-CONF-2017-037, May 2017 [4].

The publications are the result of the work of a large number of scientists within the ATLAS Collaboration.

The author's contribution

I started as a doctoral student at Stockholm University in September 2013 and became an active member of the b -tagging group in the ATLAS Collaboration. My first project focused on the ATLAS b -tagging reconstruction software. My task was to develop a more flexible configuration interface for the b -tagging software, that would allow for an arbitrary choice of b -tagging algorithms and jet collections. The details of this successfully accomplished technical task is presented in Chapter 5.

After that I worked on a new method to calibrate the b -tagging efficiency for high p_T jets. This was the first complete b -tagging calibration analysis based on the template fit method, and the first to target jets with high transverse momentum. The analysis is presented in Chapter 6 and documented in the internal ATLAS Note “*Measurement of the b -tagging efficiency of the MV1 algorithm for high- p_T jets in pp collisions at $\sqrt{s} = 8$ TeV using multi-jet events*”. I was responsible for choosing the trigger schema, the optimal template building method and the optimal binning for the templates. Further, a comparison of several different fit strategies was done by me, as well as the investigation of how the choice of binning affects the fit results. I also performed the pseudo-data experiments to validate the fits. Finally, I performed the fits using the nominal

and systematically altered templates to obtain the b -tagging efficiency scale factors as well as the systematic uncertainties on the b -tagging efficiency calibration. This analysis was performed with data from LHC Run I. It has laid the foundation for a b -tagging calibration analysis in Run II, which is expected to be published. Additionally, I have implemented the JetProb b -tagging algorithm on the D3PD level and demonstrated the possibility to calibrate the MV1 b -tagging efficiency using template fits to the JetProb output weight. Other discriminating variables were also tested, and the correlations between different variables were investigated. This study is included in Appendix F.

The next step of my doctoral studies started with joining the Dark Matter and the SUSY groups, where I have been working on the search for DM production in association with heavy flavour quarks. Within these groups I performed the study presented in Chapter 8. I applied the signal selections to the simulated samples of DM production under the Effective Field Theory assumption. By comparing the numbers of selected generated signal events with the numbers of selected reconstructed signal events published in Refs. [5,6], I derived the scaling factor needed to convert the number of selected generated events to the expected number of selected reconstructed events. Then I applied the signal selections to the simulated samples of DM production under the simplified model assumption with various parameters to obtain the numbers of selected generated signal events and scaled them with the factor derived in the previous step. Finally, I performed the hypothesis tests and derived the CL_s value and sensitivity significance for each simplified model to determine which models were expected to already be excluded at 95% confidence level, and which models should be targeted by future searches. The results of this study were used in Refs. [2,3].

My main contribution to the search for DM production at $\sqrt{s} = 13$ TeV, presented in Chapter 9, was to optimize two new signal regions. After that I defined the control regions, except for the control region enriched in $t\bar{t}Z$ events, and defined the regions to validate the background expectations. I further performed the background-only fit to derive the normalization factors for the major background processes. Finally, I performed the exclusion fits for the simplified models and derived the upper limits on the DM production cross section. This analysis is included in Ref. [4].

Part I

Theoretical Overview

1 The Standard Model

The Standard Model (SM) [7–11] of particle physics describes the fundamental particles and their interactions. It successfully explains most of the experimental results and makes a large number of predictions which have been experimentally confirmed with high precision. The SM defines the fundamental components of matter and describes their interactions by the three fundamental forces: weak, electromagnetic and strong, in terms of the gauge symmetry group of local transformations $SU(3) \otimes SU(2) \otimes U(1)$.

The elementary particles of the SM are organized as shown in Fig. 1.1. They are divided into twelve *fermions*, which are the particles with spin $\frac{1}{2}$, acting as the building blocks of matter, and five *bosons* carrying integer spin.

mass	2.3 MeV/c ²	1.275 GeV/c ²	173.21 GeV/c ²	0	126 GeV/c ²
charge	2/3	2/3	2/3	0	0
spin	1/2	1/2	1/2	1	0
	u	c	t	g	H
	up	charm	top	gluon	Higgs boson
quarks					
	4.8 MeV/c ²	95 MeV/c ²	4.18 GeV/c ²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d	s	b	γ	
	down	strange	bottom	photon	
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	0	91.2 GeV/c ²
	-1	-1	-1/3	0	-1/3
	1/2	1/2	1/2	1	1
	e	μ	τ	Z	
	electron	muon	tau	Z boson	
leptons					
	0	0	0	0	80.4 GeV/c ²
	1/2	1/2	1/2	±1	±1
				1	1
	ν_e	ν_μ	ν_τ	W	
	electron neutrino	muon neutrino	tau neutrino	W boson	

Figure 1.1: Fundamental particles of the SM: three generations of quarks and leptons, the gauge bosons and the Higgs boson (from PDG [12]).

For each fermion there is an antiparticle, which has the same mass as the particle, but its electric, lepton and baryon charges as well as the quark flavour quantum numbers (strangeness, charm, topness and bottomness) have opposite sign. In the literature the anti-particles are usually denoted with the same symbol as the corresponding particle, but have a bar above them. For example, t stands for the top quark and $\bar{t}$ for the top anti-quark. Hereafter the bar can be omitted in the notations.

The bosons obey Bose-Einstein statistics. Photons, gluons, $W^\pm$ and

The fermions obey Fermi-Dirac statistics and respect the Pauli exclusion principle. They are classified in two types: six *quarks* and six *leptons*. Both types are organized in three “generations” from the lightest particles in the first generation to the heavier particles making up the second and the third generations. For each fermion there is an antiparticle, which has the same mass as the particle, but its electric, lepton and baryon charges as well as the quark flavour quantum numbers (strangeness,

Z^0 bosons are the gauge bosons. They carry spin 1 and mediate interactions between particles. The scalar Higgs boson has spin zero and is part of the mechanism which gives mass to the SM particles.

1.1 Quarks

Quarks take part in all the fundamental interactions. There are six *flavours* of quarks: up (u), down (d), strange (s), charm (c), bottom (b) and top (t). Quarks in the top row (u, c, t) of Fig. 1.1 have electrical charge $Q = +2/3e$, while the ones in the bottom row (d, s, b) have electrical charge $Q = -1/3e$, where e is the absolute value of the electron charge ($1.602 \cdot 10^{-19}$ C). Quarks of each flavour can be in one of the three color states: red, green or blue (r, g, b). Antiquarks carry the corresponding anticolors ($\bar{r}, \bar{g}, \bar{b}$).

In the SM quarks and antiquarks can exist only within composite particles called hadrons and can never be directly observed. This phenomenon is known as color confinement. Hadrons can exist only in “colorless” or “color neutral” states, or more precisely in the $SU(3)$ “color singlet” states. There are two such types of hadrons in the SM: baryons, composed of three quarks of different colors (rgb) and mesons, composed of a quark-antiquark pair ($q\bar{q}$) with the same color and anticolor (e.g. $r\bar{r}$) or a superposition of quark-antiquark pairs (e.g. $\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$)¹. These quarks define the properties of the hadrons and are called valence quarks. They are surrounded by quark-antiquark pairs, referred to as sea quarks, which continuously annihilate to produce gluons that split and recreate $q\bar{q}$ pairs. This cloud of virtual quarks and gluons is called “the sea” and makes up most of the hadron mass.

1.2 Leptons

The charged leptons: electron (e^-), muon (μ^-) and tau (τ^-), carry negative unit charge e . They take part in the electromagnetic, weak and gravitational interactions but do not interact via the strong force. Each charged lepton has an associated partner, neutrino, that is electrically neutral. The pairs are characterized by lepton quantum numbers: L_e, L_μ, L_τ , which take values summarized in Table 1.1. For

Particle	Lepton number		
	L_e	L_μ	L_τ
ν_e	1	0	0
ν_μ	0	1	0
ν_τ	0	0	1
e^-	1	0	0
μ^-	0	1	0
τ^-	0	0	1

Table 1.1: Values of the lepton numbers.

¹Recently exotic hadrons containing more than three quarks have been discovered [13, 14].

example, the lepton number L_e is 1 for the electron, e^- , and the electron neutrino, ν_e , while it is -1 for the positron, e^+ , and the electron antineutrino, $\bar{\nu}_e$, and zero for the leptons from the second and the third generations. In the SM the lepton numbers are conserved in all processes.

1.3 Fundamental interactions and their mediators

The SM combines the theory of the strong interaction with the unified theory of the weak and electromagnetic interactions. This section gives a short introduction to these theories and a description of the main properties of the three forces (Table 1.2).

The strengths of the interactions are parametrized by the coupling constants (gauge couplings). Despite being called “constants”, they depend on the energy scale. This fact is usually referred to as the running of the couplings. The coupling constants of the electromagnetic, strong and weak interactions are very different at low energies, but they get closer with increasing energy and are expected to converge to a common value at high energies. This is a corner stone in the creation of a Grand Unified Theory (GUT), in which all the fundamental forces are unified. In the SM the couplings of the electromagnetic and weak interactions converge to a common value at the energy scale $\sim 10^2$ GeV and become approximately equal to the strong coupling at $\sim 10^{16}$ GeV.

Interaction	mediator	relative strength	range, cm
Strong	gluon (g)	1	$10^{-13} - 10^{-15}$
Electromagnetic	photon (γ)	10^{-2}	∞
Weak	$W^\pm, Z^0$	10^{-5}	$10^{-16} - 10^{-18}$
Gravity	graviton (hypothetical)	10^{-38}	∞

Table 1.2: The characteristics of the four fundamental interactions. The numerical values are approximate and are given at a centre-of-mass energy of ~ 1 GeV.

1.3.1 Strong interaction

The strong interaction is described by quantum chromodynamics (QCD). It binds quarks inside hadrons through the exchange of gluons. The simplest vertex of the strong interaction between quarks is shown in Fig. 1.2 a. Gluons carry color and anticolor and can therefore inter-

act with themselves (Fig. 1.2 b, c). When emitting a gluon, quarks change their color, but their flavour and other quantum numbers stay unchanged.

QCD is a gauge theory with symmetry group $SU(3)$, which implies the existence of eight types of gluons, each having one of the linearly independent color states. The gluons have spin 1 and have neither electrical charge, nor mass. The range of the strong interaction is 10^{-13} cm. The coupling constant of the strong interaction grows with increasing distance between the quarks. This dependency leads to asymptotic freedom, meaning that the interaction between quarks on very short distances can be neglected to first order. On the other hand, quarks can not be separated from each other by more than the confinement radius due to the retention by the gluon fields.

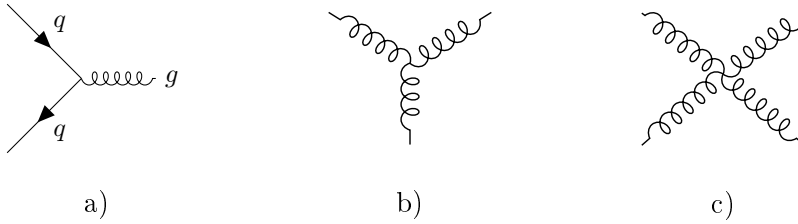


Figure 1.2: Examples of Feynman diagrams of strong interaction vertices: gluon-quark interaction (a) and gluon self-interactions (b, c).

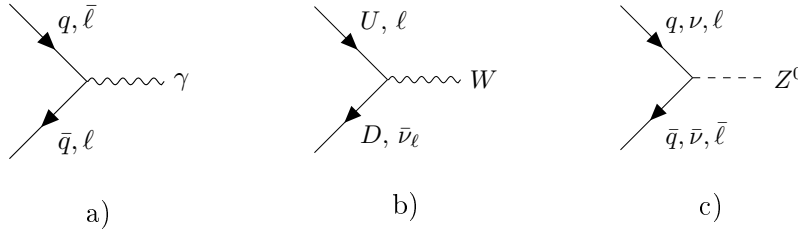


Figure 1.3: Examples of Feynman diagrams of EM (a) and weak (b, c) interactions. The charged leptons are labelled with ℓ . U stands for an up-type quark (u , c or t) and D stands for a down-type quark (d , s or b).

1.3.2 Electromagnetic interaction

Electromagnetic (EM) interactions are described by quantum electrodynamics (QED). Electrically charged particles participate in it by exchanging photons. The photon itself does not carry electric charge and therefore can not interact directly with other photons. The photon is massless, and the EM force can act over long distances. Its strength is proportional to the inverse squared distance between the interacting particles. The simplest EM vertex is shown in Fig. 1.3 a.

1.3.3 Weak interaction

All the fundamental fermions participate in weak interactions. Neutrinos and antineutrinos are the only particles that interact solely via the weak force. The weak interaction is involved in many decay processes. The $W^\pm$ and Z^0 gauge bosons are the mediators of the weak interaction. In contrast to the other gauge bosons, $W^\pm$ and Z^0 have large masses, which makes the range of the weak interaction very small, $\sim 10^{-18}$ cm, compared to the strong and electromagnetic interactions. By exchanging a $W^\pm$ boson quarks change their flavour. Most of the conservation laws that hold in strong and electromagnetic interactions are not valid in weak interactions. The simplest vertices of the weak interaction are shown in Fig. 1.3 b, c.

1.3.4 Electroweak unification

The electromagnetic and weak interactions are described as parts of the combined electroweak theory (EWT) which is invariant under the gauge symmetry group $SU(2)_L \otimes U(1)_Y$. The generators of the $SU(2)_L$ group correspond to the boson fields W_i ($i = 1, 2, 3$) with a coupling g , while the generator of the $U(1)_Y$ group is the B^0 boson field with a coupling g' . Due to the spontaneous symmetry breaking (see Section 1.4) these massless quantum fields mix and their superpositions form the physically observable particles. They are the photon and the massive $W^\pm$ and Z^0 bosons, given by:

$$W^\pm = \frac{1}{\sqrt{2}}(W_1 \mp iW_2) \quad \begin{pmatrix} Z^0 \\ \gamma \end{pmatrix} = \begin{pmatrix} \cos \theta_W & -\sin \theta_W \\ \sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} W_3 \\ B^0 \end{pmatrix}, \quad (1.1)$$

where θ_W is the weak mixing angle, $\tan \theta = g'/g$.

1.4 Higgs boson

An essential part of the SM is the Brout-Englert-Higgs (BEH) mechanism [11, 15] through which the elementary particles acquire mass. In this mechanism the Higgs field is a $SU(2)$ doublet of complex scalar fields which has four degrees of freedom. A non-vanishing vacuum expectation value of the Higgs field causes spontaneous breaking of the electroweak symmetry $SU(2)_L \otimes U(1)_Y$ down to $U(1)_{\text{EM}}$. Three of the degrees of freedom mix with the weak gauge bosons, $W^\pm$ and Z^0 , making them massive. The remaining degree of freedom appears as the massive scalar Higgs boson. Since $U(1)_{\text{EM}}$ is unbroken, electric charge is conserved and the photon remains massless. Fermions acquire their mass through Yukawa interactions with the Higgs field.

In 2012 a boson consistent with the SM Higgs boson was observed by the ATLAS [16] and CMS [17] experiments at the LHC. The mass of the new boson is $m_H = 125.7$ GeV [12].

2 Beyond the Standard Model

2.1 Shortcomings of the Standard Model

The SM is the most successful of the currently available theoretical frameworks, describing the fundamental structure of matter. However, there is a number of phenomena that are not explained in the SM.

The SM successfully unifies three of the four fundamental forces, but it does not incorporate gravity. At the energies accessible in accelerator experiments the strength of the gravitational interaction is very small, and its impact can not be observed. However, the gravitational force is expected to become comparable with the other forces at the Planck scale ($\Lambda_{\text{Planck}} = \sqrt{\hbar c/G} \sim 1.2 \cdot 10^{19}$ GeV). This implies that the SM is only valid up to a certain cut-off scale Λ , and must be a low-energy approximation of a more fundamental theory.

The observations of neutrino oscillations [18–20] indicate a nonconservation of the lepton numbers and show that neutrinos have non-zero masses and can mix between the generations, while in the SM neutrinos are massless.

A major problem in modern physics, which is not solved by the SM, is the hierarchy problem. There is no apparent reason why the scale of the electroweak interactions, set by the non-zero vacuum expectation value of the scalar Higgs field ($v_{EW} = 2.462 \cdot 10^2$ GeV), is many orders of magnitude less than the scale of the unified theory incorporating gravity, set by the Planck scale. Particularly, this problem manifests itself in the necessity of fine-tuning to stabilize the mass of the Higgs boson against loop corrections. Mathematically there are two terms contributing to the observed mass of the Higgs boson m_H . They are the bare Higgs boson mass m_{H0} and radiative corrections from the interactions between virtual particles and the Higgs field. The latter contribution is proportional to the squared cut-off scale Λ^2 , and therefore is quadratically divergent. To cancel out the divergent loop term, the fine-tuning of the high-energy parameters to a precision $\sim m_H^2/\Lambda_{\text{Planck}}^2 \sim 10^{34}$ is

needed, which is argued to be unnatural.

The SM does not explain the origin of quantum numbers and the reason why they are quantized. It includes three generations of fundamental fermions, but their mass hierarchy and the reason why there are exactly three generations are not explained. There are 19 freely adjustable parameters in the SM, and their numerical values have been established by experiments. There is also no explanation for the specific choice of symmetry groups and their representations.

There is no mechanism in the SM to explain the imbalance between baryonic and antibaryonic matter in the observable Universe. Furthermore, the SM does not predict a viable Dark Matter candidate, although many astronomical observations provide evidence for Dark Matter, as discussed in more detail in Section 2.2. The origin of the dark energy in the Universe remains even more puzzling.

Many theories have been developed to explain some of the phenomena listed above. The most popular explanation is proposed by supersymmetry (SUSY) [21], where every SM particle has a superpartner with the same quantum numbers, except for the spin, which differs by $1/2$. SUSY solves the hierarchy problem as the quadratic divergence in the SM is canceled by a contribution of loops from the superpartner particles. The weak, strong and electromagnetic coupling constants converge in SUSY. It also propose a Dark Matter candidate.

2.2 Dark Matter detection

The SM only incorporates baryonic matter, but astrophysical observations provide a compelling evidence for a non-baryonic component of the Universe [22, 23]. The existence of DM is motivated by the observations of the rotation curves of stars and gas in spiral galaxies, measurements of velocities of galaxies in clusters, observations of the gravitational lensing effect [24] and measurements of the cosmic microwave background [22]. According to the existing measurements, the DM does not consist of a baryonic material, but is composed of a new type of elementary particle. Only a small percentage of the total energy density of the Universe, about 4.9%, consists of baryonic matter, nearly 26.8% consists of Dark Matter (DM), and the remaining part, around 68.3%, is dark energy.

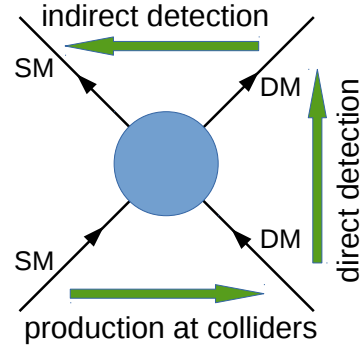


Figure 2.1: Drawing illustrating possible methods to detect DM.

Despite numerous efforts to detect DM, only its gravitational effects on visible matter and on radiation have been observed, and its nature is still an open question in particle physics and astrophysics. There are three different approaches (Fig. 2.1) to search for DM:

- direct detection via elastic scattering off nuclei in a detector,
- indirect detection through an astronomical observation of the annihilation of DM particles,
- production and detection at particle accelerators.

A typical example of indirect DM detection is the observation of a high-energy gamma-ray line by the Fermi Large Area Telescope (Fermi/LAT) [25, 26], HESS [27], MAGIC [28] and VERITAS [29]. Various direct searches for DM signatures are carried out by the DAMA/LIBRA [30], CoGeNT [31], CDMS-II [32], XENON100 [33] and LUX [34] collaborations.

Complementary to these two approaches, there are the collider searches at the LHC. The collider searches aim at detecting the signatures of the DM particle production, which are revealed as events with large momentum imbalance from the invisible DM particles produced.

2.3 Dark Matter models

Numerous theories beyond the SM propose non-baryonic candidates for the DM particle, χ . Currently the most compelling candidate for DM is a weakly interacting massive particle, WIMP. This is a stable particle which has neither electrical nor color charge and can interact only via the gravitational and the weak forces.

2.3.1 UV-complete models

An example of an ultra-violet (UV) complete model predicting a DM candidate that satisfies the WIMP definition is SUSY. A UV-complete model usually has a large number of non-SM particles, other than the DM particle, and a large number of free parameters. Therefore, considering a specific UV-complete model can complicate the interpretation of the search results. The choice of selection criteria can reduce the sensitivity to other models. Furthermore, a conversion of the results to compare with non-collider experiments can be complicated due to dependency on the parameters of the specific UV-complete model [35]. For these reasons and given the large number of viable UV-complete models, it is desirable to investigate the signatures of the DM candidate in a more generic way, e.g. by assuming that there are several exchange particles or a single mediator connecting the SM to the dark sector.

2.3.2 Effective field theory

Most of the LHC Run I studies are performed in the context of an effective field theory (EFT) [36, 37]. EFT is a relatively model-independent approach to describe the interactions between DM and SM particles. It arises as the infrared limit of a UV complete theory. The EFT assumes that the mediator of the interaction is too heavy to be produced directly and can be integrated out. Therefore this interaction is parametrized in terms of effective (non-renormalizable) contact operators $\mathcal{O}$. Interactions of the DM particle χ with SM quarks q and gluons G are given by:

$$\begin{aligned} L_{\text{eff}} &= \sum_{\text{quarks}} G_{\chi} \mathcal{O}(\chi, q) \\ L_{\text{eff}} &= G_{\chi} \mathcal{O}(\chi, G), \end{aligned} \quad (2.1)$$

where G_{χ} is the coupling constant, determined by the calculation of the thermal relic abundance of the χ . The interaction strength in the EFT is characterized by a parameter M_{*} . In the simplest possible UV completions of the EFT, where the SM particles interact with DM via a single heavy mediator ϕ , the G_{χ} of the EFT is related to parameters of the UV complete theory as

$$G_{\chi} = (g_{\chi} g_{\text{SM}}) / m_{\phi}^2 = 1 / M_{*}^2, \quad (2.2)$$

where m_{ϕ} is the mediator mass, g_{χ} is its coupling to the DM particle, and g_{SM} is the coupling of the mediator to the SM particles. DM searches under the EFT assumption are usually restricted to the cases where the DM particle is a fermion (Dirac or Majorana) or a scalar (real or complex), and couples to quarks and/or gluons. The theory is dependent on the spin of the mediator. The coupling via the mediator with spin 0, 1 or 2 is usually considered. Consequently the contact operators are given in the form $\bar{\chi} \Gamma \chi$ (for fermionic χ) with $\Gamma \in \{1, \gamma^5, \gamma^{\mu}, \gamma^{\mu} \gamma^5, \sigma^{\mu\nu}\}$, where the choice of Γ corresponds to the scalar, pseudoscalar, vector, axial-vector or tensor interaction. Several operators describing the interactions between SM partons and Dirac fermion DM or complex scalar DM are listed in Table 2.1.

The validity of the DM EFT approach has limitations [38–40]. It can be applied only if the typical momentum transfer Q_{tr} in the considered process does not exceed the mediator mass, $Q_{\text{tr}} \ll m_{\phi}$, to ensure that the mediator can not be produced directly. In direct detection the momentum transfer is low, $Q_{\text{tr}} \sim \mathcal{O}(10)$ keV, and this condition is usually satisfied. In indirect detection experiments looking for the annihilation products of DM, where the momentum transfer can be $Q_{\text{tr}} \sim 2m_{\chi}$, the EFT should hold as long as the mediator is not extremely light. However,

interaction type (mediator)	operator name	interaction with	operator, $\mathcal{O}$	G_χ
scalar	D1	quarks	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
pseudoscalar	D2	quarks	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
vector	D5	quarks	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
axial vector	D8	quarks	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
scalar	D11	gluons	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
scalar	C1	quarks	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
scalar	C5	gluons	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$

Table 2.1: Operators coupling DM to quarks and gluons [37]. The operator names starting with D and C apply to DM candidates that are Dirac fermions or complex scalars, respectively.

in collider experiments the momentum transfer can reach large values at which the EFT approach becomes inapplicable. In order for the theory to stay perturbative, the couplings have to satisfy $\sqrt{g_\chi g_{\text{SM}}} \lesssim 4\pi$. The common canonical choice of the couplings $\sqrt{g_\chi g_{\text{SM}}} = 1$ results in the validity requirement that the momentum transfer can be neglected in comparison to the energy scale of the underlying interactions, $Q_{\text{tr}} \ll M_*$, i.e. the EFT breaks down at the UV cut-off (suppression) scale M_* .

2.3.3 Simplified models

A compromise between the EFT approach and a UV-complete theory has been found in simplified models [41–43] (Fig. 2.2), extensively used in the LHC Run II searches for DM. The simplified models introduce explicitly one or several particles mediating the interactions between the DM and the SM particles. This approach is generic enough to cover features of a certain class of models and at the same time to stay valid at high energies. Resolving the contact interactions by introducing a new particle increases the number of free parameters, but the parameter space is much reduced in comparison with the complete theories. For example, the parameters in a simplified model coupling the SM quarks to DM via a single mediator can be the DM mass m_χ , the mediator mass m_ϕ , the coupling between the DM particle and the mediator g_χ , the coupling between the quarks and the mediator g_q , and the mediator width Γ_ϕ .

Part IV describes searches for DM using the simplified models [35],

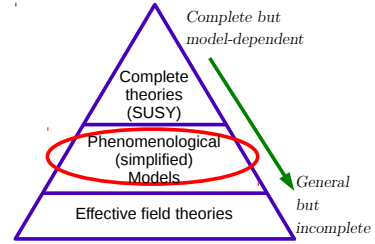


Figure 2.2: General strategy for Dark Matter searches.

where a Dirac fermion DM couples to the SM particles (quarks and charged leptons) through a spin-0 (scalar or pseudoscalar) mediator ϕ . To reduce the number of parameters to scan, the coupling g_χ of the mediator to the DM particle is set equal to its coupling to the quarks, $g_\chi = g_{\text{SM}} = g$, which is assumed to be proportional to the SM Yukawa couplings. Since the mediator width has been proven not to change kinematic distributions and there are no additional visible or invisible decays contributing to the width of the mediator, the minimal width allowed by the couplings can be chosen in order to reduce the number of free parameters. In the end, there are three free parameters in these models: the DM mass m_χ , the mediator mass m_ϕ and the coupling g .

Part II

Experimental Overview

3 The Large Hadron Collider and the ATLAS detector

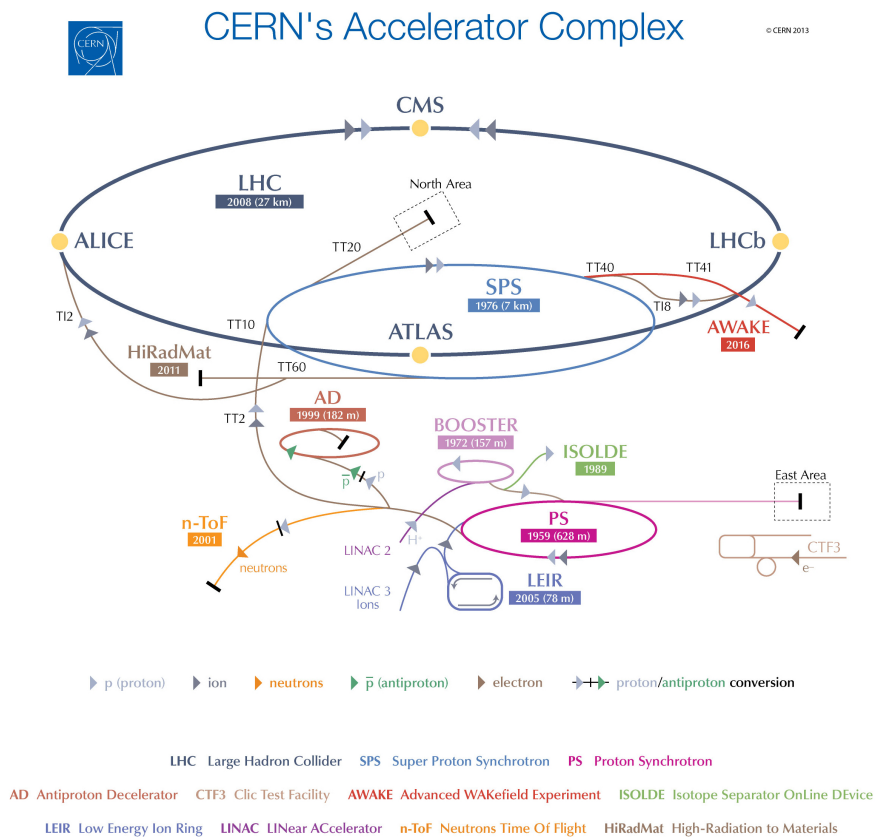


Figure 3.1: Overview of CERN's accelerator layout [44].

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [45] is the largest and most powerful particle accelerator in the world built to date. It is operated by the European Organization for Nuclear Research CERN and is built beneath the border between Switzerland and France at a depth of up to 175 m.

The main LHC ring lies in a tunnel which is 27 km in circumference. It consists of two parallel beam pipes kept at an ultrahigh vacuum. Two high-energy particle beams travel in opposite directions in the separate pipes at a speed close to the speed of light under control of superconducting electromagnets. The beam pipes intersect at four points where the particle beams collide. Before being injected into the main LHC ring the particle beams are successively accelerated in a chain of pre-accelerators. Figure 3.1 shows schematically the entire CERN accelerator complex.

There are seven detectors built along the LHC ring. The main experiments ALICE, ATLAS, CMS and LHCb, use detectors placed at four different collision points and share their facilities with the smaller experiments TOTEM, LHCf and MoEDAL. The biggest of the detectors, **ATLAS** (A Toroidal LHC ApparatuS) and **CMS** (Compact Muon Solenoid), are general-purpose detectors designed to investigate a wide range of physics processes. Having two detectors allows to collect and analyze data independently, which is necessary for cross-confirmation of any new discovery. The other detectors are more specialized and investigate specific phenomena. The **ALICE** (A Large Ion Collider Experiment) detector is designed to study the physics of strongly interacting matter at extreme energy densities using collisions between heavy ions. The high energy density allows to observe and examine quark-gluon plasma, an extreme state of matter. The main purpose of the **LHCb** (Large Hadron Collider beauty) experiment is to search for processes manifesting the slight differences between the b and $\bar{b}$ quarks to explain the matter-antimatter asymmetry in the Universe.

3.1.1 Luminosity

The rate dN_p/dt at which a certain physics process p occurs is proportional to the cross section $\sigma_p[\text{pb}]$ of this process:

$$\frac{dN_p}{dt} = L \cdot \sigma_p, \quad (3.1)$$

where $L[\text{pb}^{-1} \text{ s}^{-1}]$ is the instantaneous luminosity. The luminosity is an important characteristic of particle colliders. It only depends on the machine and not on the physics process under study.

The main physics program of the LHC is based on proton-proton

(pp) collisions. The LHC is designed to collide proton bunches 40 million times per second to provide 14 TeV pp collisions at the design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. In addition a part of the year is allotted to collide heavy ions (usually Pb - Pb nuclei) at 5.5 TeV per ion pair at a design luminosity of $10^{27} \text{ cm}^{-2}\text{s}^{-1}$.

The integrated luminosity, $\int L dt$, allows to evaluate the total number of events produced for a physics process over a given period of time. Units of the integrated luminosity are inverse barns (b^{-1}). After the Run I data-taking period (2009-2013) the LHC accelerator complex was stopped for a two-year-long shutdown for maintenance and upgrade of the accelerator, and in April 2015 the LHC was back in operation. The planned technical stop took place in order to prepare for collisions at the higher energy of 13 TeV in Run II. The analyses presented in this thesis were done using the Run I data collected in 2012 at a centre-of-mass energy $\sqrt{s} = 8 \text{ TeV}$, which corresponds to an integrated luminosity of 20.1 fb^{-1} , as well as the Run II data collected in 2015-2016 at $\sqrt{s} = 13 \text{ TeV}$, corresponding to 36.1 fb^{-1} .

3.1.2 Pile-up and underlying events

The LHC is designed to operate with 2808 bunches per beam. The bunches are organized in up to 11 trains, 1000 ns apart from each other. The nominal spacing between bunches in the train is 25 ns, and each bunch can contain about $1.15 \cdot 10^{11}$ protons. The data associated with a single collision of proton bunches is called an *event*.

Most of the physics analyses in ATLAS focus on measuring particles originating from the hardest parton-parton scattering processes. In hard scattering processes one parton from each of the two colliding hadrons interact with large momentum transfer. The *underlying event* is the part of a hadron-hadron collision that is not associated with the hard scattering process of interest. It incorporates initial and final state radiation, beam-beam remnants and multiple parton interactions.

The probability that more than one hard scattering collision occurs in the same bunch crossing is very low. However, soft interactions between the constituents of other proton-proton pairs in the same bunch crossing are common, and this effect grows with the instantaneous luminosity in the beam. Particles coming from additional pp interactions in the same bunch crossing as the collision of interest are called “in-time” pile-up. Pile-up creates a complex environment in which the particles created in the hard scattering collision need to be reconstructed, even though most of the pile-up interactions are soft and can be rejected by requiring high transverse momenta of the particles produced in the collision. “Out-of-

time” pile-up refers to particles originating from collisions in adjacent bunch crossings. To reduce this background, it is important to have a fast read-out response of the detectors, to be able to identify which bunch crossing a particle has originated from.

The amount of in-time pile-up is quantified by the number of pp interactions per bunch crossing, which follows a Poisson distribution with mean value μ . The average number of interactions per bunch crossing is calculated as

$$\langle\mu\rangle = \frac{L \cdot \sigma_{\text{inel}}}{n_{\text{bunch}} \cdot f_r}, \quad (3.2)$$

where L is the instantaneous luminosity, σ_{inel} is the total inelastic cross section, n_{bunch} is the number of colliding bunches, and f_r is the LHC revolution frequency. As the instantaneous luminosity provided by the LHC increases, the amount of pile-up increases proportionally. More details can be found in Refs. [46,47].

3.2 The ATLAS detector

3.2.1 Overall geometry and coordinate system

The ATLAS detector [48,49] is designed to identify and reconstruct particles produced in the LHC collisions for studies of a wide range of physics processes. It is 44 m long, 25 m in diameter and weighs 7000 tons (Fig. 3.2, 3.3).

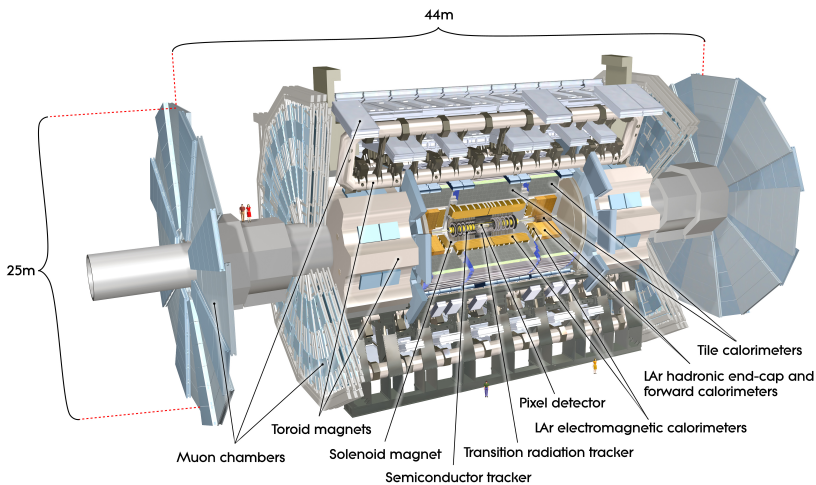


Figure 3.2: Cut-away view of the ATLAS detector showing its subcomponents (ATLAS Experiment © 2014 CERN).

There are two coordinate systems used in ATLAS. One of them is a right-handed Cartesian coordinate system. The origin is chosen in the centre of the detector, at the nominal interaction point (IP). The z -axis is defined along the beam pipe. The x -axis is oriented horizontally towards the centre of the LHC ring, and the y -axis points upwards. The other coordinate system is cylindrical with the same origin and z -axis. Its coordinates, the radial distance r and the azimuthal angle ϕ , are defined in the transverse plane (xy). A commonly used spatial coordinate, the pseudorapidity η , is defined as $\eta = -\ln(\tan(\theta/2))$, where θ is the polar angle measured from the positive direction of the z -axis. Angular distances are measured in units of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

The ATLAS detector has a sophisticated design and is composed of many individual concentric subsystems, providing hermetic coverage in the transverse plane. The main subcomponents from the interaction point towards the outer parts are: the Inner Detector (ID), the Electromagnetic (EM) and Hadronic calorimeters and the Muon Spectrometer (MS). Particles of various types produce different signatures in the subsystems of the ATLAS detector, as shown in Fig. 3.4. By combining information from the various subsystems the particles can be identified and their properties can be measured.

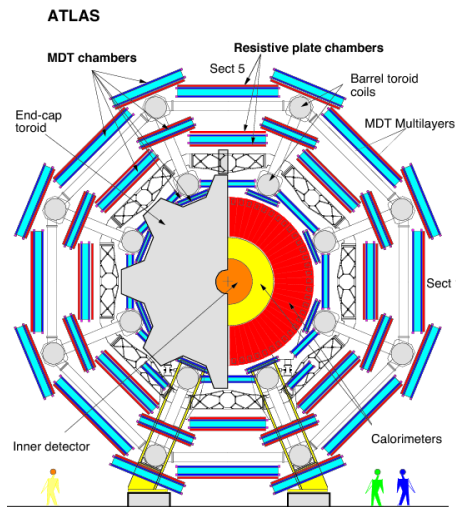


Figure 3.3: Cross-sectional cut-away view of the ATLAS detector. [50].

The Inner Detector and the Muon Spectrometer are tracking detectors which register the 3D trajectories of charged particles traversing them. In the calorimeters the energies of particles are estimated by measuring the energy deposited in the detector material. The EM calorimeter is intended to measure energies of electrons and photons. Photons are

completely absorbed in the EM calorimeter and do not leave tracks in the ID. Electrons are detected both in the ID and the EM calorimeter. The Hadronic calorimeter specializes in measuring the energy of hadrons. The absorption length of hadrons is larger than that of high energy electrons or photons, thus the hadrons will traverse the EM calorimeter and continue to the Hadronic calorimeter. Neutral hadrons are detected only in the Hadronic calorimeter, while charged hadrons also produce tracks in the ID and deposit energy in both calorimeters. Muons, being charged particles, are detected in the ID, in the calorimeters and are tracked further in the Muon Spectrometer. Neutrinos are stable particles that do not interact with detector material and travel through it without being stopped. They carry energy, and therefore in the reconstruction they are taken into account through missing transverse momentum (see Section 4.2.7). The presence of Dark Matter candidates and particles that can interact only through gravity or weak interactions can also be inferred this way.

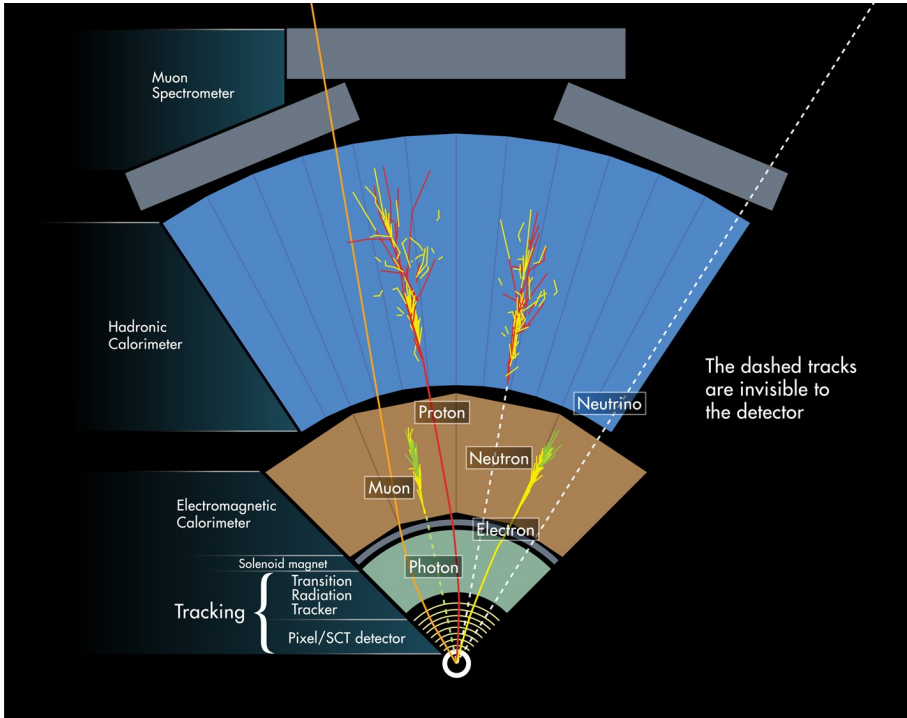


Figure 3.4: Image representing how various particles interact with different subsystems of the ATLAS detector [51].

3.2.2 Magnet system

The ATLAS detector is equipped with a system of superconducting magnets. They create a magnetic field to bend the trajectories of charged particles so that their transverse momenta can be measured. The view of the bare windings of the ATLAS magnet system is given in Fig. 3.5. It consists of the central solenoid, the air-core barrel toroid and two air-core end-cap toroids. Each of the three toroidal magnets consists of eight coils, grouped in a torus shape. The central solenoid provides magnetic field of 2 T in the Inner Detector, while the Muon Spectrometer of the ATLAS detector is supplied with an independent magnetic field of 4 T provided by the toroids.

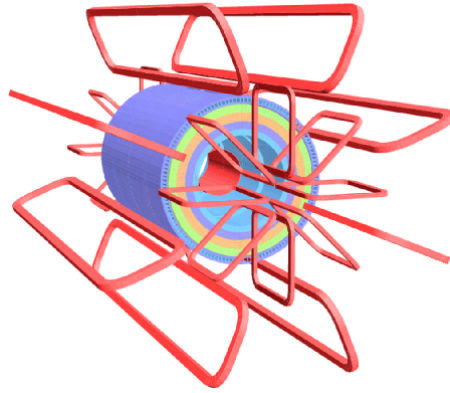


Figure 3.5: The ATLAS magnet system: the central solenoid, the 8 coils of the barrel toroid and the 2 end-cap toroids with 8 coils each [52].

3.2.3 Inner Detector

The innermost system of the detector surrounding the beam pipe is the tracking system or the Inner Detector (ID) illustrated in Fig. 3.6. It is used to measure the trajectories and momenta of charged particles in the region of $|\eta| < 2.5$. The ID is located inside the central solenoid.

A large number of charged particles are created in the interactions in each bunch crossing. The high granularity and high resolution of the ID allow to identify the tracks from these particles as well as their points of origin (vertices), and distinguish them from each other. This is vital for physics analyses and especially important for the analysis described in this thesis, where the track identification and reconstruction plays a crucial role. The average resolution of the track momentum provided by the ID is $\frac{\sigma_{p_T}}{p_T} \sim 0.05\% p_T \oplus 1\%$ ¹.

The outer radius of the ID is 1.15 m and its total length is 7 m. The ID is divided into three parts: a silicon Pixel Detector, a silicon microstrip detector (SemiConductor Tracker, SCT) and a straw-tube Transition Radiation Tracker (TRT).

The Pixel Detector in Run I was organized in three barrel layers and

¹The momentum p_T is expressed in GeV. The symbol $\oplus$ denotes quadratic sum, $a \oplus b = \sqrt{a^2 + b^2}$

three end-cap disks on either side covering the forward regions. In each of the layers a charged particle can leave a hit. During the recent long shutdown the forth, the innermost pixel layer was commissioned. This layer, called the insertable B-layer (IBL), is crucial for obtaining a good impact parameter resolution, which is very important for b -tagging (see Chapter 5).

The basic building block of the Pixel Detector is a module. A module is composed of a silicon pixel sensor and 16 read-out chips. Each module is 62.4 mm long and 21.4 mm wide, with 46080 pixels, which provide very precise measurements of the positions of the traversing charged particles. A pixel is $50\text{ }\mu\text{m}$ wide in $r - \phi$ and $300\text{ }\mu\text{m}$ long. A charged particle crossing the silicon sensor creates electron-hole pairs, that are separated by an electric field and drift to the read-out electrodes. This charge is recorded locally, identifying the position of the particle. The intrinsic resolution of the Pixel Detector is $10\text{ }\mu\text{m}$ in the $r - \phi$ plane and $115\text{ }\mu\text{m}$ in the z direction.

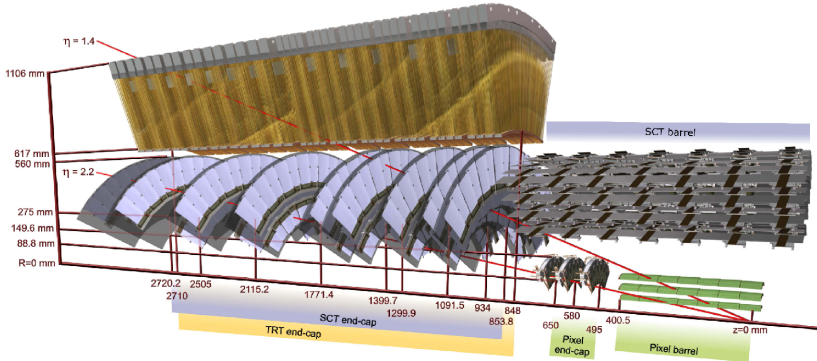


Figure 3.6: Sketch of the ATLAS Inner Detector showing its components. The distances along the beam pipe and the radial distances are shown. The TRT barrel detector is not shown [53].

The SCT consists of four barrel layers and nine end-cap disks on either side. It functions in a similar manner as the Pixel Detector but has coarser granularity and consists of silicon strips rather than pixels. Each SCT module is made of a baseboard sandwiched between silicon microstrip sensors. The top and the bottom sensors are rotated by an angle of 40 mrad with respect to each other to provide 3-dimensional information. The silicon strips are 12 cm long and have an $80\text{ }\mu\text{m}$ pitch. In the barrel the strips are arranged parallel to the beam line, while in the end-caps they are running radially. Each silicon microstrip sensor is $6.36 \times 6.40\text{ cm}$ with 768 readout strips. Since each barrel is double-sided, the SCT can provide 8 barrel hits and 9 hits in the end-cap. The

positions of charged particles are recorded to an accuracy of $16\ \mu\text{m}$ in the direction transverse to the strips and $580\ \mu\text{m}$ in the z direction.

The TRT is made of kapton drift tubes, which are 37-144 cm long and 4 mm in diameter, and are reinforced with thin carbon fibres. The straws are filled with a gas mixture and have a gold-plated tungsten wire running along their length. As the other ATLAS tracking detectors, it has a barrel and two end-cap regions. In the barrel there are 52544 straws oriented parallel to the beam. They are split in two halves and read out at both ends. In each of the end-caps there are 122880 radial straws. They have the readout at the outer radius. The TRT typically provides more than 30 hits per track with intrinsic accuracy of $130\ \mu\text{m}$ per straw (in the $r - \phi$ plane). A charged particle traversing the straw ionizes the gas and the produced free electrons drift towards the gold-plated wire. The spaces between the straws are filled with polymer fibres in the barrel and with foils in the end-caps. At the material boundaries the charged particle can emit transition radiation photons. This effect is stronger for highly relativistic charged particles. Electrons, which are the lightest charged particles, become highly relativistic already at low momenta and thus produce more transition radiation than heavier particles. This fact is used to discriminate the particle types, e.g. distinguish an electron from a pion of the same momentum.

3.2.4 Calorimeters

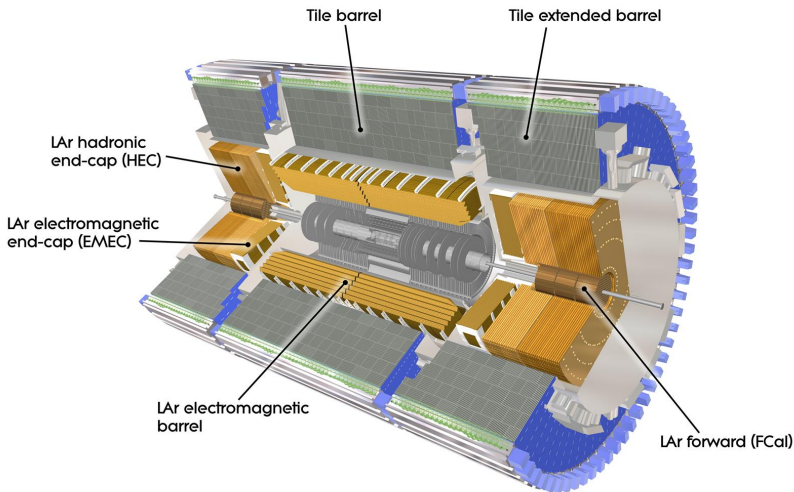


Figure 3.7: Sketch of the ATLAS calorimeter showing its different components(ATLAS Experiment © 2008 CERN).

Outside of the ID there are the calorimeters (Fig. 3.7), which measure the energies of electrons, photons and hadrons as well as provide fast triggering capabilities. The EM calorimeter, which is the closest of the two to the interaction point, consists of many layers of lead and stainless steel interleaved with copper readout electrodes. The 2 mm thick steel-plated lead absorbers are folded to an accordion shape and separated by 3.8 mm gaps filled with liquid argon (LAr). Electrons and photons entering the high density lead absorbers, interact with the material and produce “showers” of secondary particles. The secondary electrons and photons are less energetic the later in the shower they are created, and eventually they get absorbed. The energy deposited by the cascade is then sampled by a copper grid of electrodes immersed into liquid argon. The energy of the initial particle is reconstructed from the charged particles in the shower.

The EM calorimeter is divided into a central barrel and two end-caps on both ends of the detector. The barrel calorimeter covers pseudorapidity $|\eta| < 1.475$. It is divided into two identical half-barrels, separated by a gap of 6 mm. Each of the end-caps is divided into two coaxial wheels. The inner wheel covers the region $1.375 < |\eta| < 2.5$, and the outer wheel covers the region $2.5 < |\eta| < 3.2$. The total thickness of the EM calorimeter is more than 22 radiation lengths (X_0) in the barrel and more than 24 X_0 in the end-caps. Measurements in the forward region ($3.1 < |\eta| < 4.9$) are done with the Forward calorimeter (EM FCAL). The FCAL consists of three sections: one copper and two tungsten matrices traversed parallel to the beam axis by cylindrical holes with signal collecting electrodes.

Outside of the EM calorimeter there is the Hadronic calorimeter. It consists of the Tile calorimeter (TileCal) and the two LAr end-caps. The TileCal is divided into two half-barrels and two extended barrels. It is built of layers of steel plates with scintillator plates (tiles) between them, coupled to optical fibers and read out by photomultipliers. The steel plates are used as absorbers, and the scintillating tiles play the role of a sampling material. The tiles are placed radially and staggered in depth periodically along the z -axis. They are grouped in cells of different size depending on their depth and the pseudorapidity region that they cover. Hadrons interact with the steel nuclei and initiate wide showers through inelastic interactions. The TileCal gives hadronic coverage in the central pseudorapidity range ($|\eta| < 1.7$), while the LAr Hadronic end-cap calorimeter provides coverage over $1.5 < |\eta| < 3.2$. The total thickness of the Hadronic barrel and end-cap calorimeters is about 7.4 and more than 10 interaction lengths (λ_{int}), which provides an effective absorber for hadrons.

The design energy resolution² of the EM calorimeter is $\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 0.7\%$. The FCAL is designed to provide a resolution of $\frac{100\%}{\sqrt{E}} \oplus 10\%$. The energy resolution of the Hadronic barrel and end-cap calorimeters is $\frac{50\%}{\sqrt{E}} \oplus 3\%$, where the constant term of 3% is mostly due to nonlinearities of the non-compensating ATLAS calorimeters.

3.2.5 Muon Spectrometer

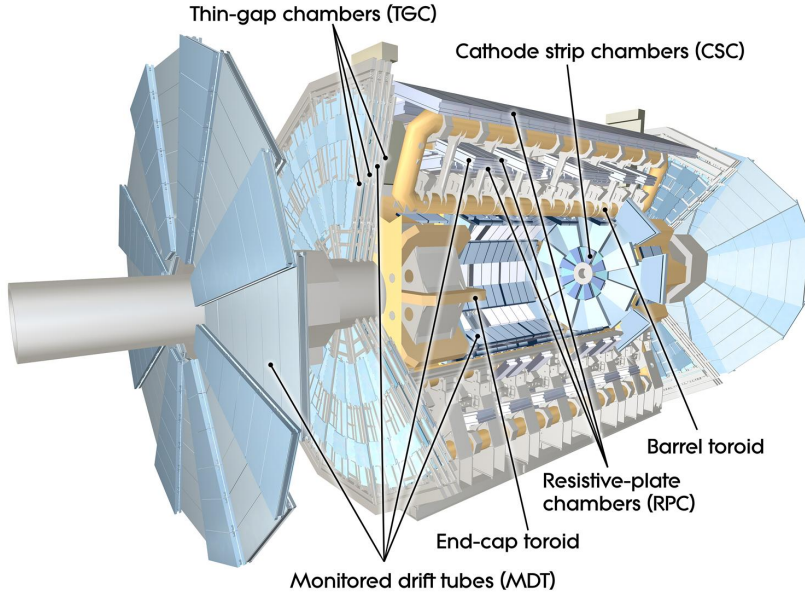


Figure 3.8: Schematic picture of the ATLAS Muon Spectrometer (ATLAS Experiment © 2008 CERN).

The Muon Spectrometer, illustrated in Fig. 3.8, defines the overall shape and size of the ATLAS detector. It is the outermost detector subsystem, as muons usually penetrate the material of the ID and the calorimeters without showering. The Muon Spectrometer performs fast triggering of muons and measures the muon momentum with high resolution. It is designed to measure the p_T of muons within $3 < p_T < 250$ GeV

²The energy resolution of calorimeters is usually parametrized as $\frac{\Delta E}{E} = \frac{\alpha}{\sqrt{E}} \oplus \beta \oplus \frac{\gamma}{E}$, where E is expressed in GeV. The term $\frac{\alpha}{\sqrt{E}}$ is a stochastic term representing statistical fluctuations caused by the choice of absorber, active material, thickness of the sampling layers and so on. It dominates in the 10-100 GeV energy range. The β term is a constant that depends on the detector depth, on non-uniformities of the signal, temperature, cracks in the calorimeters and losses of energy in dead material. It dominates at high energy. The γ term describes electrical noise, signal pile-up and such, and dominates at low energy.

with 3% resolution and muons up to 1 TeV with 10% resolution.

The subsystems responsible for precision measurements are the Monitored Drift Tubes (MDTs) and the Cathode Strip Chambers (CSCs). They comprise three barrel layers, covering pseudorapidity $|\eta| < 1$, and four end-cap wheels, extending the coverage to $|\eta| = 2.7$. The MDTs are proportional chambers that consist of aluminum tubes with a diameter of 30 mm, filled with a gas mixture, and a tungsten-rhenium wire running along each tube. In the barrel region MDTs are organized in three cylindrical layers and in the end-cap region they are arranged in three wheels. The MDTs cover the region $|\eta| < 2.7$, except for the innermost end-cap wheel, where the pseudorapidity coverage is $|\eta| < 2.0$. The MDTs provide average spatial resolution (η) per tube of $80\ \mu\text{m}$. The inner-most end-cap ring, covering the forward region $2.0 < |\eta| < 2.7$ is constructed of CSCs. The CSCs have higher granularity and time resolution to be able to operate at high data rates. They consist of multiple anode wires and two layers of cathode strips filled with a gas mixture. The two layers of strips are rotated with respect to each other by an angle of 90° , which allows to measure the 3D trajectories with spatial resolution in coordinates η and ϕ of respectively $60\ \mu\text{m}$ and $5\ \text{mm}$.

Due to the different data rates in the barrel and in the end-caps, two different detectors are used for triggering, both having fast response: Resistive Plate Chambers (RPCs) in the barrel ($|\eta| < 1.05$) and Thin Gap Chambers (TGCs) in the end-caps ($1.05 < |\eta| < 2.7$). The basic element of the RPC is two parallel resistive plates separated by a 2 mm gap filled with a gas mixture. The designed spatial resolution (ϕ) of RPCs is 1 cm and the time resolution is 1.5 ns. The TGCs are multi-wire proportional chambers. They are designed similarly to the CSCs but the anode wire pitch is larger than the distance between the cathode and anode. The TGCs provide a spatial resolution of 2-7 mm and a time resolution of 4 ns.

3.2.6 Trigger

The LHC produces extremely high rates of interactions. Bunches of about 10^{11} protons cross each other at 40 MHz. However, the events interesting to physics analyses occur quite rarely. The aim of the ATLAS Trigger and Data Acquisition (TDAQ) systems is to reduce in real time the amount of data, keeping only potentially interesting collisions for permanent storage and further analysis.

Each filtering stage considers the decision made by the previous trigger and passes on a smaller amount of data. After all the levels the data rate is reduced to a manageable level. The ATLAS detector uses a two-

stage trigger system: a hardware level 1 (L1) and a software-based high level trigger (HLT). The first level trigger analyzes all the events and reduces the initial 40 MHz rate to less than 75 kHz in Run I and 100 kHz in Run II. The L1 decision is made extremely quickly, in $2.5 \mu\text{s}$. To achieve this rate, the L1 reconstruction and selection algorithms are implemented directly in the hardware. Coarse information from the calorimeters and muon chambers is available to the L1 trigger. In Run I the L1 trigger included three components: the muon trigger, the calorimeter trigger and the central trigger processor (CTP). In Run II additionally new L1 topological trigger modules have been introduced. The calorimeter trigger uses digitized signals from the calorimeters to identify various types of high- E_T objects. The muon trigger uses track information from the fast muon chambers, the RPCs and TGCs (see Section 3.2.5), to identify high- p_T muon candidates. The CTP generates the final decision whether the event will be accepted or not, based on the L1 trigger “menu”, which represents the logical combination of the L1 calorimeter and muon triggers. The new L1 topological trigger modules calculate event topological quantities between L1 objects and allow the CTP to perform L1 selections based on these quantities. The L1 trigger determine regions of interest (RoIs) that are analyzed further by the HLT.

The HLT runs on computer farms and is based on optimized software algorithms. In Run I the HLT consisted of a level 2 (L2) and an event filter (EF), and in Run II these two parts got merged into a single event-filter farm. The data reconstruction algorithms used at L2 had an average event processing time of 40 ms. The L2 trigger had an access to the detailed detector information with the full granularity, but only within the RoIs. The output rate of the L2 trigger system was 2-5 kHz. The final selection in Run I was done by the EF. It used all high-precision detector information and reduced the event rate to a few hundreds Hz. The EF considered fully built events and thus was based on data reconstruction algorithms that are very similar to those used offline in physics analyses. After the EF the events had an average size of 1.6 MB and were saved in data storage for use in physics analyses. In Run II the HLT reduces the event rate to approximately 1 kHz on average within a processing time of about 200 ms, providing an average event size of 2 MB.

4 Experimental techniques

“No guarantees are therefore given for the proper functioning of the program, nor for the validity of physics results. In the end, it is always up to you to decide for yourself whether to trust a given result or not.”

PYTHIA 6.4 physics and manual [54]

4.1 Production of simulated samples

Most of the physics analyses in ATLAS utilize Monte Carlo (MC) simulated samples of events produced at the LHC. They are used in studies of the detector response, for development of various algorithms, for modelling of the physics processes to compare theoretical predictions with experimental data and for other purposes.

The production of MC samples is done in two main steps, which are further subdivided into smaller tasks. The first step is performed by an event generator, that generates the physics process as follows. Each proton is characterized by a parton distribution function (PDF), that defines its partonic substructure. When two protons collide, one incoming parton from each of the two protons enters the hard process, where a number of outgoing partons is produced. As the main characteristics of the event are determined by the hard process, its matrix element is computed. In ATLAS it is usually done at leading or next-to-leading order (LO, NLO) in the strong coupling constant. The initial partons from each proton as well as the outgoing partons can emit a virtual gluon, which can itself initiate a parton shower. This initial-state and final-state radiation is modelled in the generator and then matched to the hard process modelling. The partons in each of the protons, that don't take part in the hard process, can interact semi-hard, leading to “multiple parton-parton interactions” or can form color-connected remnants, that scatter off each other. Next, the outgoing partons form color neutral hadrons due to the

QCD confinement. The hadronization process also has to be modelled, as well as subsequent decays of the produced hadrons.

The output of the event generation is a set of stable final state particles, called *truth particles*. They are stable in the sense that their lifetimes are longer than 10 ps, so that they can be detected before they decay. The four-vectors of the generated particles and their full parent-daughter relations are saved in so-called *Truth records*, and the MC samples containing the Truth records will be referred to as *Truth samples* in the following. These samples can already be used in various studies at generator level.

Many different event generators are used in ATLAS. Some of them, such as SHERPA [55], PYTHIA6 [54], PYTHIA8 [56,57] and HERWIG++ [58], are full or multi-purpose generators, while the others have a specific purpose. The parton level generators, e.g. MADGRAPH5 [59], MADGRAPH5_AMC@NLO [60] and POWHEG BOX [61], require an interface to a full generator to perform the parton shower and the fragmentation. A variety of PDF sets are used to model the partonic substructure of the colliding protons, e.g. CTEQ6L1 [62], NNPDF3.0LO [63] and CT10 [64].

The second step of the MC sample production is to propagate the generated particles through a simulation of the ATLAS detector, based on the Geant4 toolkit [65], to simulate and record the detector response. These records consist of the hits and energy deposits that the particles leave when traversing the detector. The simulated quantities are digitized and converted to the same format as the experimental data produced by the detector. The accurate modelling of the complex detector geometry and physics descriptions in Geant4 requires large computing resources. Many fast simulation programs are developed in ATLAS for different use-cases, when the level of detail contained in the full simulation is not required. AtlasFast II [66] is a fast simulation in which the calorimeter simulation by Geant4 is replaced by a set of parametrizations. At this point both the experimental data from the detector and the simulated data are reconstructed using the same algorithms [67]. The MC samples containing records of reconstructed events will be referred to as *Reco samples*.

4.2 Object reconstruction

The ATLAS detector records electrical signals created by particles stemming from the pp collisions as they travel through the detector volume. From these signals, by processing quantities such as measured times and voltages, physical objects are reconstructed to further be used in physics

analyses. The conversion of the basic signals recorded by the detector into physical objects is called object reconstruction. The reconstruction is performed by algorithms which have been developed and tested on simulated samples or early data samples and are constantly being improved. They are optimized taking into account the changing energy and pile-up conditions of the collisions.

4.2.1 Track reconstruction

Efficient reconstruction of tracks and vertices is crucial for many physics analyses. The track reconstruction is especially challenging in conditions with high track densities and event rates at the LHC.

To reconstruct tracks, the trajectories of charged particles need to be identified with high precision. This is done using measurements made by the Inner Detector (ID) and the Muon Spectrometer (MS). Charged particles traversing these detectors leave hits along their path. Track reconstruction algorithms aim to associate the measurements made by the detector sensors with the trajectories of individual particles. Two main strategies for track reconstruction in the ATLAS Inner Detector are used: inside-out and outside-in (or back-tracking). The inside-out sequence consists of the following steps:

- clusterization and space-point formation
- pattern recognition (track seed finding and track candidate building)
- ambiguity solving
- extension to the TRT

The contiguous pixels and strips with hits in a given sensor in the silicon detectors (the Pixel Detector and the SCT) are grouped into clusters [68]. The measurements of the clusters in the Pixel Detector map directly into three-dimensional space-points. The SCT clusters are transformed into space-points, using a combination of the cluster information from the strips on the front and back sides of a module. The distance between the module sides and the angle between the track and the module introduce an uncertainty in the space-point reconstruction. For this reason the space-points are not used anymore after pattern recognition, but information of the silicon pixel and strip hits is used instead.

During pattern recognition very loose track candidates are built. Track seeds are constructed from combinations of space-points in the three pixel layers and the first SCT layer. The seeds are used to define roads which then are extended throughout the SCT. The silicon clusters

in the outer SCT layers within the road window are added to the seed to form track candidates.

Many of the track candidates have shared hits. They can also have holes (if a track crossed an active silicon sensor, but the associated cluster is absent). A track candidate can also be constructed from hits not originating from the same particle, referred to as a fake track. To remove such track candidates an ambiguity solving algorithm is used. First, a track-fitting algorithm is run on the track candidates, resulting in a global parameter, χ^2/ndf . This parameter is not a strict measure to distinguish between a good and a fake track, therefore the track candidates are additionally ranked in their likelihood to describe the real trajectories of particles. A score is assigned to the track candidates based on the number of holes and hits, number of shared clusters, p_T of the track candidate, impact parameters, the fit χ^2 and other quantities. Shared hits are assigned to the track candidates with higher score, while the remaining track candidates are refitted. After several iterations the track candidates with a score below a certain quality cut are rejected.

The selected track candidates are extrapolated outwards to the TRT. After that, they are refitted using information of hits in all three detectors. The extended track is removed if its score is less than the score of the silicon-only track candidate.

Not all the tracks can be found with the inside-out sequence. Tracks from secondary decays or from photon conversions may have no hits in the silicon detectors. They can be reconstructed with the outside-in sequence, where unused track segments in the TRT are extended inwards into the SCT and the Pixel Detector. More details on track reconstruction in ATLAS can be found in Refs. [69, 70].

4.2.2 Vertex reconstruction

A vertex is a production point of a set of particles. Typical classes of vertices in ATLAS are the primary vertices (PV), pile-up vertices and secondary (and higher order) vertices (Figure 4.1). The latter can have various origins, like photon conversions and long-lived particles decay chains [71].

The primary vertex is the point of the primary interaction. It is defined as the vertex with the highest sum of squared transverse momenta of the tracks associated to it, $\sum_{i=1}^N (p_T^i)^2$. Primary vertices are reconstructed using an iterative vertex finding algorithm [72]. A single vertex is built from all the reconstructed tracks passing pre-selection criteria. A global maximum is found in the distribution of the longitudinal

impact parameters z_0 ¹ of all tracks, and is taken as a vertex seed. A χ^2 -based iterative vertex fitting algorithm assigns a weight to each track, representing a measure of its compatibility with the vertex. Tracks incompatible with the initial vertex by more than 7σ are used to create new seeds and assigned to another vertex. The procedure is iteratively repeated until no new vertices can be found or no available tracks are left in the event.

Many physics analyses targeting processes involving hadron decay chains (e.g. b -tagging, Section 5) use the reconstruction of secondary vertices. There are several approaches for a secondary vertex reconstruction in ATLAS, and the main ones are the *inclusive* and the *topological* vertex finders. Both of them start with building all two-track pairs, significantly displaced from the PV. Vertices compatible with originating from a photon conversion or a material interaction are rejected.

The inclusive vertex finder combines the selected two-track vertices into a single inclusive geometrical vertex, using an iterative fitting procedure. Tracks not passing a certain cut on χ^2 (so-called outliers) are removed one-by-one from the fit, and the fit is repeated until the overall vertex χ^2/ndof is below a predefined threshold.

The topological vertex finder relies on the assumption that the primary, secondary and tertiary vertices lie on the same line, and tries to identify the whole decay chain topology. For b -tagging this chain is $\text{PV} \rightarrow b \text{ hadron} \rightarrow c \text{ hadron} \rightarrow X$. All the tracks stem from either the b - or c -hadron decay and thus intersect the b -hadron flight axis, which reduces the degrees of freedom of the fit from 3 to 1. Compatible vertices including the PV are then clustered two-by-two iteratively, until a well defined topology is obtained.

4.2.3 Calorimeter cluster reconstruction

Particles traversing the calorimeters deposit their energy in the calorimeter cells. These cells are grouped using clustering algorithms to form calorimeter clusters.

Two main algorithms for cluster reconstruction are used in ATLAS [73]. The first of them is the *sliding-window* algorithm. It forms calorimeter “towers” by grouping calorimeter cells within fixed-size rectangles in the $\eta - \phi$ space containing the local maximum of the transverse energy. The second is the *topological* algorithm. It reconstructs “topological clusters”, using an iterative procedure to group together neighboring cells

¹The longitudinal impact parameter z_0 of a track is defined as the longitudinal distance of closest approach of the track to the primary vertex. See Section 5.1.2 to compare with the transverse impact parameter d_0 .

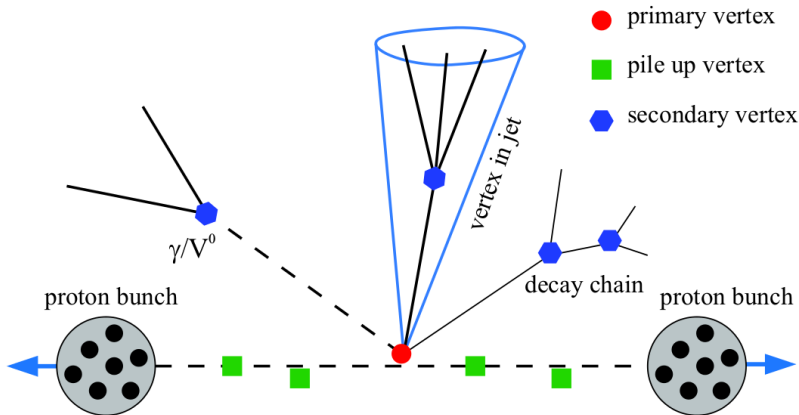


Figure 4.1: Vertex topologies important for physics analyses in ATLAS [71].

that presumably follow the shower development, if the signal in the cells is significant compared to the noise.

Clusters are classified as electromagnetic or hadronic. Since different cells in the calorimeters have different precision, the individual clusters have to be calibrated using their local properties such as calorimeter depth, energy density and isolation with respect to nearby clusters. Various scale corrections are applied to the clusters to make them correspond to the energy of the initial particles, accounting for nuclear binding energy losses in the Hadronic calorimeter, energy losses in dead material, energy leakage, electronic noise and other detector effects. One of the most common calibration techniques accounting for the calorimeter non-compensation (the calorimeter response to hadronic and electromagnetic particles is different) is the local cluster weighting calibration (LCW) [74–76], in which the calibration factors are derived separately for the electromagnetic and hadronic clusters.

4.2.4 Electron and photon reconstruction

Electrons and photons have very similar signatures in the EM calorimeter, therefore they are reconstructed in parallel. Reconstruction in the central region of the ATLAS detector ($|\eta| < 2.47$) starts with finding an EM cluster formed with the sliding-window algorithm around the “seeds” with a total cluster transverse energy above 2.5 GeV. To build an electron candidate, the EM cluster is loosely matched to an ID track originating from a vertex found close to the beam interaction. If the matched track is consistent with originating from a photon conversion and a conversion vertex is reconstructed, then the corresponding candidate is classified as a (single-track or double-track) converted photon.

The candidates without a matched track are considered as unconverted photons. After matching to the tracks, the cluster sizes are optimized taking into account the energy distributions in the different regions of the calorimeter and leakages. The energy of the electron candidates is calibrated to the original electron energy [77].

Since the forward region ($2.5 < |\eta| < 4.9$) is not covered by the ID acceptance, and the electron reconstruction is based only on the information from the EM end-caps and FCAL, it is impossible to distinguish between electrons and photons reconstructed in this region. In this case the clusters are formed with the topological clustering algorithm. More details on electron and photon reconstruction in ATLAS can be found in Refs. [78–81].

4.2.5 Jet reconstruction

A collimated bundle of hadrons, travelling in approximately the same direction, is called a *jet*. A jet can be produced e.g. by the hadronization of a high-energy parton originating from the hard scattering process or a subsequent decay, or from initial or final state radiation.

There are two main classes of jet reconstruction algorithms used in ATLAS: cone algorithms and k_t algorithms. Cone algorithms assume that the jets have conical shape, and clusters which fall into a cone of a certain radius are considered as part of the jet. Such algorithms are easy to implement, but they contain non-physical constants.

In the analyses described in this thesis jets are reconstructed with the anti- k_t algorithm [82] which is an extension of the k_t [83] and Cambridge/Aachen [84] algorithms. The algorithm is applied to entities, such as calorimeter clusters, tracks or truth particles. For example, to reconstruct calorimeter jets, the algorithm is applied to the clusters reconstructed from the energy deposited by hadrons in the calorimeters. First of all, distances d_{ij} between entities i and j and a distance d_{iB} between entity i and the beam (B) are introduced:

$$\begin{aligned} d_{ij} &= \min(k_{Ti}^{2p}, k_{Tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}, \\ d_{iB} &= k_{Ti}^{2p}, \end{aligned} \tag{4.1}$$

where the transverse momentum of particle i is denoted as k_{Ti} , and $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ are the geometrical scales, where y_i and ϕ_i are respectively rapidity² and azimuth angle. R is the radius parameter,

²Rapidity is defined as $y = \frac{1}{2} \ln \frac{E+p_L}{E-p_L}$, where p_L is the longitudinal momentum. If the particle is massless the rapidity coincides with the pseudorapidity.

which is usually put to 0.4. The other parameter p governs the relative power of the energy versus the geometrical scales. If $p = -1$, the procedure described above refers to the anti- k_t jet-clustering algorithm, while $p = 1$ yields the k_t algorithm and $p = 0$ corresponds to the Cambridge/Aachen algorithm. The smallest of the distances is identified, and if it is d_{ij} , the entities i and j are combined, while if it is d_{iB} , the entity i is called a jet and removed from the list of entities. The distances are recalculated, and the procedure repeated until no entities are left.

The jets reconstructed from calorimeter clusters will be referred to as calo-jets in the following. For studies at MC generator level (Section 4.1) “truth jets” are used. To form them the jet-clustering algorithm is applied to stable particles at generator level (excluding μ and ν).

In addition to the calo-jets, track-jets are exploited for many physics purposes. Track-jets are built by applying a jet-clustering algorithm to the reconstructed tracks in the event. Using track-jets is suitable for the identification of b hadrons because b -tagging algorithms (Sections 5.2.3, 5.2.1) only use information from the Inner Detector. Track-jets are explicitly chosen to originate from the PV, which significantly reduces the dependence of the b -tagging algorithms’ performance on pile-up.

Track-jets can be used either independently or in conjunction with the calo-jets, matching them to the latter. The simplest way to do the matching is to choose the closest calo-jet in terms of the angular distance $\Delta R(\text{track-jet}, \text{calo-jet})$, but this method can lead to ambiguities. A more robust matching can be done via the ghost association technique [85, 86]. A four-vector of a so-called “ghost” particle is created from each of the track-jets (or in general other objects that need to be associated) by setting their p_T to an infinitesimally small value and keeping the direction. The ghost particles are then added to the list of input entities for jet finding, and the reconstruction of the calo-jets is rerun. Due to the low p_T of the ghost particles they do not affect the reconstruction result. The kinematic properties and content of the reconstructed calo-jets will remain the same, and the only difference is possible additional ghost particles clustered into the jets or the appearance of jets containing only ghost particles. A track-jet is considered matched to a calo-jet if the ghost particle of the track-jet is clustered as a constituent of the calo-jet.

Association of tracks to jets

The tracks reconstructed in the Inner Detector are associated with the jets in the event based on the distances between the track and the jet axis $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. A cut on ΔR varies as a function of the

jet p_T [87]. The cone is smaller for energetic jets, since they are more collimated than the jets with low p_T . This reduces the number of tracks from fragmentation and pile-up interactions. If a given track satisfies the association criterion with respect to more than one jet, the jet with the smallest ΔR is chosen. Another possible way to associate tracks to jets is the ghost association.

Pile-up jet rejection

In many physics analyses jets originating from pile-up interactions are rejected using a discriminant, the jet vertex fraction (JVF), which measures the probability that a jet originates from a particular vertex. The JVF [47] is the fraction of summed p_T of the tracks matched to the jet and associated with the PV, relative to the total summed p_T of all the tracks matched to the jet. For a jet i the JVF with respect to vertex j in the event is defined as

$$\text{JVF}(\text{jet}_i, \text{vtx}_j) = \frac{\sum_k p_T(\text{trk}_k^{\text{jet}_i}, \text{vtx}_j)}{\sum_n \sum_l p_T(\text{trk}_l^{\text{jet}_i}, \text{vtx}_n)}. \quad (4.2)$$

JVF is bounded by 0 and 1, but jets without associated tracks are assigned a value of $\text{JVF} = -1$. Imposing a lower limit on JVF is very effective in hard-scatter jets identification and pile-up jets rejection, but it has limitations at higher luminosity conditions. A more sophisticated algorithm, called jet vertex tagger (JVT) [88, 89] is designed to address this issue. The JVT is a multivariate combination of two variables constructed to correct the JVF for the dependency on pile-up.

JES and JER

The energy of a reconstructed jet has to be scaled to bring it in agreement with the energy of the original parton. The jet energy scale (JES) [74, 76, 90] is calibrated in several stages using a combination of MC-based methods and *in situ* techniques. MC-based calibrations correct energy and p_T of a reconstructed jet to that of the truth jet. This part of JES is computed taking into account the energy offset caused by pile-up interactions, corrections to the calorimeter jet direction (so that the jet points back to the PV), biases in the jet η reconstruction (e.g. due to changes in calorimeter granularity), fluctuations in the jet composition and its shower shape, energy distribution within a jet and other differences in the jet response. *In situ* techniques are employed to measure the residual difference in jet response in the calorimeter between data and MC simulation. This correction is applied to jets in data only.

Measurement of the jet energy in the detector is performed with a

finite resolution, and energies of the reconstructed jets, that originate from truth particles with the same energy, will approximately follow a Gaussian distribution. The jet energy resolution (JER) [91,92] can be defined as the width of this Gaussian distribution.

4.2.6 Muon reconstruction

Muons are reconstructed based on information from the MS, the ID and the calorimeters. The MS chambers are assembled in “stations”. Muon hits in these stations are fitted in straight lines to produce track segments. The main methods for the identification and reconstruction of muons [68, 93–95], are briefly described below. *Standalone muons* are reconstructed by the Muonboy algorithm, which links segments in the MS to each other to form tracks and extrapolates them back to the interaction point, taking into account energy loss, measured in the calorimeters. *Combined muons* are found by matching the standalone muon tracks to the tracks independently reconstructed in the ID. A statistical method STACO combines the vectors and covariance matrices of the standalone muon tracks and ID tracks to reconstruct full tracks. This strategy improves the track momentum resolutions. *Segment-tagged muons* are built from ID tracks with sufficient momentum, which were not used by the STACO algorithm, by matching them to the track segments reconstructed in the MS. This strategy enables the reconstruction of muons with low momenta, and is implemented in the spectrometer tagging algorithm MuTag. *Calo-tagged muons* are reconstructed from ID tracks if they are matched to energy deposits in the calorimeter compatible with minimum-ionizing particles. This type of muons has the lowest purity, but they recover the acceptance of the MS in the region around $|\eta| \sim 0$. If two muons reconstructed with different algorithms share the same ID tracks, only one of them is kept. The preference is given to combined muons, then to segment-tagged, and finally to calo-tagged muons.

4.2.7 Missing transverse momentum

The presence of particles that escape the detector volume without being detected can be revealed by an energy and momentum imbalance in the plane transverse to the beam axis. The amount of total missing energy can not be determined, because the longitudinal momentum of the partons in the colliding hadrons is a priori not known and because the energy from the hadron remnants can not be measured in the forward region close to the beam axis. However, the total momentum of the initial particles in the plane transverse to the beam axis is always zero, and this constraint can be used to deduce the missing transverse

momentum $\vec{E}_T^{\text{miss}}$. The missing transverse momentum is calculated from the negative vector sum of the transverse momenta matched to the high- p_T reconstructed physics objects (“hard terms”), which include charged leptons, photons and jets, and a “soft term” formed by the signals not associated to any high- p_T physics object:

$$\vec{E}_T^{\text{miss}} = -\sum \vec{p}_T^e - \sum \vec{p}_T^\mu - \sum \vec{p}_T^\tau - \sum \vec{p}_T^\gamma - \sum \vec{p}_T^{\text{jet}} - \sum \vec{p}_T^{\text{soft}}. \quad (4.3)$$

Several algorithms are designed to reconstruct the soft term $\sum \vec{p}_T^{\text{soft}}$ using calorimeter energy deposits, tracks reconstructed in the ID or both [96, 97]. The missing transverse energy E_T^{miss} is defined as the magnitude of $\vec{E}_T^{\text{miss}}$.

In the SM the missing transverse energy, E_T^{miss} , can occur only due to neutrinos, while there are several hypothetical particles in extensions of the SM which can give rise to E_T^{miss} , e.g. Dark Matter particles. It can also arise from mismeasurements. The E_T^{miss} is commonly used in analyses where channels with non-detectable particles are studied. In simulated events the E_T^{miss} is defined as the magnitude of the vector sum of p_T of non-interacting particles computed from the generator information.

4.3 Statistical tools

4.3.1 Template fitting

The template fit method attempts to estimate the contribution of various components to the experimental observable, by fitting the measured distribution of the observable with a set of pre-determined templates.

Assume that there are n types of objects, each characterized by a different distribution $f_i(x)$ ($i = 1, \dots, n$) of the variable x . For instance, we consider jets of $n = 3$ different flavours (b , c and light flavours, see Section 6.1), and distributions $f_i(x)$ look different for the three flavours, e.g. the x can be the probability for a jet that all tracks associated with it originate from the primary vertex. Experimentally it is possible to measure the sum of the n contributions, but the proportions in which the different types of objects contribute to the measured distribution are unknown. To find how many objects of type i are present in the experimental data, the template fit technique can be used. Specifically, in Section 6.4 the template fit is used to extract the fraction of b -flavour jets in a jet sample for which the flavour composition is a priori unknown.

The expected distributions $f_i(x)$ are simulated and used as shape templates. A model is chosen, assuming that the experimentally measured distribution can be described by a linear combination of $f_i(x)$:

$$f^{\text{model}}(x) = c_1 \cdot f_1(x) + c_2 \cdot f_2(x) + \dots c_n \cdot f_n(x) \quad (4.4)$$

$$c_1 + c_1 + \dots + c_n = 1,$$

where coefficients c_i correspond to the fraction of each contribution (fraction of jets of each flavour). To find the coefficients c_i , a least-square fit is performed with the analysis tool Minuit2 [98,99], commonly used in particle physics.

The fit is based on minimization of a χ^2 function:

$$\chi^2(x) = \sum_{k=1}^K \frac{(Y_k - f^{\text{model}}(x))^2}{\sigma_k^2}, \quad (4.5)$$

$$\sigma_k = \sqrt{Y_k}, \quad (4.6)$$

where K is the number of measurements, Y_k are the measured values of the variable x (outcomes of the experiment) and σ_k are the errors.

4.3.2 Hypothesis test

In particle physics experiments hypothesis testing is used when searching for new phenomena that have been predicted by some model but not yet observed. The purpose of hypothesis tests can be to exclude a signal (setting an upper limit on the model parameters) or to establish a discovery. In the discovery formalism a null hypothesis H_0 describing only known processes (the SM background) is defined. It can be either tested alone or against an alternative hypothesis H_1 that includes both the SM background and the possible signal which is being searched for. If the goal of a test is not a discovery but exclusion of a signal model, the hypothesis including both signal and background is denoted as H_0 and is tested against the background-only hypothesis H_1 . To avoid confusion with the notations of H_0 and H_1 in the discovery and exclusion formalisms, we will talk about the “signal-plus-background” hypothesis H_{s+b} and about the “background-only” H_b hypothesis.

To quantify, within observed data, the difference in behavior of the null and the alternative hypotheses, a test statistic q_μ is chosen. Using the known distribution of the test statistic it is possible to quantify the level of agreement of the observed data with a given hypothesis by calculating a p -value [100]. The test statistic q is assumed to follow the distribution $f(q|s+b)$ under the H_{s+b} hypothesis, and $f(q|b)$ under the H_b hypothesis (see Fig. 4.2 a). The value of the variable q observed in data is denoted q_{obs} . The p -value of the H_{s+b} hypothesis is the probability of observing the same or a more extreme test statistic than the one

observed, under the assumption that H_{s+b} is true

$$p_{s+b} = \text{Prob}(q \geq q_{\text{obs}} | H_{s+b}) = \int_{q_{\text{obs}}}^{\infty} f(q|s+b) dq. \quad (4.7)$$

Similarly, the p -value of the background-only hypothesis will be:

$$p_b = \text{Prob}(q \leq q_{\text{obs}} | H_b) = \int_{-\infty}^{q_{\text{obs}}} f(q|b) dq. \quad (4.8)$$

For example, in a discovery test, if the p -value of a H_b hypothesis is less than or equal to a specified threshold α (*significance level*), it indicates an evidence against this hypothesis. If the observed p -value

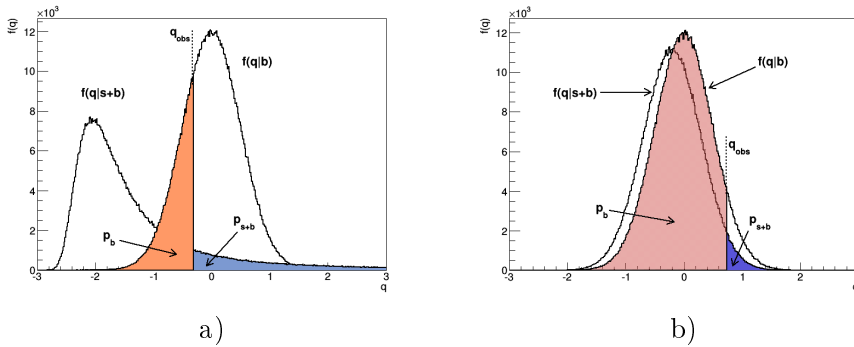


Figure 4.2: Distribution of the test statistic q under the signal-plus-background H_{s+b} and background-only H_b hypotheses; a) general case b) when the sensitivity to the signal model is very low. The p -values correspond to the shaded areas.

is greater than α , then there is no significant evidence against the H_b hypothesis and it is not rejected.

The p -value is often converted into an equivalent significance, the Z -score. The one-sided Z -score is obtained by finding the point, such that the integral from Z to infinity of a standard Gaussian distribution is equal to p , as shown in Fig. 4.3. For a null hypothesis with a standard Gaussian probability density function the area under the right tail would correspond to the probability to find the same or bigger value of the test statistic than observed under H_b . The Z -score represents the number of standard deviations away from the population mean in a normal distribution. It is given by $Z = \Phi^{-1}(1 - p)$, where the function $\Phi^{-1}(x)$ is the quantile function of the normal distribution. In the particle physics community the convention is to require a significance of at least $Z = 5$ (“five sigma” level), i.e. $p \leq 2.87 \cdot 10^{-7}$,

in order to reject the H_b hypothesis and declare a discovery. If $3 \leq Z < 5$ the data are said to suggest an evidence for a phenomenon. It is also common in many fields of science to set upper limits with $1 - \alpha = 95\%$ *confidence level* using the p -value threshold $p < \alpha = 0.05$ corresponding to $Z = 1.64$. The problem of this approach is that hypotheses with very low sensitivity will be excluded with probability close to α . This happens when the expected number of signal events is much less than the expected number of background events, and the distributions of q under H_{s+b} and H_b almost overlap with each other. This situation is illustrated in Fig. 4.2 b). To prevent rejecting such models, the particle physics community widely uses CL_s (Ref. [101]) as a figure of merit for exclusion, which is defined as

$$\text{CL}_s = \frac{\text{CL}_{s+b}}{\text{CL}_b} = \frac{p_{s+b}}{1 - p_b}. \quad (4.9)$$

In this approach the signal model is rejected if $\text{CL}_s \leq \alpha$. For example, if $\text{CL}_s \leq \alpha = 0.05$, the signal model is regarded as excluded at a confidence level of $1 - \alpha = 95\%$. CL_s is the default figure of merit at the LHC.

4.3.3 Sensitivity estimators

Before performing an analysis, one needs to estimate the experimental sensitivity. The sensitivity serves as a figure of merit when optimizing the analysis, and it is chosen differently depending on the primary aim of the analysis.

If the aim is to exclude the signal model, the sensitivity should characterize the signal acceptance, while the background amount plays a secondary role. Often the CL_s exclusion formalism is used for this purpose. A more easily calculable figure of merit can be defined as follows. Suppose that the total number of events in the region selected by the analysis is

$$N_{\text{tot}} = N_{\text{sig}} + N_{\text{bkg}}, \quad (4.10)$$

where N_{sig} and N_{bkg} are the expected number of signal and background events, and N_{tot} is characterized by a poissonian fluctuation $\sigma_{\text{tot}} = \sqrt{N_{\text{tot}}}$.

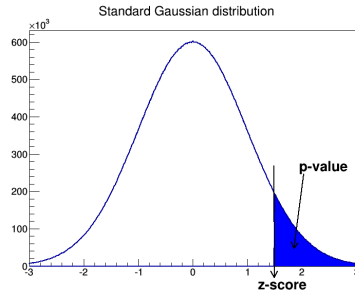


Figure 4.3: The shaded area represents the one-sided p -value of a hypothesis, and its boundary corresponds to the Z -score. The probability density function of the hypothesis follows the normal distribution.

Then the uncertainty on N_{sig} is

$$\sigma_{\text{sig}}^2 = \sigma_{\text{tot}}^2 + \sigma_{\text{bkg}}^2 = N_{\text{tot}} + \sigma_{\text{bkg}}^2, \quad (4.11)$$

where σ_{bkg} stands for an estimate of the total uncertainty on the background prediction (systematic uncertainty and uncertainty from limited MC statistics). The quantity

$$\mathcal{S} = \frac{N_{\text{sig}}}{\sigma_{\text{sig}}} = \frac{N_{\text{sig}}}{\sqrt{N_{\text{tot}} + \sigma_{\text{bkg}}^2}} = \frac{N_{\text{sig}}}{\sqrt{N_{\text{sig}} + N_{\text{bkg}} + \sigma_{\text{bkg}}^2}} \quad (4.12)$$

represents the number of standard deviations away from zero signal, and hence can be a good figure of merit for exclusion. The DM study at $\sqrt{s} = 8$ TeV, presented in Chapter 8, utilizes alternatively this figure of merit and CL_s .

To optimize an analysis for a discovery, the sensitivity is chosen to reflect the signal-to-background ratio. In this case the highest sensitivity is obtained with the largest possible number of signal events and the lowest possible number of background events in the sample. Usage of the discovery p -values is problematic, because to compute values of the order 10^{-7} a large number of pseudoexperiments has to be generated. This process requires significant computing resources, and is therefore very slow [102]. The analysis aiming to make a discovery normally seeks a small signal, $N_{\text{bkg}} \gg N_{\text{sig}}$. Then an approximate form of the estimator 4.12 is valid:

$$\mathcal{S} = \frac{N_{\text{sig}}}{\sqrt{N_{\text{bkg}} + \sigma_{\text{bkg}}^2}}. \quad (4.13)$$

This figure of merit grows rapidly with a decreasing number of background events. One way to avoid selecting a region of parameter space where the background expectation is too small, when optimizing the analysis, is to add one to the expression under the square root:

$$\mathcal{S} = \frac{N_{\text{sig}}}{\sqrt{1 + N_{\text{bkg}} + \sigma_{\text{bkg}}^2}}. \quad (4.14)$$

This metric stems from the ATLAS convention for DM searches, and is used in the DM analysis at $\sqrt{s} = 13$ TeV, presented in Chapter 9. For cross-checks the one sided Z-score and the estimator given by Eq. 4.13 are used.

Part III

b -tagging

5 Identification of b -jets

5.1 Motivation and methodology

The flavour of a jet is defined by the flavour of the heaviest quark initiating it. Jets originating from the hadronization of a b or c quark are called b or c jets, while the jets which originate from hadronization of light quarks (u , d and s) or gluons are called light jets. Identifying b jets and distinguishing them from light jets is the goal of *b -tagging*, which is widely used in the ATLAS experiment at the LHC.

5.1.1 Applications of b -tagging

In many physics analyses where signal events have one or more b jets in the final state b -tagging plays an important role. It is a necessary tool for precision measurements in the top quark sector, since the SM dominant mode of the top quark decay is to a b quark and a W boson. Another area where b -tagging is essential is the studies of the Higgs boson, since the dominant decay of the Higgs boson in the SM is to a $b\bar{b}$ pair. In addition to selecting processes containing b jets, b -tagging is also important for physics analyses that need to reject background events with b jets. For example, the $t\bar{t}$, $t\bar{t}$ +jets and tW backgrounds can be suppressed by vetoing b -tagged jets. And finally it is very useful in searches for physics beyond the SM, since many of these models predict processes which give rise to b jets in the final state.

5.1.2 Properties of b hadrons

The ability to identify b jets relies on the specific properties of b hadrons. Since b hadrons have long life time ($\tau \sim 1.4 \cdot 10^{-12}$ s, $c\tau \sim 470 - 500$ μm), which results in a significant flight length, a b hadron produced in an LHC collision can typically travel a few millimeters in the transverse plane from the PV before decaying. Therefore the tracks from the b hadron decay originate from a displaced secondary vertex. The distance of closest approach in the transverse plane between the PV and the track is called the transverse impact parameter d_0 . Similarly, the longitudinal

impact parameter z_0 is defined as the difference between the z coordinates of the PV and of the track at the point of closest approach in the $r - \phi$ projection. The d_0 of the tracks associated with b jets tend to take on larger values compared to those associated with light jets. A sketch of a jet from a long-lived particle decay is shown in Fig. 5.1.

A b hadron has large mass ($5 - 10 \text{ GeV}/c^2$) and retain most of the original b quark momentum. Therefore the decay products can have large transverse momenta with respect to the jet axis.

The b hadron properties mentioned above can all be used to identify b jets. The identification of b jets can either be done by measuring the impact parameters d_0 of the tracks associated with the b jet, or by explicitly reconstructing the displaced secondary vertex. In both cases, precise measurements of the track parameters are a key ingredient.

A b hadron can also be identified by the presence of a soft lepton coming from a semileptonic decay, for example $B \rightarrow \ell + \nu + X$ and $B \rightarrow D \rightarrow \ell + \nu + X'$, where ℓ is a lepton (e or μ). Because of the large mass of b hadrons the transverse component of the lepton momentum relative to the jet axis direction can be large.

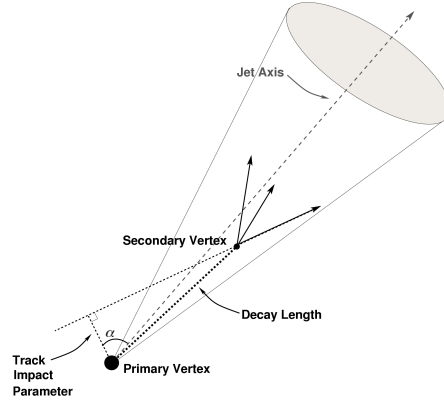


Figure 5.1: A long-lived particle is characterized by a displaced secondary vertex and large transverse impact parameters of the tracks in the jet with respect to the primary vertex [103].

5.1.3 Jet flavour labelling

To define the flavour of a reconstructed jet in MC simulation, the jet direction is compared with the directions of the generated particles in the event. According to the strategy used in Run I the jet is labelled as a b jet, if a generator level b quark with transverse momentum $p_T > 5 \text{ GeV}$ is found in a cone of size $\Delta R = 0.3$ around the jet direction. If there are several jets satisfying this requirement, only the closest jet is considered. If there is no generator level b quark matched to the jet, the procedure is repeated for c quarks and then for τ leptons. If none of these are matched to the jet, it is labelled as a light jet. In this approach the jets originating from gluon splitting ($g \rightarrow b\bar{b}$) will be labelled as b jets. In

Run II the labelling is done using generator level b hadrons instead of b quarks.

5.1.4 High- p_T b -tagging

Identification of b jets with high p_T is a matter of particular interest, since many processes studied or sought for in ATLAS give rise to energetic b jets. At high p_T the flight distance of the decaying b hadrons increases, but at the same time the number of decay products increases, therefore the fraction of tracks originating from the b hadron decay decreases. Moreover, the opening angles of the tracks from the b hadron decay are reduced (since the jets become more collimated), and the number of shared hits in the silicon detectors grows, leading to an increase in the uncertainty of the reconstructed positions of the secondary vertices. The number of fake tracks increases as well. One more difficulty is that the decay of the b hadron can occur beyond the first layer of the ID. All of these effects lead to degradation of the b -tagging performance at high p_T .

5.1.5 Transverse impact parameter significance S_{d_0}

Most of the b -tagging algorithms use as input the signed transverse impact parameter (IP) significance of the tracks associated to a jet. This variable is defined as follows:

$$S_{d_0} = \frac{d_0}{\sigma(d_0)} \cdot s_j, \quad (5.1)$$

where d_0 is the transverse IP of a track, $\sigma(d_0)$ is the uncertainty on the measured d_0 , and s_j is the sign of d_0 with respect to the jet axis. The sign is defined using the jet direction measured by the calorimeters. It is positive if the angle between the jet axis and the line joining the primary vertex and the point of closest approach on the track is smaller than 90° , and negative otherwise. Following this definition, the sign of the d_0 illustrated in Fig. 5.1 is positive, since the angle $\alpha < 90^\circ$.

Tracks originating from b hadron decays tend to have large and positive S_{d_0} values. This fact allows to distinguish them from tracks originating from the PV and therefore discriminate b jets from non- b jets. The distributions of the signed transverse IP significance of the tracks associated to b , c and light jets in MC simulated samples are shown in Fig. 5.2 (left).

The S_{d_0} of the track in the jet with the largest $|S_{d_0}|$ is a powerful variable to discriminate between b jets and non- b jets. This variable will be referred to in the following as $S_{d_0}^{t1}$, and its distribution is illustrated

in Fig. 5.2 (right). The signed transverse IP significance of the second and third highest $|S_{d0}|$ tracks, denoted as S_{d0}^{t2} and S_{d0}^{t3} , have also been considered. Distributions of these variables are shown in Fig. 5.3.

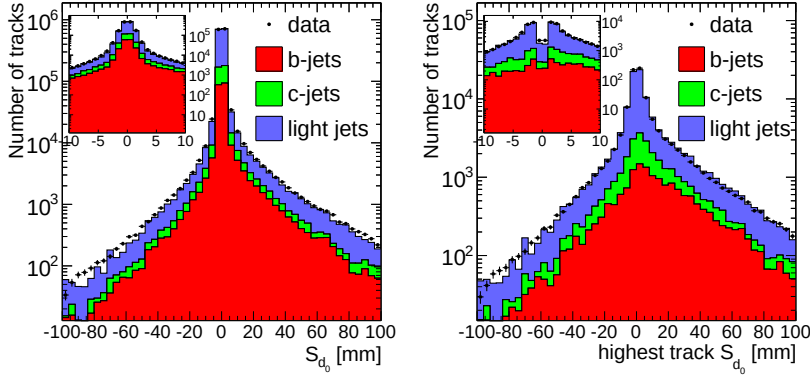


Figure 5.2: Distribution of the signed transverse IP significance, S_{d0} , for all selected tracks (left) and of the highest- $|S_{d0}|$ track (right) associated to b , c and light jets in simulated data (filled histograms) and in experimental data (solid black points). The distributions in simulated data are obtained from the unfiltered multi-jet MC samples (see Section 6.2) after dR selection (see Section 6.3.5).

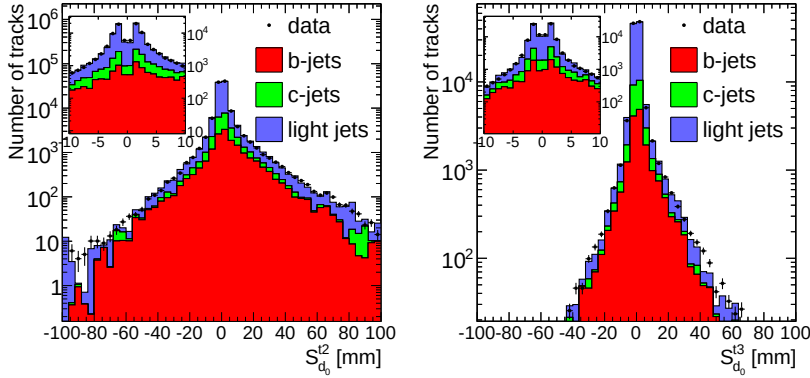


Figure 5.3: Distribution of the second and third highest tracks signed transverse IP significance, S_{d0}^{t2} and S_{d0}^{t3} , in b , c and light jets in simulated data (filled histograms) and in experimental data (solid black points). The distributions in simulated data are obtained from the unfiltered multi-jet MC samples (see Section 6.2) after dR selection (see Section 6.3.5).

5.2 b -tagging algorithms

5.2.1 Overview

Various b -tagging algorithms have been developed and used in ATLAS [68, 87]. The simplest of them rely on either of these three methods:

- measuring the IP significances of the tracks in jets;
- reconstructing secondary vertices (SV);
- identifying soft leptons in jets.

Examples of b -tagging algorithms based on combining the IP significances of all the tracks in the jet are IP1D, IP2D, IP3D and JetProb (discussed in detail in Sec. 5.2.2). IP1D relies on the longitudinal IP, while IP2D and JetProb rely on the transverse IP. IP3D is a more sophisticated algorithm, which utilizes two-dimensional histograms of the longitudinal versus the transverse IPs, taking advantage of their correlations.

The SV0, SV1, SV2 and JetFitter algorithms are the b -tagging algorithms based on the explicit reconstruction of displaced vertices (Section 4.2.2). The SV0 algorithm makes use of the significance of the reconstructed flight distance (see Fig. 5.1), while the SV1 and SV2 algorithms also exploit the properties of the reconstructed secondary vertex: the invariant mass of all tracks associated to the SV; the ratio of the sum of the energies of the tracks associated to the SV over the sum of the energies of all tracks in the jet; the number of two-track vertices. The SV1 algorithm exploits a 2D-distribution of the two first variables and a 1D-distribution of the third. The SV2 algorithm relies on a 3D-histogram of all three variables.

JetFitter is a more refined b -tagging algorithm, based on the topological structure of weak b -hadron and c -hadron decays inside the jet. It aims to reconstruct the whole decay chain assuming that the PV and the decay vertices of the hadrons containing b and c quarks lie approximately on the same line.

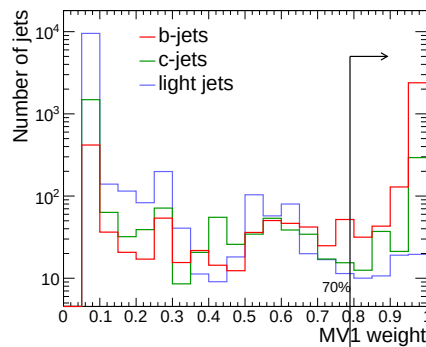


Figure 5.4: The MV1 b -tagging algorithm weight for the dR selection (see Section 6.3.5) derived from the unfiltered simulated samples. The black vertical line shows the 70 % working point.

To further enhance the tagging performance, more advanced, multivariate b -tagging algorithms have been designed. They are based on Artificial Neural Networks (ANN), using the information from the b -tagging algorithms described above as input. The combined algorithms are trained with b jets as signal and a combination of light jets and c jets as background. Among such algorithms there are JetFitterCombNN (based on IP3D and JetFitter) and MV1 (based on IP3D, JetFitter and SV1). The MV1 was the most commonly used flavour tagging algorithm in ATLAS during Run I. The MV1 weight is shown in Fig. 5.4.

5.2.2 The JetProb algorithm

JetProb is an implementation of the tagging algorithm [104] used extensively in ALEPH (LEP)¹ and later at the Tevatron². This algorithm is simple and robust with respect to statistical fluctuations, and it is based on the signed transverse IP significance S_{d_0} of the tracks in a jet. This algorithm was used for b -tagging analyses at the beginning of Run I. JetProb has poorer performance than other more sophisticated algorithms but is well suited to be used as a calibration algorithm, because of its simplicity. An advantage of JetProb as a calibration algorithm is the possibility to derive the expected shape of the discriminating variable distribution from an auxiliary data sample. For most other algorithms this can only be derived from MC simulated events, which introduces additional sources of systematic uncertainty.

JetProb defines the probability that a jet is a light jet as the probability that each of the selected tracks associated to the jet originates from the primary vertex. To measure the probability that track i originates from the primary vertex, the signed IP significance S_{d_0} of each selected track associated to a jet is compared to a resolution function $\mathcal{R}$ [105]:

$$\mathcal{P}_{\text{trk}_i} = \int_{-\infty}^{-|S_{d_0}^i|} \mathcal{R}(x) dx \quad (5.2)$$

The individual probabilities of each of the N tracks associated to the jet are then combined to obtain a jet probability, $\mathcal{P}_{\text{jet}}$, which discriminates

¹The large electron-positron collider (LEP) at CERN was shut down in 2001, and its tunnel is now used to house the LHC. ALEPH was a particle physics experiment installed at LEP.

²Tevatron was a proton-antiproton collider at the Fermi National Accelerator Laboratory (Fermilab), and was shut down in 2011.

between b jets and light jets:

$$\mathcal{P}_{\text{jet}} = \mathcal{P}_0 \sum_{j=0}^{N-1} \frac{(-\ln \mathcal{P}_0)^j}{j!}, \quad (5.3)$$

where

$$\mathcal{P}_0 = \prod_{i=1}^N \mathcal{P}_{\text{trk}_i}. \quad (5.4)$$

The jet probability $\mathcal{P}_{\text{jet}}$ is simply the product, $\mathcal{P}_0$, of all the individual track probabilities, multiplied by a normalization factor depending on the track multiplicity. For light jets, the distribution of $\mathcal{P}_{\text{jet}}$ is expected to be flat, while it should peak close to zero for b jets. The distribution of the probability $\mathcal{P}_{\text{trk}}$ for tracks associated to jets is shown in Fig. 5.5, while the $\mathcal{P}_{\text{jet}}$ distribution is presented in Fig. 5.6. For further applications the JetProb weight is transformed to $-\log_{10}(\mathcal{P}_{\text{jet}})$, which has high values for b jets. The $-\log_{10}(\mathcal{P}_{\text{jet}})$ distributions for b , c and light jets are shown in Fig. 5.7.

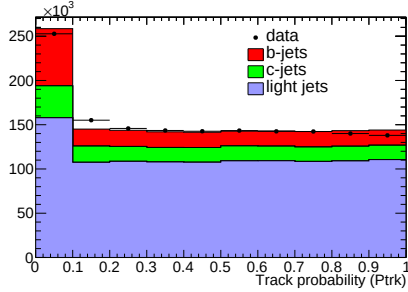


Figure 5.5: Distribution of the probability $\mathcal{P}_{\text{trk}}$ for a track in a jet to originate from the primary vertex in experimental data (solid black points) and in simulated data (filled histograms).

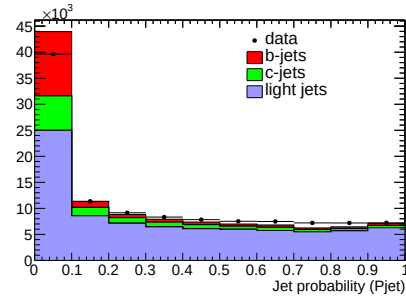


Figure 5.6: Distribution of the probability $\mathcal{P}_{\text{jet}}$ for a jet to be compatible with a light jet in experimental data (solid black points) and in simulated data (filled histograms).

The resolution function $\mathcal{R}$ is $\mathcal{P}_{\text{jet}}$ built in the following way. The negative part of the distribution of the IP significance S_{d_0} of all selected jets (b , c and light) is symmetrized around zero. To make the method more robust against statistical fluctuations and to avoid a dependence on the binning, this distribution is fitted with a functional form corresponding to the sum of two Gaussian cores and two exponentials to describe the tails:

$$\mathcal{R}(x) = p_0 e^{-x^2/2p_1^2} + p_2 e^{-x^2/2p_3^2} + e^{-p_4 - p_5|x|} + e^{-p_6 - p_7|x|}. \quad (5.5)$$

The resolution function can be derived either on jets in data or MC, and have the same functional form but different parameters. The resulting distributions fitted with the modified Gaussian form are illustrated in Fig. 5.8.

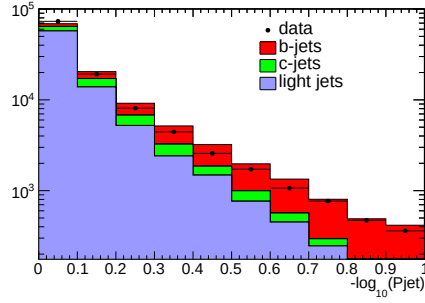


Figure 5.7: The distribution of $-\log_{10}(\mathcal{P}_{\text{jet}})$ for experimental data (solid black points) and for simulated data (filled histograms).

5.2.3 Performance of the tagging algorithms

In ATLAS b -tagging is done via algorithms that analyze a jet and derive a weight for the probability that the jet is originating from a b quark. All the jets with weights exceeding a certain weight cut are considered b -tagged. This cut value has to be chosen to achieve the best performance of the used algorithm (schematically illustrated in Fig. 5.9). When imposing the weight cut, some light jets will mistakenly be b -tagged, while some b jets will not be b -tagged. The performance of the b -tagging algorithms is characterized by the fraction of b jets which are b -tagged, referred to as b -tagging efficiency, ϵ_b :

$$\epsilon_b = \frac{\#b\text{-tagged jets}}{\#b \text{ jets}}, \quad (5.6)$$

as well as the light-jet tagging efficiency ϵ_{light} , often referred to as the mistag rate:

$$\epsilon_{\text{light}} = \frac{\# \text{ tagged light-jets}}{\# \text{ light jets}}. \quad (5.7)$$

Often the light-jet rejection, defined as $1/\epsilon_{\text{light}}$, is used instead of the mistag rate. The light-jet rejection is illustrated in Fig. 5.10 as a function of the b -tagging efficiency for several b -tagging algorithms described in Section 5.2.1. The higher the light-jet rejection for a given value of the b -tagging efficiency is, the better the algorithm performs. For each b -tagging algorithm a set of operating (working) points is defined based on the average b -tagging efficiency as measured in simulated $t\bar{t}$ events (e.g. $\epsilon_b = 60, 70, 80\%$).

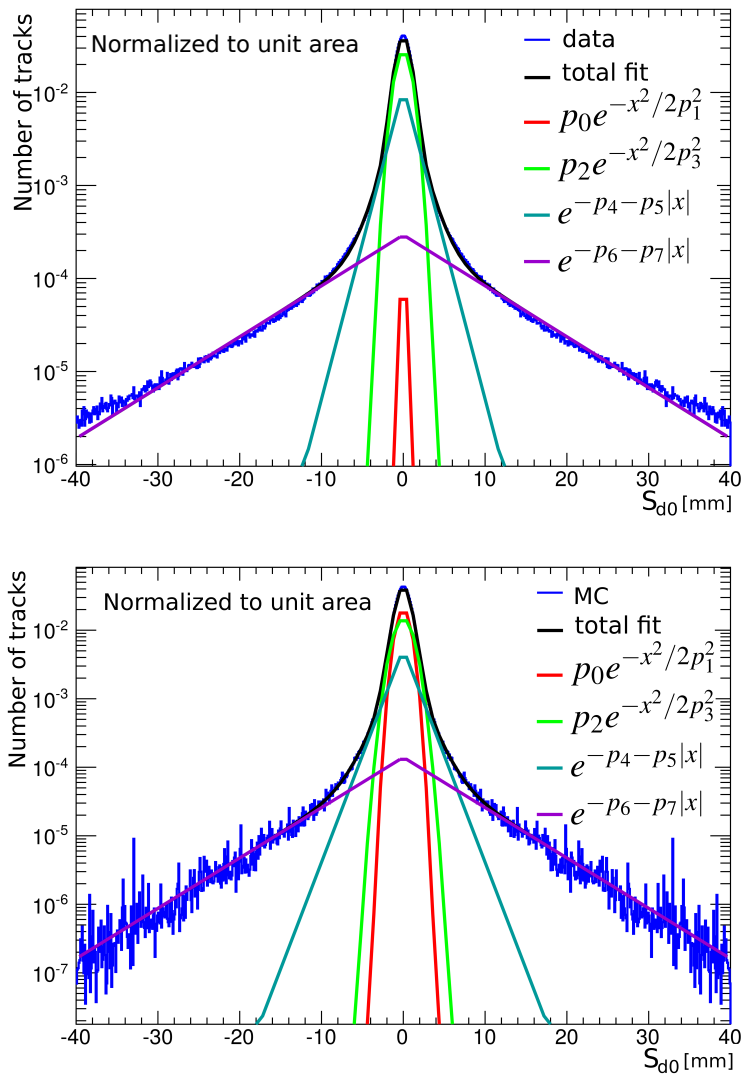


Figure 5.8: Distribution of the transverse IP significance S_{d_0} for tracks with negative d_0 in experimental data (top) and in the MC simulated data (bottom), symmetrized around $S_{d_0} = 0$ and fitted with the functional form.

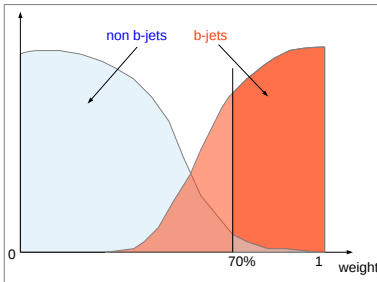


Figure 5.9: A schematic plot to illustrate choice of b -tagging weight cut.

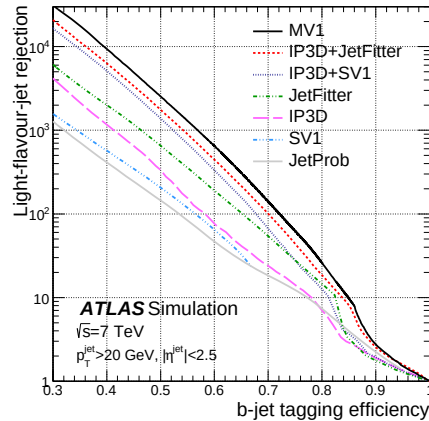


Figure 5.10: Light-jet rejection as a function of the b -tagging efficiency for various b -tagging algorithms, in simulated $t\bar{t}$ events [87].

5.3 ATLAS b -tagging software

5.3.1 Data formats

The ATLAS detector produces about 10 PB of data per year. ATLAS computing operates a data storage and maintains the infrastructure for utilizing this vast amount of information [107]. The offline software is developed to process the data, deliver it to the physicists and equip them with tools to produce physics results.

To enable access to the data for physics analysis purposes, the data goes through several stages (Fig. 5.11). Events arriving from the final stage of the High Level Trigger (Event Filter, see Section 3.2.6 for details) are saved in the RAW format and have a size of 1.6 MB per event. There is a range of data types, Simulated Event Data (SIM), in which the simulated events at different stages of the MC production (see Section 4.1) are stored. The simulated events are about 2 MB in size. The RAW/SIM data are used for reconstruction of physical objects. The output of the

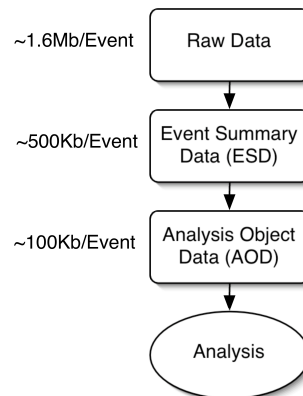


Figure 5.11: The layers of the ATLAS computing model [106].

reconstruction is saved in the format Event Summary Data (ESD). It contains tracks, calorimeter clusters and other combined reconstructed objects (Section 4.2). This information is sufficient to allow particle identification, jet calibration, tuning of reconstruction algorithms, detector studies etc. The average size for the ESDs is 500 kB per event. The ESD events give access to detailed information which is not necessary for most physics applications, and their size is too large for frequent reads. The primary format used for physics analyses is the Analysis Object Data (AOD). It is derived from the ESDs and contains physics objects: electrons, muons, jets, E_T^{miss} etc. The average size for the AODs is 100 kB per event. To further reduce the data size and to increase the reading speed, the data are customized for different physics applications. A reduced version of the full AOD/ESD datasets is Derived Physics Data (D3PD). In the D3PD only events and objects interesting for the specific types of studies are kept. The average size of a D3PD event is 10 kB. A new data format, named xAOD, was introduced during the long shutdown to be used in Run II. It combines the functionality of the AOD and the D3PD, comprising a manageable data size and the possibility to access the information that is currently stored in AODs.

5.3.2 Update of the b -tagging software

The ATLAS software is implemented in the Athena framework [108,109]. It is an object-oriented control framework designed with a modular component architecture. All stages of data processing, including the High Level Trigger, event simulation, reconstruction and many analyses, are realized within the Athena framework. Athena comprises core packages, a complex set of various tools and distributed services. The core part of Athena is written in C++, while the configuration part is written in Python, and some modules are Java-based.

To perform b -tagging in ATLAS a dedicated software is developed. The b -tagging is done during the reconstruction, and its results are saved in the AODs. For a particular set of analyses it might be necessary to redo the b -tagging after reconstruction using different jet collections³ and an improved or different b -tagging algorithm (Section 5.2.1). In this case the output of the b -tagging is stored in D3PDs. During the long LHC shutdown in 2013-2014 the ATLAS software was refined and improved. The b -tagging software needed an upgrade as well. The motivation of the project described in this section is to develop a more flexible config-

³A jet collection is a set of jets reconstructed with a particular algorithm. Reconstructed tracks and particles are also organized in collections depending on the algorithm used to reconstruct them.

uration interface to the b -tagging reconstruction software.

The main module performing b -tagging is BTagTool. It can either be called from JetBTaggerTool to perform b -tagging during reconstruction, or from BJetBuilder if b -tagging is done after reconstruction. Before the upgrade the code performing the association of tracks to jets (see Section 4.2.5), flavour labelling of the jets (Section 5.1.3) and secondary vertex reconstruction (Section 4.2.2) was included in the BTagTool. Therefore these three parts could not be run separately, instead they always had to be executed sequentially when running the entire b -tagging code. The structure of the code is shown in Fig. 5.12 a.

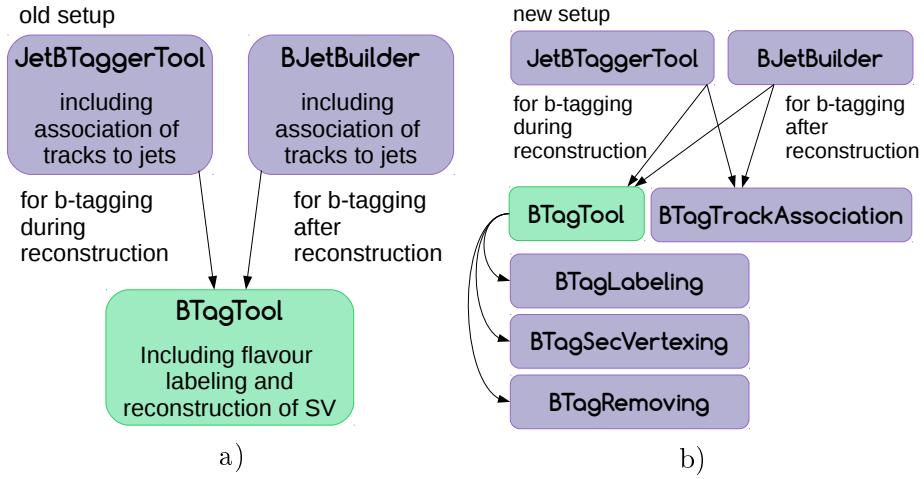


Figure 5.12: Block diagram representing the b -tagging software before (a) and after (b) the improvement. Track association, flavour labelling and secondary vertex reconstruction are decoupled from the main code and put into three separate tools. The final overall removal is also moved to a new tool.

To make the code more modular and flexible the three parts were extracted and moved to separate tools. The flavor labelling and secondary vertex reconstruction are done in the **BTagLabeling** and **BTagSecVertexing** tools that can either be called standalone or from the main **BTagTool**. Track association is done in the **BTagTrackAssociation** tool, that can be called standalone or from either **JetBTaggerTool** (for b -tagging during reconstruction) or **BJetBuilder** (for b -tagging after reconstruction). The latter two tools call **BTagTool**, and therefore all the three parts are executed. The structure of the code after the modifications is shown in Fig. 5.12 b. This separation allows the user to perform track association, flavour labelling or secondary vertex reconstruction on demand without executing the entire b -tagging code.

In the upgraded setup several **BTagTool** instances can run, each with

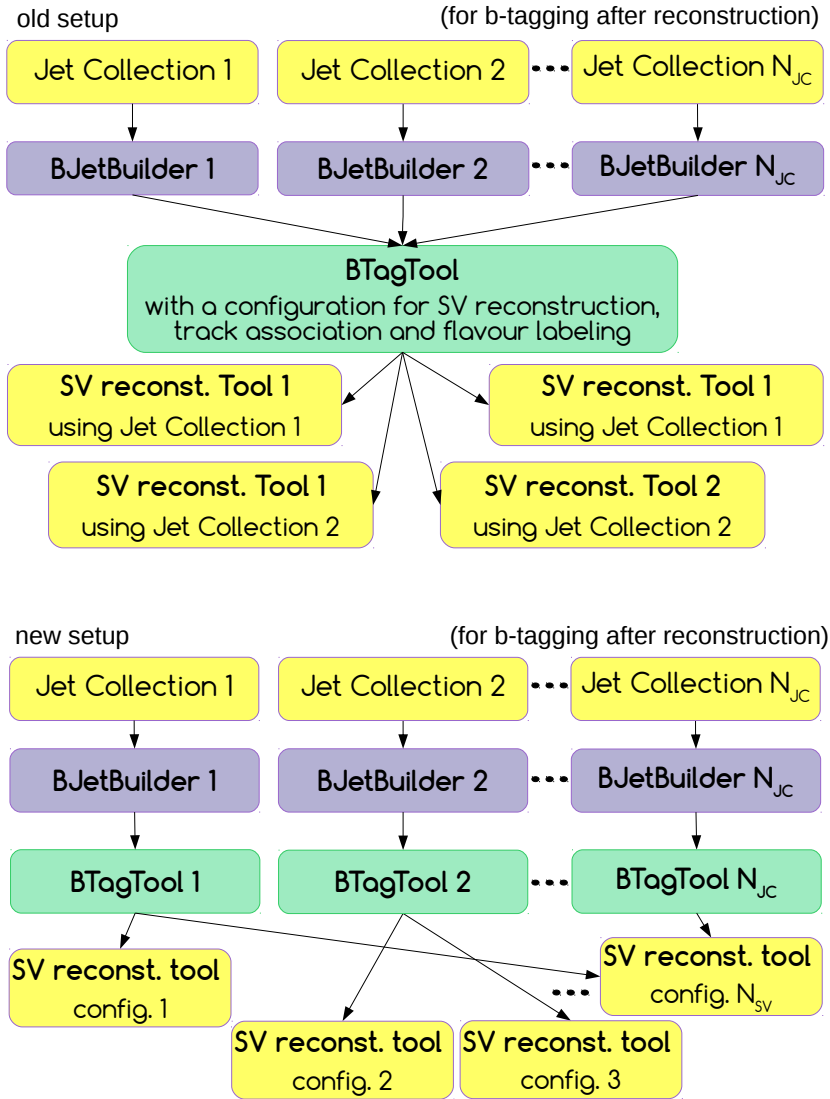


Figure 5.13: Architecture of the b -tagging code in the old setup (top) and after allowing for a customized list of b -tagging algorithms to run on each jet collection (bottom). In this example, b -tagging is done after reconstruction. In case b -tagging is performed during reconstruction, JetBTaggerTool is called instead of BJetBuilder. In the old setup there is only one instance of BTagTool for all the jet collections, therefore all instances of e.g. the SV reconstruction tool have identical configurations. In the new setup the different instances of the SV reconstruction tool run on different jet collections and each has its own configuration.

an arbitrary choice of flavour labelling, SV reconstruction and track association tools. This design also makes it possible to run several instances of a tool with different configurations. For example, one instance of the track association tool can use tracks in a narrow cone in ΔR around the jet axis, while another instance can use tracks in a wider cone. As jets can also be b -tagged based on the presence of soft leptons in the jet, electrons, photons and muons also have to be associated to jets. Previously the BTagTool could only handle one instance of the association tool per particle type. In the updated software there is a vector of the tool instances for each particle type.

More flexibility was added to the code by implementing the possibility for a tool to use multiple collections of jets, tracks and particles. In other words, one instance of the SV reconstruction tool can be run on one jet collection and another instance on another jet collection. A list of collections was added to the BTagLabeling, the BTagSecVertexing and the BTagTrackAssociation tools. For each BTagTrackAssociation tool associating electrons, muons, photons or tracks to jets a list of collections of the corresponding particles or tracks was added. An example for the SV reconstruction tool is illustrated in Fig 5.13.

The part of the code responsible for the final removal of the objects present after SV reconstruction and track and particle association, that are not to be stored permanently, was moved to a new removal class. This class is called at the end of the BTagTool, after track association and SV reconstruction are done. It contains a list of SVs and a list of tracks to remove.

The updated code was included in release 19.0.1 of the ATLAS b -tagging software, which was used at the restart of LHC for Run II data-taking.

6 Calibration of the b -tagging efficiency for high p_T jets

6.1 Introduction

Monte Carlo simulation is a powerful instrument for comparing experimental data with theoretical predictions, but it can not perfectly reproduce the data. As a consequence, the performance of b -tagging algorithms needs to be calibrated in data. The calibration results are presented in the form of data-to-simulation efficiency scale factors:

$$\kappa_b^{\text{data/sim}}(p_T) \equiv \epsilon_b^{\text{data}}(p_T)/\epsilon_b^{\text{sim}}(p_T), \quad (6.1)$$

where ϵ_b^{data} and ϵ_b^{sim} are the b -tagging efficiencies measured in data and simulation, respectively (see equation 5.6). These p_T -dependent scale factors are later on used in physics analyses as weights per jet, applied to MC simulation, in order to correct the b -tagging efficiency to the values measured in data.

This chapter describes an analysis which aims to calibrate the b -tagging performance in high- p_T jets. The method has been applied to the combined MV1 b -tagging algorithm, which was widely used in ATLAS Run I physics analyses (Section 5.2.1). Both calo-jets and track-jets are calibrated (see Section 4.2.5 for definitions). The 70% b -tagging efficiency operating point of the MV1 algorithm is calibrated, which corresponds to the following cut values on the MV1 weight: $\text{MV1} > 0.7892$ for calo-jets and $\text{MV1} > 0.8644$ for track-jets. The event samples before and after applying the cut on the MV1 weight will be referred to as pretag and posttag samples respectively.

The discriminating variables used by the b -tagging algorithms, and thus the b -tagging efficiency itself, usually depend on jet p_T . Therefore the calibration is generally performed in jet p_T bins. The calibration techniques currently exploited in ATLAS only reach jet p_T of approximately 300 GeV [87]. The new technique [105] presented in this chapter

is based on template fits and allows to calibrate the efficiency of the *b*-tagging algorithm up to 1200 GeV. The calibration is performed with multi-jet events, as this process provides significantly improved statistics in the high- p_T region compared to $t\bar{t}$ events which are commonly used to calibrate the *b*-tagging efficiency at lower jet p_T [87].

6.2 Data and simulated samples

The calibration analysis is based on pp collision data collected at a centre-of-mass energy $\sqrt{s} = 8$ TeV by the ATLAS detector during 2012, in Run I of the LHC. The data sample corresponds to an integrated luminosity of 20.1 fb⁻¹.

The calibration analysis makes use of the Monte Carlo simulated samples of multi-jet events listed in Table 6.1. The MC events are generated using PYTHIA8 with the next-to-leading order PDF set CT10. To enhance the statistics of high- p_T jets, the MC samples were simulated in slices of jet p_T . The slices are called JZXW¹, where X refers to the number of the slice. To reproduce the kinematic distributions in data, the contribution of each JZXW sample is normalized to the corresponding leading order cross section. There are two kinds of multi-jet event MC samples used for the main analysis. In the first of them at least one muon with $p_T > 3$ GeV and $|\eta| < 2.8$ is required to be present at generator level. This is done to enhance the heavy-flavor fraction, since *b* hadrons can decay semileptonically. These samples will be referred to as “muon-filtered” samples. The second set of samples has no such requirements applied and will be referred to as “unfiltered” samples.

To estimate the impact of the parton shower and hadronization modelling, a third kind of multi-jet samples is used. These samples are generated with HERWIG++ with the CTEQ6L1 PDF set, with no muon filter applied. Details about these samples are given in Table 6.2.

6.3 Event and object selection

6.3.1 Pre-selection

Only data events satisfying ATLAS quality requirements are used for the analysis. These criteria ensure that the data events were collected in luminosity blocks corresponding to stable beam periods, in which magnets and all the subdetectors were fully operational, and the level of noise was acceptable. Events are selected by the following cuts:

- Good PV: the selected PV has at least 3 reconstructed tracks.

¹The letter “W” in the names JZXW stands for “weighted”.

	Dataset name	jet p_T [GeV]	σ [nb] $\times \varepsilon_{\text{filter}}$	Number of events
Muon-filtered	JZ1W	20-80	$1.393 \cdot 10^5$	7.9 M
	JZ2W	80-200	$3.996 \cdot 10^3$	9.9 M
	JZ3W	200-500	$4.055 \cdot 10^1$	3.9 M
	JZ4W	500-1000	$2.705 \cdot 10^{-1}$	1.9 M
	JZ5W	1000-1500	$5.341 \cdot 10^{-3}$	1.9 M
Unfiltered	JZ1W	20-80	$9.4006 \cdot 10^6$	0.5 M
	JZ2W	80-200	$1.0518 \cdot 10^5$	1.5 M
	JZ3W	200-500	$6.6499 \cdot 10^2$	1.5 M
	JZ4W	500-1000	4.5653	1.5 M
	JZ5W	1000-1500	$8.5502 \cdot 10^{-2}$	1.5 M
	JZ6W	1500-2000	$1.9462 \cdot 10^{-3}$	1.5 M
	JZ7W	2000+	$5.9308 \cdot 10^{-4}$	1.5 M

Table 6.1: List of the nominal MC simulated multi-jet samples used for the calibration. The third column states the cross section σ multiplied by the efficiency $\varepsilon_{\text{filter}}$ of a filter, that selects events with jets in the p_T interval specified in the second column.

	Dataset name	jet p_T [GeV]	σ [nb] $\times \varepsilon_{\text{filter}}$	Number of events
Unfiltered	JZ1W	20-80	$5.262 \cdot 10^6$	0.9 M
	JZ2W	80-200	$4.869 \cdot 10^4$	1.0 M
	JZ3W	200-500	$3.092 \cdot 10^2$	1.4 M
	JZ4W	500-1000	2.262	1.4 M
	JZ5W	1000-1500	$4.565 \cdot 10^{-2}$	1.4 M
	JZ6W	1500-2000	$1.150 \cdot 10^{-3}$	1.4 M
	JZ7W	2000+	$3.7 \cdot 10^{-4}$	1.4 M

Table 6.2: List of the MC simulated multi-jet samples used for systematic studies. The third column states the cross section σ multiplied by the efficiency $\varepsilon_{\text{filter}}$ of a filter, that selects events with jets in the p_T interval specified in the second column.

- Event Cleaning: events with noise burst in the LAr calorimeter, corrupted TileCal events and incomplete events (where some detector information is missing from the event) are removed.
- Jet cleaning: jets that are not associated to real energy deposits in the calorimeters are removed. They can arise from various sources, e.g hardware problems, LHC beam conditions, and cosmic-ray showers.
- At least two reconstructed calo-jets are required to be present in the event.

The distribution of the average number of interactions $\langle\mu\rangle$ per bunch crossing (Section 3.1.2) in simulated events is reweighted to match that of the data.

The analysis is performed in 9 calo-jet p_T bins, listed in Table 6.3. The lower bins are aligned with those used by other calibration analyses to allow an easy comparison. The boundaries of the three highest p_T bins are optimized to ensure sufficient statistics in each bin.

The distribution of the transverse momentum of the leading- p_T calo-jet is shown in Fig 6.1. The events are collected using single jet triggers. An event with the leading calo-jet in a certain p_T bin is required to fire the corresponding Event Filter trigger from Table 6.3. The triggers used for the event selection are prescaled², something which is not modelled in the simulation. However, since the analysis is done in jet p_T bins, and only one prescaled trigger is applied in each bin, the data and MC distributions within each p_T bin agree up to a single normalization factor. The p_T spectrum after normalization of the MC simulated samples is shown in Fig. 6.2, and it is in good agreement with the distribution in data.

Trigger	p_T [GeV]
EF_j35_a4tchad	(60, 90]
EF_j55_a4tchad	(90, 145]
EF_j110_a4tchad	(145, 200]
EF_j145_a4tchad	(200, 300]
EF_j220_a4tchad	(300, 400]
EF_j360_a4tchad	(400, 520]
EF_j460_a4tchad	(520, 610]
EF_j460_a4tchad	(610, 800]
EF_j460_a4tchad	(800, 1200]

Table 6.3: List of the single-jet triggers used to select events in each of the 9 leading calo-jet p_T bins.

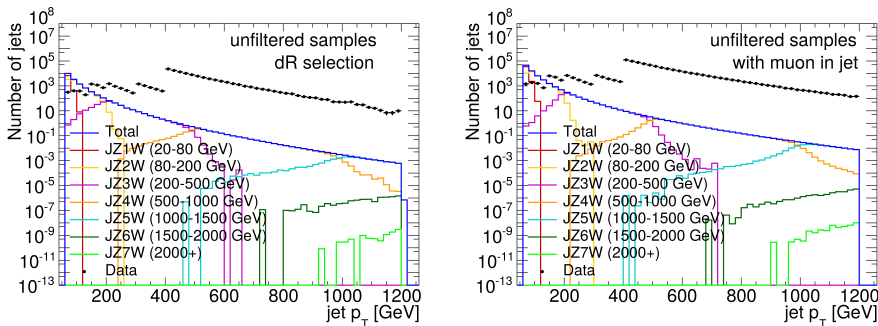


Figure 6.1: The distribution of the transverse momentum of the leading calo-jets after the dR selection (left) or the muon-in-jet selection (right), described in Section 6.3.5, in the experimental data (solid black points) and the unfiltered MC simulated samples (colored histograms: each color represents one simulated p_T slice JZXW).

²If a trigger is prescaled, only a fraction of the events satisfying the criteria for that trigger is recorded.

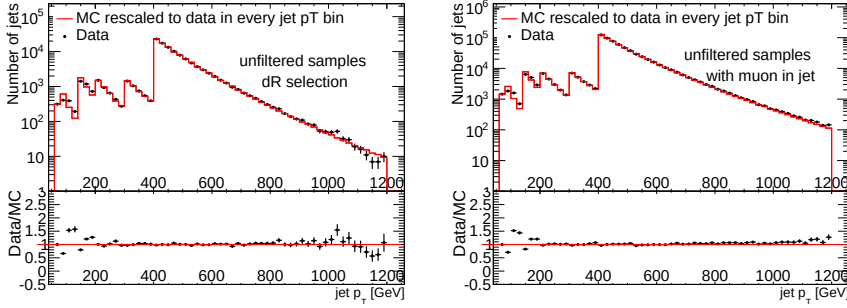


Figure 6.2: The calo-jet p_T distribution in the unfiltered MC simulated samples (red), scaled to that in the data (black) in each jet p_T bin. The distributions are shown for the dR selection (left) and the muon-in-jet selection (right) described in Section 6.3.5. The bottom pads show the ratio between the calo-jet p_T distributions in the data and MC simulated samples.

6.3.2 Jet selection

Jets reconstructed with the anti- k_t algorithm (see Section 4.2.5) with a radius parameter of 0.4 are used for calibration. They are selected according to the following criteria.

Calo-jets

Among all the calo-jets in each event only the leading ones are used for calibration. They are required to have transverse momentum in the window $50 < p_T < 1200$ GeV and to be within $|\eta| < 2.5$ to ensure coverage of the associated tracks by the tracking detector.

Track-jets

Only the track-jet matched to the leading calo-jet is considered. The matching is done using the ghost association procedure. If more than one track-jet is matched to the same calo-jet, the one with highest p_T is selected. Track-jets are required to originate from the vertex with the highest JVF parameter, to have transverse momentum $p_T > 13$ GeV and pseudorapidity $|\eta| < 2.5$. Details on the ghost association and JVF can be found in Sections 4.2.5.

6.3.3 Track selection

Tracks are a crucial ingredient of b -tagging. In order to reject fake tracks and select only well-measured tracks, the tracks associated with the selected calo-jets and track-jets, as described in Section 4.2.5, are required to fulfill the following requirements:

- transverse momentum $p_T > 500$ MeV;
- pseudorapidity $|\eta| < 2.5$;
- at least one hit in the *b*-layer of the Pixel Detector;
- at least two hits in the Pixel Detector;
- a sum of at least seven hits in the Pixel Detector and the SCT.

The distributions of the number of selected tracks in data and tracks associated with *b*, *c* and light jets in the simulated samples are shown in Fig. 6.3. The track multiplicity distributions in data and in the simulated samples do not match perfectly. To account for this discrepancy a systematic uncertainty on the measured *b*-tagging efficiency is estimated as described in Section 6.5.3.

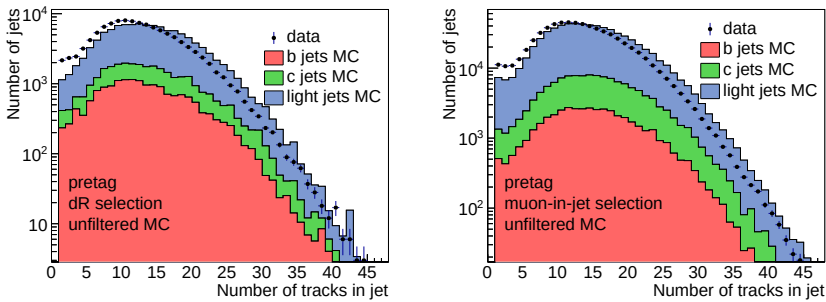


Figure 6.3: The distribution of the number of selected tracks associated with *b*, *c* and light jets in the unfiltered MC simulated samples (filled histograms), and for experimental data (solid black points). The dR selection (left) or the muon-in-jet selection (right), described in Section 6.3.5, is applied.

6.3.4 Muon selection

The muons considered in the muon-in-jet selection (see Section 6.3.5) are reconstructed with the STACO algorithm (see Section 4.2.6) and are required to fulfill the following criteria:

- transverse momentum $p_T > 4$ GeV;
- pseudorapidity $|\eta| < 2.5$;
- at least one hit in the Pixel Detector, a sum of at least four hits, and no more than two holes in the Pixel Detector and the SCT;
- for a muon track in the region of full TRT acceptance ($0.1 < |\eta| < 1.9$) the number of TRT hits must be greater than five;

- small transverse and longitudinal IPs computed with respect to the PV: $|d_0| < 2.0$ mm and $|z_0 \sin \theta| < 2.0$ mm.

6.3.5 Event selections

Events are required to pass one of the following two selections, and the calibration is done with the two sets of selected events separately.

- **Muon-in-jet selection:** The selected jet is required to be spatially matched to a muon ($\Delta R(\text{jet}, \mu) < 0.4$) that passes the selection criteria listed in Section 6.3.4.
- **dR selection:** The selected jet is required to be close to a b -tagged jet, $\Delta R(\text{jet}, b \text{ jet}) < 1.5$, using the MV1 b -tagging algorithm at the 70% efficiency operating point.

The muon-in-jet requirement enhances the fraction of heavy flavour jets in the samples, by exploiting the semileptonic decays of b hadrons. The top four plots in Fig. 6.4 show the fraction of selected b -flavoured calo-jets in the MC simulated samples, containing zero, one or two or more b hadrons. As seen from the two upper plots, a sizable fraction of the jets in the muon-in-jet sample contains two b hadrons, and the fraction increases with jet p_T . Generally such jets originate from gluon splitting to a pair of b quarks that are reconstructed as one merged jet. The dR selection reduces the effect of gluon splitting. The second two plots in Fig. 6.4 show that the fraction of selected calo-jets with only one b hadron inside becomes dominant after applying the dR selection. The fraction of events with b jets from gluon splitting is not expected to be well-modelled by the simulation, and therefore the dR selection is chosen as the main one, while the muon-in-jet selection is used as a cross-check. The expected fractions of b , c and light jets before and after tagging with the MV1 algorithm (pretag and posttag) are shown in the four bottom plots in Fig. 6.4. The sample with the dR selection has better b purity in comparison with the muon-in-jet selection. The total numbers of events satisfying the dR and the muon-in-jet selections are summarized in Table. 6.4.

6.4 Template fit

6.4.1 Strategy

To derive the b -tagging efficiency in data, ϵ_b^{data} , it is necessary to know the number of b jets before and after tagging. They are extracted using the template fit method. In this method a distribution of a discriminating variable in data is fitted with templates of this variable derived in MC.

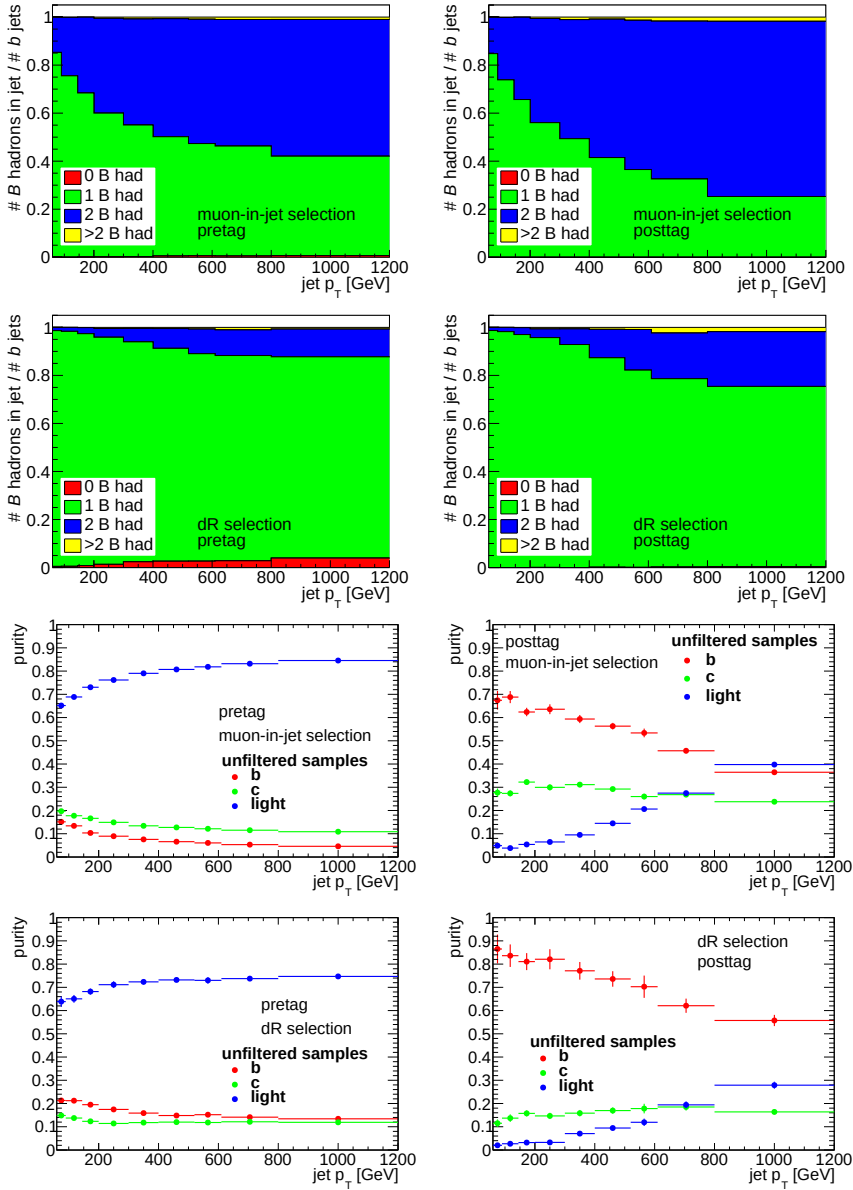


Figure 6.4: Fraction of *b* jets containing 0, 1, 2 or > 2 *b* hadrons as a function of the jet p_T (top) and flavour composition of calo-jets in the unfiltered MC simulated samples (bottom) in the pretag (left) and posttag (right) samples after the muon-in-jet selection (first and third rows) or the dR selection (second and forth rows).

# of events in p_T [GeV]	Muon-filtered samples			
	dR selection		Muon-in-jet selection	
	pretag	posttag	pretag	posttag
60-90	982.594	232.846	13021.840	5327.723
90-145	464.446	116.135	4131.437	1809.633
145-200	83.297	18.897	556.0103	225.033
200-300	28.249	5.259	155.486	55.382
300-400	4.299	0.669	21.449	6.251
400-520	0.927	0.107	4.727	1.123
520-610	0.114	0.009	0.729	0.116
610-800	0.061	0.004	0.400	0.050
800-1200	0.011	0.001	0.084	0.009
	Unfiltered samples			
	dR selection		Muon-in-jet selection	
	pretag	posttag	pretag	posttag
60-90	12092.063	2284.616	55881.167	9630.833
90-145	3480.117	637.667	16175.704	2460.021
145-200	536.803	91.449	2400.735	296.793
200-300	164.771	23.199	756.697	76.535
300-400	23.547	2.687	120.639	9.937
400-520	5.339	0.491	31.252	2.184
520-610	0.987	0.087	6.622	0.412
610-800	0.508	0.041	3.858	0.221
800-1200	0.0941	0.006	0.901	0.048

Table 6.4: Number of selected events in the calo-jet p_T bins in the muon-filtered and unfiltered MC samples after normalizing by the total number of events.

The discriminating variable chosen for this analysis is the highest track transverse IP significance, S_{d0}^{t1} , (Section 5.1.5) signed with respect to the jet direction. As an alternative, the second and the third highest track IP significances, S_{d0}^{t2} and S_{d0}^{t3} , and the JetProb weight (Section 5.2.2) were also studied in this analysis. Since all of these variables depend on the jet p_T , the templates are derived in bins of calo-jet p_T . The templates are derived separately for the pretag and posttag samples to exclude possible influence of the correlation between the MV1 weight and the discriminating variable. The correlation between the MV1 weight and S_{d0}^{t1} is shown in Fig. 6.5. The correlations between the other discriminating variables are considered in Appendix F.1. Most of the fits are performed in a 3-component configuration including b -jet, c -jet and light-jet templates. As the expected fraction of light jets in the

posttag sample for jet p_T bins below 300 GeV is very small, resulting in large statistical fluctuations in the light-jet templates, 2-component fits (with *b*-jet and *c*-jet templates only) are performed in these cases.

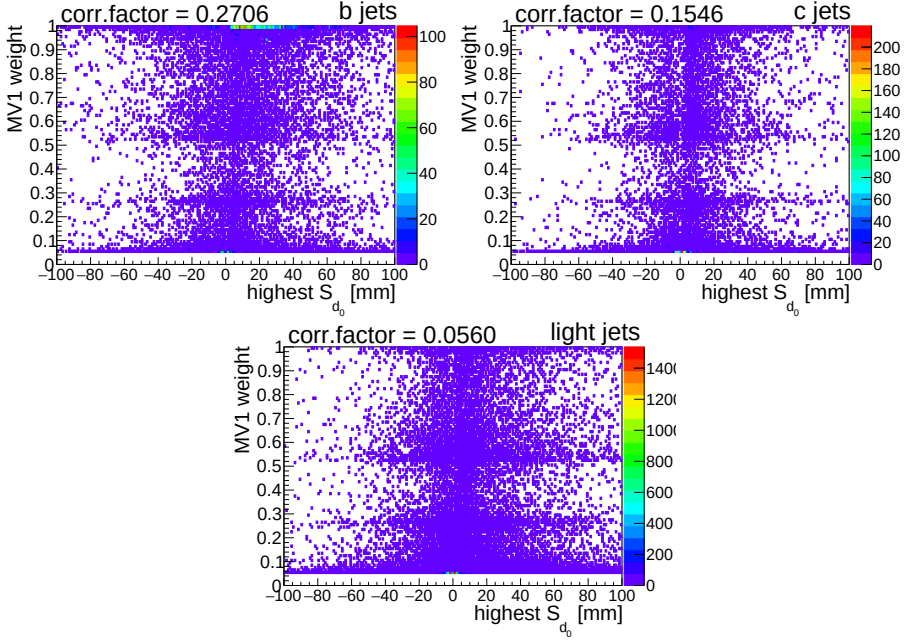


Figure 6.5: Correlations of the MV1 weight with $S_{d_0}^{t1}$, for *b* jets (left), *c* jets (middle) and light jets (right) passing the dR selection.

6.4.2 Fit model

All the fits are performed with the RooFit toolkit [110]. In this framework the distribution of a discriminating variable is usually described by a probability density function (PDF). In our case there are three PDFs represented by the three templates which are normalized to one over the area of the distribution in data. For the 3-component fits a model is built as a linear combination of the PDFs:

$$\text{Model} = f^b \text{PDF}^b + f^c \text{PDF}^c + (1 - f^b - f^c) \text{PDF}^{\text{light}},$$

where f^b and f^c are the free parameters. The normalization of the templates to the data area ensures that the free parameters correspond to the flavour fractions. The 2-component fits are performed with the model:

$$\text{Model} = f^b \text{PDF}^b + (1 - f^b) \text{PDF}^c,$$

where the fraction of *b* jets, f^b , is the only free parameter. The starting values of the parameters f^b and f^c are set to the expected fractions of *b*

and c jets in the unfiltered MC samples, excluding the fraction of light jets from the calculations for the 2-component fit. The fit is performed as described in Section 4.3.1. The template fits have been validated with pseudo-data experiments described in Appendix C.

6.4.3 Construction of the fit templates

The light-jet templates are built from the unfiltered MC samples. The b - and c -jet templates are built from the unfiltered MC samples in case of the dR selection or from the muon-filtered MC samples in case of the muon-in-jet selection. The $S_{d_0}^{t1}$ binning is chosen in each jet p_T bin to ensure a sufficient number of events in each $S_{d_0}^{t1}$ bin. The procedure to define the optimal binning starts from the centre of the $S_{d_0}^{t1}$ histogram with 200 bins from -100 to 100, and moves outwards in both directions. Adjacent bins are merged until the relative statistical uncertainty is less than some pre-defined threshold. For calo-jets passing the dR (muon-in-jet) selection the threshold is 24%(5%) for $p_T \leq 200$ GeV and 18%(8%) for $p_T > 200$ GeV. For track-jets the corresponding thresholds are 26%(5%) for $p_T \leq 200$ GeV and 19%(9%) for $p_T > 200$ GeV. These numbers are chosen in order to allow more than 10 bins in the templates. The requirement on the relative statistical uncertainty is applied to all the three pretag templates and to the posttag b -jet template. Figure 6.6 shows examples of the pre- and posttag templates for calo-jets passing the dR selection in a subset of the jet p_T bins. The templates in the remaining jet p_T bins, as well as the templates for the muon-in-jet selection and for track-jets can be found in Appendix A.

6.4.4 Validation of the fit

The performance of the fit has been validated with the following complementary methods.

- The fit results were reproduced with an independent fitting code based on a likelihood function.
- To investigate how much the statistical uncertainties in the simulated samples affect the fit result, the fits were repeated with a more complex model including additional adjustable parameters. Each PDF was generated as a binned distribution with a nuisance parameter for each bin of the template histogram. This way the PDF becomes a function with $N_{\text{bins}}-1$ free parameters, where N_{bins} is the number of bins in the template. Once the PDFs of the components are generated, there are two steps to complete the test.
 - Do a fit to the MC dataset containing only b jets, fixing fractions

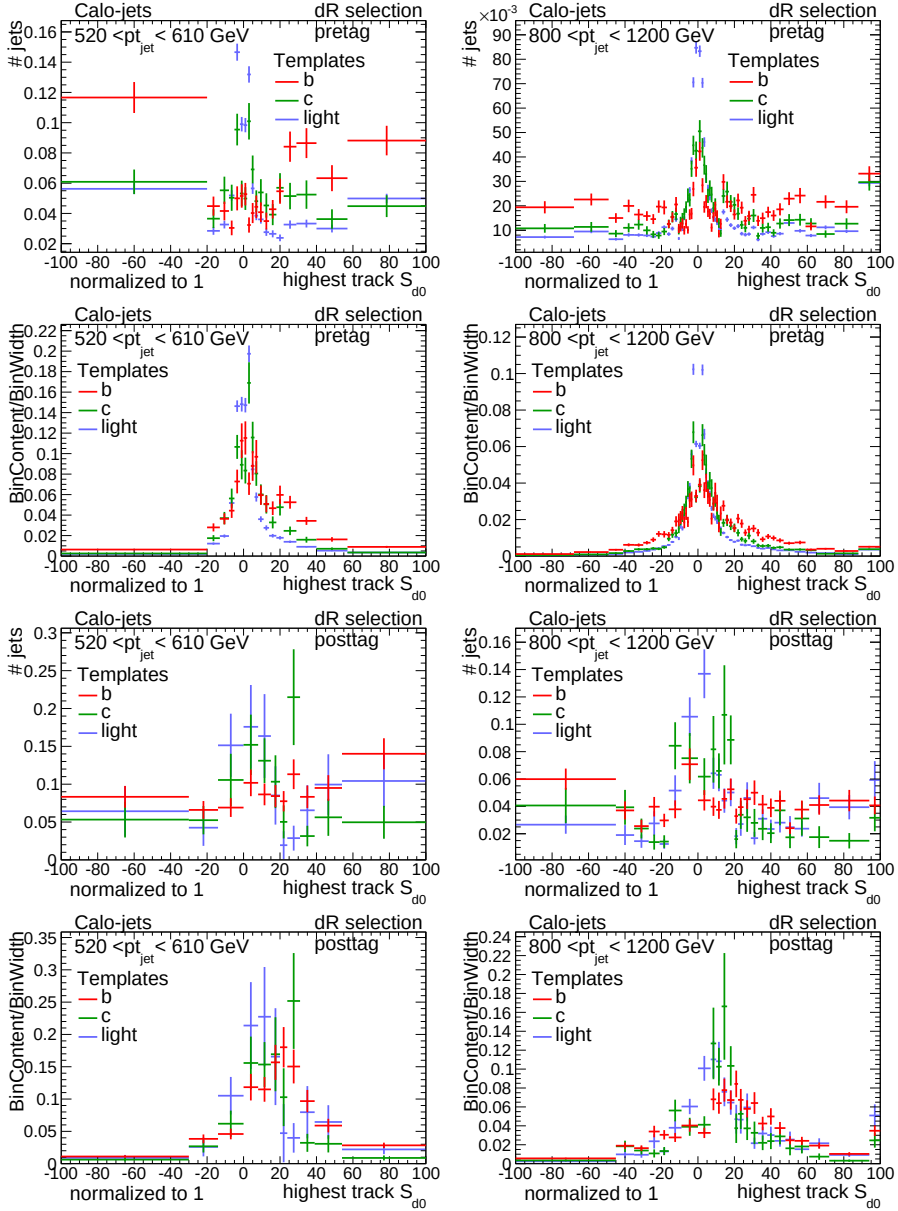


Figure 6.6: Pretag (top four) and posttag (bottom four) *b*-, *c*- and light-jet templates for calo-jets for the dR selection in jet p_T bins in GeV: [520-610) - left, [800-1200) - right. The templates in the first and third rows are used in the fit; in the second and forth rows the number of events in each bin of the templates is divided by the bin width to illustrate the physical shape.

of c and light jets (f^c and f^{light}) to zero, and leaving the b fraction (f^b) floating. Do analogous fits to the MC datasets containing the other two components, one at a time, and fixing fractions of the other components to zero³. This provides the nominal values for the nuisance parameters and the uncertainties related to them in the form of full covariance matrices.

- Do a fit to data, leaving all the flavour fractions floating, but adding a multi-Gaussian term to the model to constrain the nuisance parameters within the uncertainties allowed by the fits to the MC in the previous step.

The results of the fit performed with this strategy do not reveal a significant deviation from the results obtained using the standard fit, which demonstrates that the impact of the limited statistics in the simulated samples on the fit results is negligible.

- To ensure that the fit performance does not suffer from adding the third component, the 2-component fits were performed in all the jet p_T bins for both the pre- and posttag samples. To build the non- b -template for the dR selection, the $S_{d_0}^{\text{t}1}$ distributions for c and light jets from the unfiltered samples were simply summed up. For the muon-in-jet selection the c -jet distribution was taken from the muon-filtered samples, scaled to the number of c -jet events in the unfiltered samples, and after that summed up with the light-jet distribution from the unfiltered samples.
- To investigate whether the choice of the binning, or the modelling of the negative part of the $S_{d_0}^{\text{t}1}$ spectrum (Fig. 5.2) give rise to systematic biases, the following tests were done.
 - Coarser and finer binnings of the $S_{d_0}^{\text{t}1}$ templates were tested.
 - Templates with coarse binning around $S_{d_0}^{\text{t}1}$ of zero and finer binning in the tails were tested
 - Fits to only the part of the templates with $S_{d_0}^{\text{t}1} > 0$ were performed.

None of these tests changed the fit results significantly, which shows the absence of major systematic effects from the considered sources.

³The procedure is described for the 3-component fit. A similar check was done for the 2-component fit.

6.5 Systematic uncertainties

Systematic uncertainties that can affect the shape of the templates and therefore bias the fitted *b* fractions are evaluated one by one. These uncertainties can be related to the track and vertex reconstruction, to the jet reconstruction and to the modelling of physics processes. This section describes the systematic uncertainties that have been evaluated. The estimation of systematic uncertainties from other sources, e.g. the impact parameter smearing, is ongoing and not described in this work. Samples with a single systematic uncertainty variation implemented are produced and used to build altered $S_{d_0}^{t1}$ templates. The templates modified by the systematic uncertainty variation are used to fit the data, and the derived *b*-tagging efficiency is compared to that computed from fits with the nominal templates f_b^{nominal} . The results of the comparisons for the dR selection are summarized in Table 6.5 for calo-jets, and Table 6.6 for track-jets. Similar summary tables for the muon-in-jet selection can be found in Appendix E. The systematic uncertainties from several sources show sizable bin-to-bin fluctuations. In addition, variations in opposite directions (such as JES up and JES down) give rise to differences in the *b*-tagging efficiency that go in the same direction. Both features indicate that there is a large statistical component in the estimated systematic uncertainties. This needs to be understood and mitigated in the future.

6.5.1 Jet energy scale

The systematic uncertainty originating from the jet energy scale (JES) correction (see Section. 4.2.5) can lead to migration of jets from one jet p_T bin to another, and therefore affect the shape of the templates. To estimate the uncertainty on the *b*-tagging efficiency the p_T of each selected jet in the simulation is scaled up and down with the JES uncertainty, which corresponds to one standard deviation and depends on the p_T and η of the jet [75].

6.5.2 Fake tracks

Some of the reconstructed tracks can be formed from a random association of hits and track segments. The fraction of fake tracks is reduced by track quality cuts. As the fraction of fake tracks might be poorly modelled by the simulation, a systematic uncertainty is derived by randomly removing 10% of the fake tracks associated with jets in the simulation. If the highest $|S_{d_0}|$ track is removed, it is substituted with the second highest $|S_{d_0}|$ track.

6.5.3 Track multiplicity reweighting

The multiplicity of tracks associated with jets observed in data is not exactly reproduced in simulations (see Fig. 6.3). It can be due to an imperfect modelling of the fragmentation process or differences between the efficiency of track reconstruction in data and simulation. A high track multiplicity increases the probability to mistakenly b -tag a light jet. The ratio between the multiplicity distributions (the number of tracks associated to jets) in data and unfiltered simulated samples was used as a function to reweight the events in the unfiltered samples before tagging. Such reweighting functions were obtained separately for calo-jets and track-jets, for both the dR selection and the muon-in-jet selection and in each jet p_T bin. To estimate the systematic uncertainty, the reweighting functions were applied to the corresponding sets of jets in the simulated samples.

6.5.4 Impact of long-lived particles

Long-lived particle decays (K_s , Λ and other neutral hyperons) and secondary interactions, such as photon conversion or hadronic interactions, can be confused with b -hadron decays by the b -tagging algorithm due to the similarity of the vertex topologies. The modelling of the rate of such events in the simulated data can be imperfect. The impact of this effect is estimated by rejecting 15% of the jets which contain a K_s or a Λ with $p_T \geq 500$ MeV within a cone of radius 0.4 around the jet axis.

6.5.5 Gluon splitting

The properties of jets containing one b or c quark are different from those with two b or c quarks inside. The latter generally originate from a gluon splitting to a $b\bar{b}$ or $c\bar{c}$ pair which gets merged into one jet. The Pythia8 multi-jet MC simulations underestimate the fraction of $g \rightarrow b\bar{b}$ events [111, 112] by a factor of ~ 1.6 . We assume that the $g \rightarrow c\bar{c}$ process is mismodelled at the same level. To evaluate the systematic uncertainty from this effect, all MC events in which the jet contains two b or c hadrons within a cone of radius 0.3 around the jet axis, are given a weigh of 1.6.

6.5.6 Hadronization and parton showering

The Pythia and Herwig generators use different approaches to parton shower fragmentation and hadronization. These may result in differences in the flavour composition of the selected events and the properties of the selected jets. The uncertainty originating from the choice of MC

generator was evaluated by producing templates from altered samples generated with Herwig (see Section 6.2).

6.5.7 Track-jet reconstruction uncertainties

Several systematic uncertainties affecting the track-jet reconstruction are evaluated. The first of them arises from the difference in the reconstruction efficiency of tracks with $p_T > 0.5$ GeV between data and MC simulation due to imperfect ID material description in the simulation and alignment uncertainties. To account for this effect, tracks are randomly removed from the track-jet, and the track-jet four-vectors are recomputed. This systematic uncertainty is referred to as the track reconstruction efficiency uncertainty. The second uncertainty arises from the track reconstruction efficiency in high- p_T calo-jets. Tracks found inside of high- p_T calo-jet are randomly removed. If any of these tracks are found within a track jet, the track is also removed from the track-jet, and after that the track-jet four-vectors are recomputed. Next, the uncertainty on the momentum scale of the tracks is derived by increasing or reducing (variation “up” and “down”) the p_T of all the tracks in the track-jets simultaneously with the same factor. The last considered uncertainty, the ID track momentum smearing, is related to potential mismodelling of the track momentum resolution in the ID. To evaluate this systematic uncertainty each track p_T is altered using a Gaussian distribution with a mean equal to the nominal value. Since the varied value can be more or less than the nominal one, two uncertainties are derived: “up” and “down”. The scale uncertainty and the smearing function are obtained from the known p_T of muons in the $Z \rightarrow \mu\mu$ process. After applying these variations to the tracks, the track jet four-vectors are recomputed.

6.6 Results

Figure 6.7 shows an example of a template fit to the $S_{d_0}^{t1}$ distribution of calo-jets in data for the dR selection in the first jet p_T bin. The fits in the other bins and fits for the muon-in-jet selection, as well as the results obtained using track-jets, are included in Appendix B.1. The values of the fit χ^2/ndf are adequate. In the pretag fits in the jet p_T bin [400, 520) GeV the χ^2/ndf values are higher than in the other bins, and the reason for this is currently not understood. The *b*-tagging efficiency and the data-to-simulation scale factors vs calo-jet p_T for the dR selection, calculated using eq. 6.1, are presented in Fig. 6.8. The top and the bottom plots are obtained from the template fits for calo-jets and track-jets respectively. The results obtained with the muon-in-jet selection are

discussed in Appendix D.

p_T [GeV]	60-90	90-145	145-200	200-300	300-400	400-520	520-610	610-800	800-1200
JES up	-4.04	-5.94	1.23	-4.27	1.72	4.09	2.03	1.72	-14.54
JES down	-5.26	-5.39	5.71	-9.17	-0.12	0.3	4.8	-8.63	-9.64
K_s , Λ	2.25	0.75	0.07	0.74	1.41	3.19	6.27	2.75	10.25
Fake tracks	-1.4	-3.28	-1.4	-3.13	-5.42	-7.35	-6.37	-7.96	-15.81
Gluon splitting	0.28	0.69	-0	-0.14	0.34	1.1	2.45	-0.27	2.44
Trk mult. reweight.	-7.41	-0.73	-6.06	-8.56	-12.17	-15.47	-30.47	-9.44	-33.22
Herwig	-26.96	-5.9	9.13	-16.43	-11.1	-26.43	-64.11	-44.14	-67.01
Total syst. unc.	28.86	10.56	12.49	21.35	17.49	31.94	71.78	46.76	79.12

Table 6.5: Relative systematic uncertainties (in %) on the *b*-tagging efficiency for calo-jets passing the dR selection.

p_T [GeV]	60-90	90-145	145-200	200-300	300-400	400-520	520-610	610-800	800-1200
K_s , Λ	0.65	1.68	-0.58	1.86	1.41	1.66	4.53	0.78	2.6
Fake tracks	-4.56	-4.89	-4.16	-11.38	-11.12	-16.02	-26.5	-26.09	-57.86
Gluon splitting	0.09	0.27	-0.4	0.37	1.64	1.48	2.11	-2	0.86
Trk multip. reweight.	-0.27	-0.04	-0.04	0.06	0.29	-0.13	0.24	-0.56	-0.09
Herwig	70.24	-19.83	11.72	-25.43	-38.42	-15.19	-41.46	-20.93	29.51
Trk reconst. eff.	-18.68	3.39	3.84	-5.89	-4.01	1.41	-0.22	-10.11	-22.64
Trk eff. high p_T	-23.18	-2.28	-0.52	-12.28	-8.09	3.65	2.96	-6.1	-2.28
Trk. smearing down	-26.02	4.95	3.29	-11.77	-7.37	-4.32	-4.85	-7.63	3.37
Trk. smearing up	-10.3	2.02	-10.08	-9.98	-6.21	5.34	9.42	-10.79	6.7
Trk. scale down	-25.13	-2.38	5.96	-13.88	-5.24	5.28	-2.12	-3.32	-23.07
Trk. scale up	-20.41	-0.32	3.56	-13.87	-3.83	2.83	-2.47	-4.88	-19.18
Total syst. unc.	87.59	21.7	18.19	39.86	42.67	24.3	50.77	38.37	75.5

Table 6.6: Relative systematic uncertainties (in %) on the *b*-tagging efficiency for track-jets passing the dR selection.

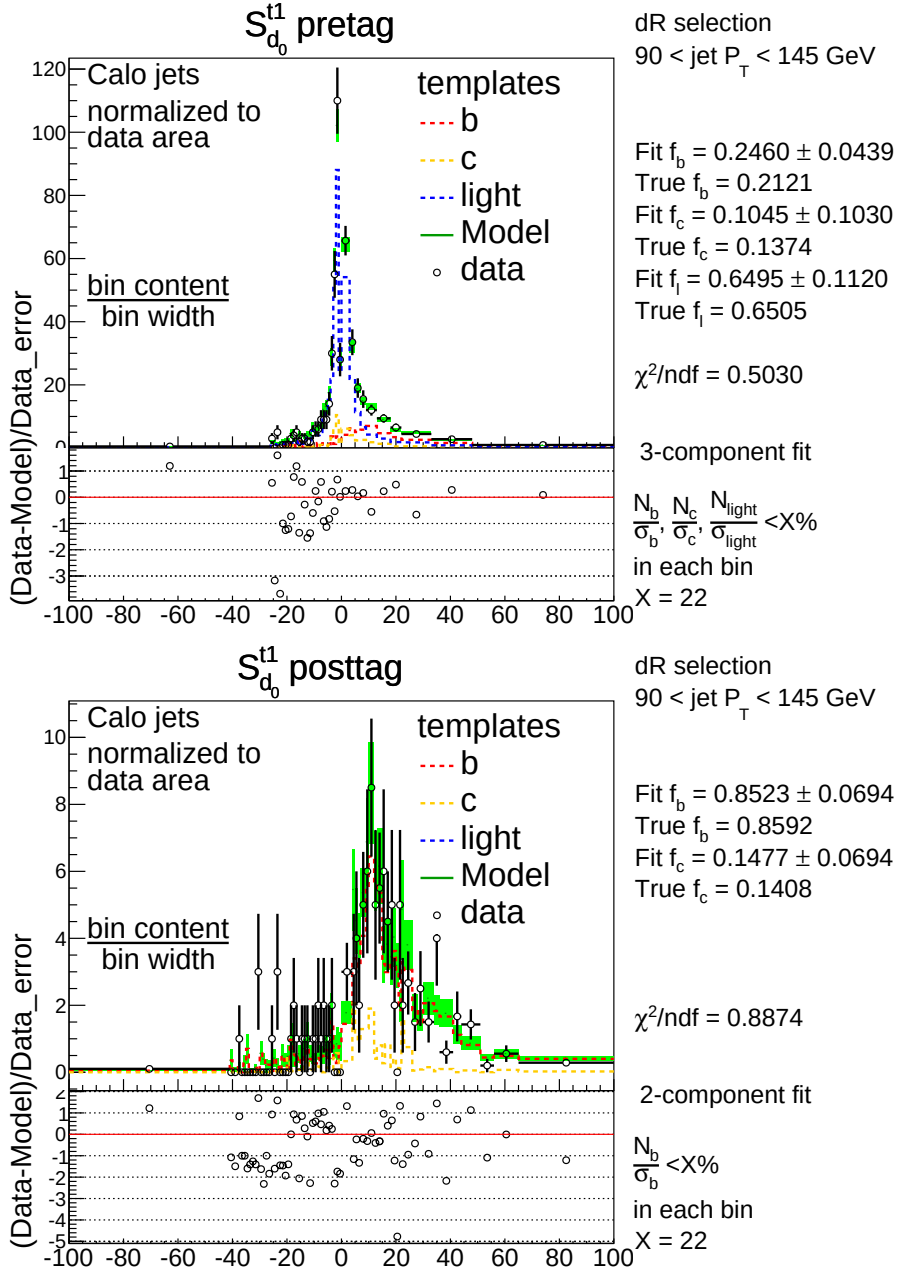


Figure 6.7: Template fits to the pretag (top) and posttag (bottom) $S_{d_0}^{t1}$ distributions of calo-jets for the dR selection in jet p_T region $[90,145)$ GeV. The filled green area corresponds to the statistical model uncertainty.

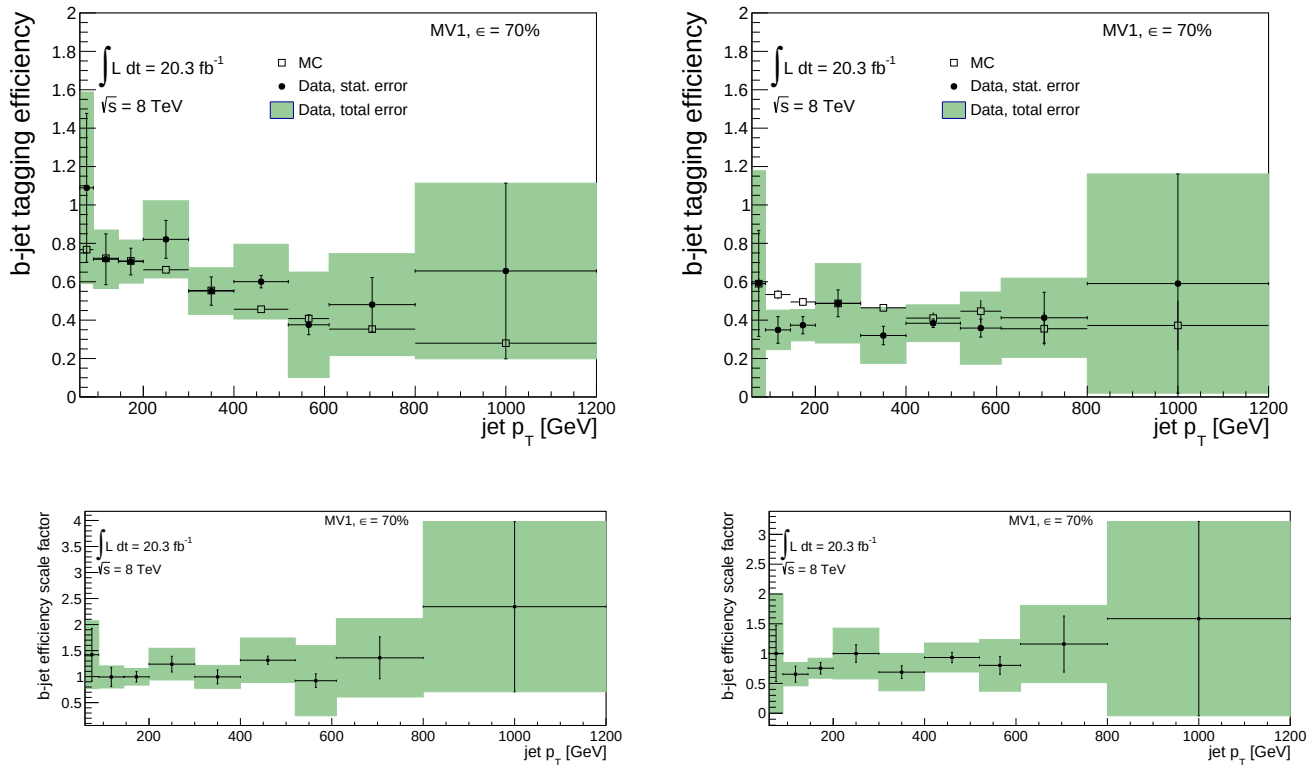


Figure 6.8: The b -tagging efficiency and the data-to-simulation scale factors as a function of calo-jet p_T obtained from template fits to the S_{d0}^{t1} distribution of the tracks associated to calo-jets (left) and to track-jets (right) passing the dR selection.

6.7 Conclusion and outlook

The efficiency of the MV1 b -tagging algorithm has been measured in data and MC simulation using template fits to the highest track signed transverse IP $S_{d_0}^{t1}$. The data-to-simulation scale factors as a function of calo-jet p_T have been computed. The template fit method applied to the multi-jet events has allowed to calibrate the performance of the MV1 b -tagging algorithm up to calo-jet $p_T = 1200$ GeV, using both calo-jets and track-jets. The calibration is done with the dR selection and cross-checked with the muon-in-jet selection. Complementary, the possibilities and prospects of extending the template fits to use also the JetProb weight and the variables $S_{d_0}^{ti}$ ($i = 2, 3$) have been shown.

Part IV

Search for Dark Matter

7 Strategy of the Dark Matter searches

While the existence of Dark Matter is well established, very little is known about the nature of DM. The most common candidate for a DM particle is WIMP (see Section 2.3), which is only involved in gravitational and weak interactions. This chapter introduces the strategy for the DM searches presented in Chapters 8 and 9. The main methods utilized in these studies are introduced here.

7.1 Motivation for DM searches in heavy flavour final states

If DM particles, within the WIMP paradigm, are produced in a pp collision, they do not interact with the detector material and do not produce any signals in the detector. The presence of the DM particles can be revealed by a large momentum imbalance, $E_{\text{T}}^{\text{miss}}$, and an additional visible SM particle X in the final state. The particle X can for example be a gluon, quark, photon, weak gauge boson or Higgs boson. A variety of signatures involving objects X recoiling against large $E_{\text{T}}^{\text{miss}}$ have been looked for by ATLAS [113–117] and CMS [118–122].

In the simplified models under investigation the strength of the scalar or pseudoscalar interaction between a Dirac fermion χ and a quark q is proportional to the mass of the quark m_q . The same is true in the EFT framework:

$$\begin{aligned} L^{\text{scalar}} &= \frac{m_q}{M_*^3} \bar{\chi} \chi \bar{q} q, \\ L^{\text{pseudo}} &= \frac{im_q}{M_*^3} \bar{\chi} \gamma^5 \chi \bar{q} q. \end{aligned} \tag{7.1}$$

Therefore, the coupling to the heavy quarks is stronger than that to the light quarks, and the considered DM searches at the LHC are expected to have higher sensitivity to the interaction with heavy quarks. The searches presented here target the DM production in association with the third-generation quarks, namely top and bottom pairs [123]. Figure 7.1

shows the diagrams for the signal processes, $DM+tt$ and $DM+bb$, under the EFT and the simplified model approaches.

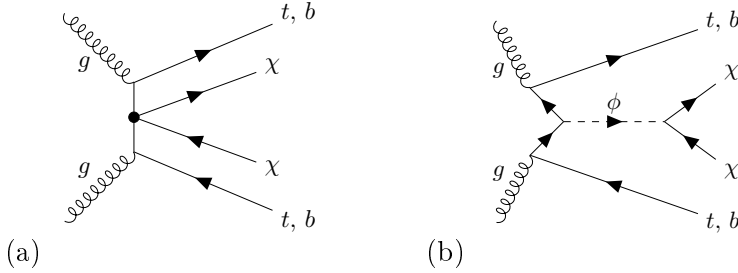


Figure 7.1: Diagram for s-channel Dark Matter production in association with a pair of heavy quarks (top or bottom) at LHC a) in the framework of EFT, b) under the assumption of a simplified model.

7.2 Signal models

In any search for phenomena beyond the SM, a potential signal is expected to be observed as an excess over the SM prediction. In the searches presented here the signal is represented by two final states of DM production in association with heavy quarks, $DM+bb$ and $DM+tt$. The signature of $DM+bb$ production is two b jets and E_T^{miss} . The most recent searches for the DM production in association with a pair of b quarks performed by ATLAS and CMS are presented in Refs. [3, 124].

The signatures of the $DM+tt$ production can be divided into three types. The top quarks almost always decay into a b quark and a W boson (branching ratio $\approx 100\%$ [12]), resulting in $tt \rightarrow bWbW$. Therefore the event topology of a tt decay is fully determined by the decay modes of the two W bosons. Each of them can decay either hadronically ($W \rightarrow qq$) or leptonically ($W \rightarrow \ell\nu$). Consequently, there are three channels of a tt event: all-hadronic, semileptonic and dileptonic. Their branching ratios are 45.7%, 43.8% and 10.5%, respectively [12]. The latest published ATLAS search for DM production targeting all-hadronic, semileptonic and dileptonic final states is presented in Refs. [2, 125, 126]. Results of CMS searches for $DM+tt$ production in the dileptonic and fully hadronic channels are published in Ref. [124], and in the semileptonic channel in Ref. [127].

In the search described in this thesis, the semileptonic channel is considered, where one of the two W bosons decays hadronically, producing a pair of jets, and the other one decays leptonically, $W \rightarrow \ell\nu$, where ℓ refers to e, μ . The channel $W \rightarrow \tau\nu$ is not included, but the leptonically

decaying τ enters the selections. A diagram for the semileptonic DM+ tt process is shown in Fig. 7.2. The event topology of the addressed DM+ tt signal is characterized by large E_T^{miss} , four jets, two of which are b jets, and exactly one charged lepton (e or μ).

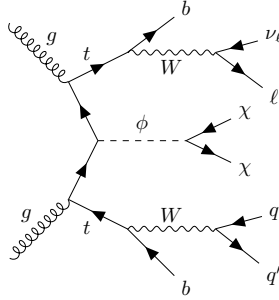


Figure 7.2: Feynman diagram for the DM production in association with a pair of top quarks, one of which decays leptonically and the other decays hadronically.

7.3 SM background processes

The SM processes, whose signatures are similar to that of the signal process, are the sources of background in the analysis. The background events can pass all signal selection criteria. A background process that has exactly the same signature as that expected for the signal is called irreducible, since it can not be suppressed by any selection without removing signal events. The Z boson production in conjunction with jets, followed by the decay $Z \rightarrow \nu\nu$ is the irreducible background for the DM+ bb signal. Similarly, the $ttZ(\rightarrow \nu\nu)$ events production is the irreducible background for the DM+ tt signal.

The dominant reducible background processes in the analyses presented in this thesis are the tt pair production, the single top production (for DM+ tt mainly in the Wt -channel) and the associated production of a W boson with jets. Since there are no leptons in the DM+ bb final state, the tt events in the all-hadronic channel can serve as a background or in the semileptonic tt channel, where the lepton is not identified¹. The presence of exactly one lepton in the semileptonic DM+ tt final state distinguishes it from the hadronic tt final state, but the semileptonic tt events can still pass the signal selection criteria, as well as the dileptonic tt events where one lepton is not identified. Even if a signal selection

¹The lepton can be outside of the detector acceptance or fail to be reconstructed.

requires an isolated lepton, it still can be contaminated by the multi-jet QCD events. This can happen when a jet is misidentified as an isolated lepton, when a lepton produced in a heavy-flavour jet decay satisfies the isolation criteria, and when the jet energy is mismeasured. In the DM+ $b\bar{b}$ analysis the QCD multi-jet background is estimated using data-driven methods [5], which in the DM+ $t\bar{t}$ analyses most of the QCD multi-jet background is rejected by the signal selection criteria. An additional small source of background is the production of pairs of vector bosons (WW , WZ , ZZ).

7.4 Analysis strategy

The statistical treatment of the observed data and the simulated events, including the technical implementation of the analysis strategy described below, as well as the likelihood fit (Sec. 9.7) and interpretation of the results, are performed with a software framework for statistical data analysis called HistFitter [128].

To select events corresponding to the final state of the signal process a signal region (SR) is defined. A SR is a region of phase space in which the signal, predicted by a particular model, is enhanced, while the background is suppressed. The selection criteria of a SR are optimized with MC simulated events to maximize the discovery sensitivity (see Sec. 4.3.3).

The contamination in the DM+ $t\bar{t}$ SR by events stemming from one of the the major background processes is estimated using a data-driven approach, where the background predictions are normalized to data in so-called control regions (CRs). For each DM+ $t\bar{t}$ SR a set of CRs is defined: TZCR (for the $t\bar{t} + Z(\rightarrow \nu\nu)$ background), T1LCR (for the semileptonic $t\bar{t}$ background), T2LCR (for the dileptonic $t\bar{t}$ background), WCR (for the W +jets background) and STCR (for the single top background). Each CR is designed to have a high purity for one type of background and to have a negligible signal contamination. The background estimates in the CRs are extrapolated to the SR, and the simulation is only used for this purpose. To ensure as little extrapolation as possible,

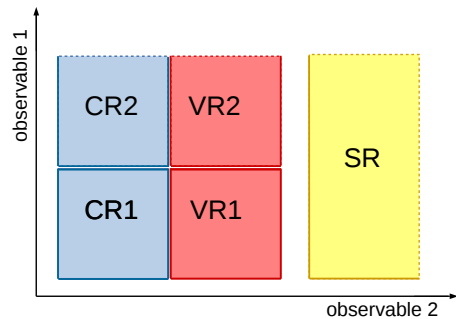


Figure 7.3: Schematic diagram illustrating a signal region, two associated control regions in the background-rich regions of phase space and two validation regions in between.

the CRs are built kinematically as close as possible to the SR, but with some selection criteria inverted, to ensure orthogonality between the CRs and the SR. The prediction of the number of background events in the SR is validated using validation regions (VRs). A VR is typically placed kinematically in between the corresponding CR and the SR, and defined to be orthogonal to both of them.

An example of an ensemble of a SR, two associated CRs, and two VRs is shown in Fig. 7.3. The exact signal and background selections will be described in much more detail in subsequent sections. For each SR, a simultaneous likelihood fit (see Sec. 9.7) is performed to the number of observed events in the SR itself and in the associated CRs. The VRs are not included in the fit. Statistical tests are performed to quantify the presence of a potential excess in the SR. In case no excess is observed with respect to the expected SM background, exclusion limits are set on the signal models.

7.4.1 Blinding criteria

A blind analysis is performed without looking at the data in regions where a signal is expected to be present. The aim of blinding an analysis is to eliminate the experimentalist's unintended bias of a result in a particular direction. The SRs are fully blinded until the selection criteria, background estimates and systematic uncertainties are frozen. The data in the CRs and VRs are not blinded and are used for comparison with the MC modelling of the kinematic distributions.

7.5 Discriminating variables

To discriminate between the signal and the SM backgrounds, a number of variables describing the kinematics of the events are used. A very powerful rejection against the semileptonic $t\bar{t}$ and W +jets backgrounds can be achieved by placing a requirement on the **transverse mass** formed by the lepton and missing transverse momenta, m_T . This variable is defined as

$$m_T = \sqrt{2E_T^{\text{miss}}p_T^{\text{lep}}(1 - \cos \phi)}, \quad (7.2)$$

where ϕ is the angle in the transverse plane between the direction of the $\vec{p}_T^{\text{miss}}$ and the lepton, and it is assumed that the lepton mass is negligible. In the semileptonic $t\bar{t}$ and W +jet events the E_T^{miss} originates from the neutrino produced together with the lepton in the W boson decay. Hence the transverse mass is bounded to be below the W boson mass and mainly populates the region with $m_T < 90$ GeV. In the signal processes the DM particles contribute to the $\vec{p}_T^{\text{miss}}$, and therefore the m_T

can take larger values.

Two variations of the **asymmetric transverse mass (stransverse mass)** m_{T2} [129] are used to reject signatures where two particles are not directly detected. The second particle can be either partly or fully undetected. The am_{T2} [130–132] is designed to suppress dileptonic tt events with one lost lepton, and the other variable, m_{T2}^τ , targets dileptonic tt events where one of the two W bosons decays via a hadronically decaying τ lepton. The asymmetric transverse mass targets decay topologies with two branches, a and b . Each branch includes visible particles with transverse momenta $\vec{p}_T^i$ and masses m_p^i , where $i \in \{a, b\}$, and invisible particles whose total transverse momenta are denoted as $\vec{q}_T^i$ and some assumptions (examples below) are made on their masses m_q^i . The m_{T2} is constructed as

$$m_{T2} = \min_{\vec{q}_T^a + \vec{q}_T^b = \vec{p}_T^{\text{miss}}} \{ \max(m_T^a, m_T^b) \}, \quad (7.3)$$

where m_T^a and m_T^b are the transverse masses of the particles in branches a and b :

$$m_T^i{}^2 = \left(\sqrt{p_T^i{}^2 + m_p^i{}^2} + \sqrt{q_T^i{}^2 + m_q^i{}^2} \right)^2 - (\vec{p}_T^i + \vec{q}_T^i)^2. \quad (7.4)$$

The minimization is done over all possible ways of splitting $\vec{p}_T^{\text{miss}}$ between the two branches. The variable m_{T2} can be interpreted as the minimal mass which the mother particle needs to have in order to decay producing a specific event topology. In case of am_{T2} the mother particle is a top quark decaying leptonically (Fig. 7.4 left), and for dileptonic tt events with a lost lepton am_{T2} should not exceed the top quark mass. The am_{T2} distribution is shown in Fig. 7.5. The invisible particles are the W boson on one side of the chain and the neutrino on the other side. The visible particles are the b jet on side a , and the system of the other b jet and the charged lepton on side b . The assumed masses are: $m_q^a = m_W = 80$ GeV and $m_q^b = m_\nu = 0$ GeV. In case of m_{T2}^τ the mother particle is a W boson (Fig. 7.4 right), and for events with a hadronically decaying τ lepton m_{T2}^τ is limited from above by the W boson mass. The invisible particles in branch a are the neutrino associated with the τ lepton and the neutrino produced in the hadronic τ decay, while the invisible particle in branch b is the neutrino associated with the charged lepton. The measured particles are the hadronic products of the τ decay in branch a and the charged lepton in branch b . Two jet with the highest b -tagging weight are used in the am_{T2} and m_{T2}^τ calculations.

The DM+ tt signals under consideration can be distinguished from the dileptonic tt , W +jets and the diboson backgrounds by the presence of

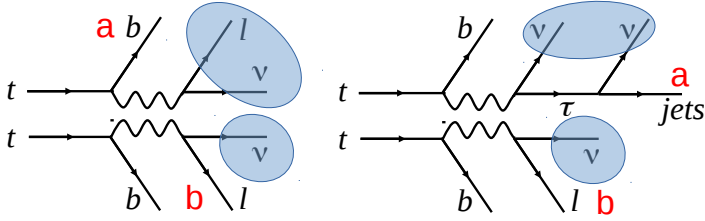


Figure 7.4: Illustration for the definition of the am_{T2} and m_{T2}^τ variables used to suppress dileptonic tt background where one lepton is lost (left) or where the W boson produces a hadronically decaying τ lepton (right). The blue ellipses indicate the invisible objects.

a hadronically decaying top quark. There are three alternative methods to reconstruct the hadronic top decay and to define the **hadronic top mass**, m_{top} , which is expected to be close to the top quark mass for the signal. According to the first definition, which was used in early versions of the DM search at 8 TeV [5, 6] and in the truth study presented in Chapter 8, the m_{top} is an invariant mass of a three-jet system constructed the following way. Pairs of jets with invariant mass above 60 GeV are found by iterating over possible combinations of the leading four jets. Among these pairs the one with the smallest angular separation ΔR is chosen to form the hadronically decaying W boson. After that, the third jet closest in ΔR to the momentum vector of the hadronically decaying W boson is included to reconstruct the hadronically decaying top quark. In some signal selections re-optimized in Ref. [6], a requirement on m_{top} led to a low selection efficiency for signal events, thus another approach to reconstruct the hadronic top decay (targeting events where the top quark is produced with moderate p_T) was developed and used in Ref. [6] and later for the DM SRs in the first search at 13 TeV [2]. According to the second definition, the hadronic top mass $m_{\text{top}} \equiv m_{j_1, j_2, b_i}$ is constructed by minimizing

$$\chi^2 = \frac{(m_{j_1, j_2, b_i} - m_t)^2}{\sigma_{m_{j_1, j_2, b_i}}^2} + \frac{(m_{j_1, j_2} - m_W)^2}{\sigma_{m_{j_1, j_2}}^2}, \quad (7.5)$$

where $i = 1$ or 2 ; m_t is set to 170 GeV; b_1 and b_2 are the two jets with the highest b -tagging weights; j_1 and j_2 are the highest p_T jets from the selected jets in the event excluding b_1 and b_2 and

$$\begin{aligned} \sigma_{m_{j_1, j_2, b_i}}^2 &= m_{j_1, j_2, b_i}^2 (r_{j_1}^2 + r_{j_2}^2 + r_{b_i}^2) \\ \sigma_{m_{j_1, j_2}}^2 &= m_{j_1, j_2}^2 (r_{j_1}^2 + r_{j_2}^2), \end{aligned} \quad (7.6)$$

where r_i is the fractional jet energy uncertainty for jet i determined by dedicated studies. In the third approach (targeting events where the top is significantly boosted), which is currently used [4], the hadronic top decay is reconstructed based on clustering the jets in the event using the anti- k_t algorithm with a large radius parameter $R_0 = 3.0$. Each of the resulting large-radius jets is iteratively shrunk, until its radius matches its p_T , following the approximation $R(p_T) = 2m/p_T$. The mass of a large-radius jet selected this way is taken as m_{top} .

Requiring a large azimuthal angle $\Delta\phi(\ell, \vec{E}_T^{\text{miss}})$ between the lepton and the direction of $\vec{E}_T^{\text{miss}}$ helps to separate the signal and the dileptonic background from the other backgrounds, where most of $\vec{E}_T^{\text{miss}}$ is due to the neutrino produced together with the lepton in the W boson decay.

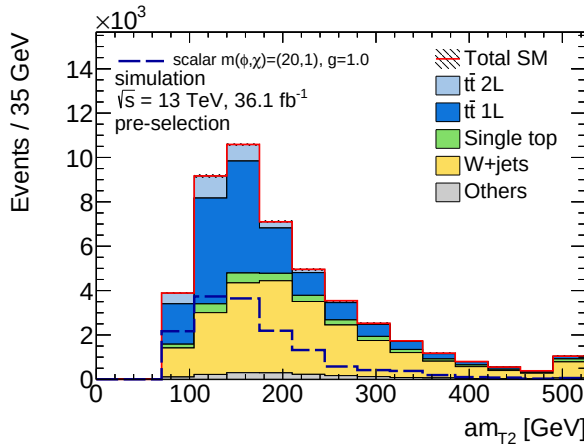


Figure 7.5: Distribution of am_{T2} after the pre-selection defined in Section 9.4. The background predictions are normalized to the theoretical cross sections. The signal prediction is scaled up by factor 10. The last bin contains overflow.

The mismeasured jet energy in the QCD multi-jet events can give a rise to a fake $\vec{E}_T^{\text{miss}}$ aligned with one of the jets. The following variables are exploited to reduce the multi-jet QCD background:

- $|\Delta\phi(j_i, \vec{E}_T^{\text{miss}})|$, $i = 1, 2$, the azimuthal opening angle between the missing transverse momentum and the directions of the two or four leading jets is required to be above a threshold value to suppress the multi-jet QCD background with mismeasured jet energies.
- A requirement on the missing transverse energy significance $E_T^{\text{miss}} / \sqrt{H_T}$, is imposed to distinguish real missing transverse energy due to particles that do not interact with the detector material, from missing transverse energy originating from mismeasured jet

energies. The H_T is a measure of the total hadronic energy in the event, calculated as the scalar sum of transverse momenta of the four leading jets in the event $H_T = \sum_{i=1}^4 p_T(j_i)$, and $\sqrt{H_T}$ represents the resolution of the hadronic energy measurement.

- $H_{T,\text{sig}}^{\text{miss}}$, an alternative missing transverse momentum significance, defined as

$$H_{T,\text{sig}}^{\text{miss}} = \frac{|\vec{H}_T^{\text{miss}}| - M}{\sigma_{|\vec{H}_T^{\text{miss}}|}}, \quad (7.7)$$

where $\vec{H}_T^{\text{miss}}$ is the negative sum of the jets and lepton transverse momentum vectors in the event, $\sigma_{|\vec{H}_T^{\text{miss}}|}$ is the per-event resolution of the jets, and the lepton is assumed to be well-measured. The scale M is fixed at 100 GeV based on optimization studies [133].

An additional minor background suppression is achieved using the angles between the signal lepton and the leading jet, $\Delta R(j_1, \ell)$, or a leading b jet, $\Delta R(bj_1, \ell)$, based on the event topology.

8 DM search at $\sqrt{s} = 8$ TeV

8.1 Motivation and models

A search for DM pair production in association with a pair of bottom or top quarks was performed by the ATLAS experiment at $\sqrt{s} = 8$ TeV [5,6] and the results were interpreted in the EFT framework. The energy increase in Run II provides an increase in cross sections, which gives better sensitivity to the signal models. The aim of the study presented here is to retroactively interpret the results of the $\sqrt{s} = 8$ TeV EFT search in the context of simplified models (Section 2.3), and to choose benchmark models for future searches in Run II at $\sqrt{s} = 13$ TeV.

To study the evolution of the signal kinematics, 31 benchmark models (Tab. 8.1) are considered following the DM forum¹ recommendations [42]. The motivation for the choice of the parameter grid is to find a minimal set of models covering a wide range of phenomenology. The range of mediator masses, m_ϕ , is chosen based on the expected sensitivity. The DM candidate masses, m_χ , are chosen to cover the off-shell ($2m_\chi > m_\phi$), the on-shell ($2m_\chi < m_\phi$) and the transition ($2m_\chi \approx m_\phi$) regimes. The points at high mediator mass (5000 GeV) are added to produce kinematic distributions similar to those in the EFT model. Two possible

m_χ [GeV]	m_ϕ [GeV]								
1	10	20	50	100	200	300	500	1000	5000
10	10	15	50	100					
50	10		50	95	200	300			
150	10				200	295	500	1000	5000
500	10						500	995	
1000	10							1000	5000

Table 8.1: The parameter scan for the simplified model. The m_ϕ stands for the mediator mass and m_χ is the DM candidate mass.

¹The Dark Matter forum was created by the ATLAS and CMS experiments to harmonize the DM benchmarks used by the two experiments and to provide a set of recommendations for the LHC Run-II DM searches.

values of the coupling g_χ are considered: 2 and 3.5, where the latter corresponds to the maximum possible value in the perturbative regime ($g_\chi g_{\text{SM}} < 4\pi$), providing the highest cross section of the signal processes and consequently the highest sensitivity to the models, while the choice of 2 corresponds to a more moderate coupling.

8.2 Simulated samples

This study is performed at Truth level, meaning that the MC simulated samples contain generated events, but the simulation of the detector response is omitted due to the provisional purpose of the study (see details on MC simulation in Sec 4.1). The DM+ tt and DM+ bb signal events at $\sqrt{s} = 8$ TeV are generated for each of the simplified model benchmarks using MADGRAPH5 and PYTHIA8 with the NNPDF3.0LO set. MADGRAPH5 handles the matrix element calculation, where no extra jets in the final state (in addition to the top quarks) are generated. PYTHIA simulates the parton showering and hadronization. Samples for most of the signal benchmarks are passed through the fast simulation of the ATLAS detector (AtlasFast II) and several samples are also produced in full simulation as a cross check. A requirement of $E_{\text{T}}^{\text{miss}} > 60$ GeV is applied at truth level in the DM+ bb samples, while a requirement of $E_{\text{T}}^{\text{miss}} > 60$ GeV or at least 1 lepton with $p_{\text{T}} > 20$ GeV is applied in the DM+ tt samples. The couplings for the interactions of the mediator with the DM and the SM particles are assumed to be equal $g_\chi = g_q = 1$ for all the benchmarks. Since the kinematic properties of the events do not depend on the coupling choice [42], the samples can be safely rescaled to the cross section corresponding to another coupling. The Truth EFT DM+ tt and DM+ bb events are generated with the same setup for $m_\chi = 100$ and 10 GeV respectively, and cross sections $\sigma = 1.336 \cdot 10^{-10}$ nb and $3.7691 \cdot 10^{-11}$ nb. The Reco EFT samples used in the study [5] were produced using MADGRAPH5 and PYTHIA6 with the CTEQ6L1 PDF set.

8.3 Signal regions

The SRs used in this study are adopted from Refs. [5, 6]. The DM+ bb and the DM+ tt events are selected with the SRs, that will be referred to as SR1 and SR_mix, respectively. The selection requirements of both SRs are described in this section and summarized in Table 8.2.

Requirement \ SR	SR_mix	SR1
Number of leptons	1	0
Number of jets	≥ 4	1 or 2
Jet p_T [GeV] >	80-70-50-25	-
Number of b jets $\geq$	1	1
Leading b jet p_T [GeV] >	60	100
$E_T^{\text{miss}} / \sqrt{H_T}$ [GeV $^{1/2}$] >	9	-
E_T^{miss} [GeV] >	270	300
m_T [GeV] >	130	-
am_{T2} [GeV] >	190	-
m_{top} [GeV] <	360	-
$\Delta R(j_1, \ell) <$	2.75	-
$\Delta R(bj, \ell) <$	3.0	-
$ \Delta\phi(j_i, \vec{E}_T^{\text{miss}}) , i \in \{1, 2\} >$	0.6	1.0
$ \Delta\phi(\ell, \vec{E}_T^{\text{miss}}) >$	0.6	-
Targeted signal	DM+ tt	DM+ bb

Table 8.2: Requirements for the signal regions SR_mix and SR1.

8.3.1 Selection of DM+ tt events

SR_mix is similar to the SR which is called SR4 in Ref. [5] and tNbC_mix in Ref. [6], but the requirement on the topness and the τ -veto are omitted for simplicity. These requirements are difficult to properly implement at Truth level, but they have a very small effect on the sensitivity, and therefore can be neglected. To enter the SR_mix region, events are required to have exactly one lepton (either electron or muon) with $p_T > 25$ GeV. At least four jets must be reconstructed in the event and have transverse momenta $p_T > 80, 70, 50$, and 25 GeV respectively. At least one b jet is required in the event, and the most energetic b jet must have $p_T > 60$ GeV. Events must have $E_T^{\text{miss}} > 270$ GeV. The significance $E_T^{\text{miss}} / \sqrt{H_T}$ is required to be greater than 9 $\sqrt{\text{GeV}}$ to suppress events with fake missing transverse energy originating from jet energy mismeasurements. To remove most of the semileptonic tt and W +jets events, the requirement on the transverse mass m_T between the lepton and $\vec{E}_T^{\text{miss}}$ is required to be greater than 130 GeV. To reject the dileptonic tt events in SR_mix, am_{T2} is required to be above 190 GeV. The hadronic top mass, m_{top} , is required to be less than 360 GeV. The azimuthal angle $|\Delta\phi(j_i, \vec{E}_T^{\text{miss}})|$ is required to be greater than 0.6 rad, to remove the QCD multi-jet events where $\vec{E}_T^{\text{miss}}$ is aligned with a jet. To further suppress tt and W +jets backgrounds and reduce the QCD multi-jet background to

a negligible level, selection criteria are imposed on the angular distance between the (b) jet and the lepton.

Table 8.3 shows the efficiencies of the selection criteria in the Truth EFT DM+ tt sample with $m_\chi = 100$ GeV. The number of events satisfying the selection criteria is denoted $S_{\text{raw}}^{\text{Truth}}$ (raw signal yield), while the total number of events in the sample is $S_{\text{total}}^{\text{Truth}}$. These event counts compared and agree well with the yields and efficiencies obtained using the reconstructed events for the search presented in Refs. [5, 6], which validates the implementation of SR_mix at Truth level.

Requirement	$S_{\text{raw}}^{\text{Truth}}$	$\frac{S_{\text{raw}}^{\text{Truth}}}{S_{\text{total}}^{\text{Truth}}}$	relative to previous requirement
-	40000	1	-
One lepton	13565	0.34	0.34
≥ 4 jets, $p_T > 25$ GeV	11331	0.28	0.84
$E_T^{\text{miss}} > 150$ GeV	7581	0.19	0.67
$m_T > 50$ GeV	7045	0.18	0.93
≥ 1 b jet	6906	0.17	0.98
Jet p_T and b jet p_T	4672	0.12	0.68
$ \Delta\phi(j_i, \vec{E}_T^{\text{miss}}) > 0.6, i \in \{1, 2\},$ $ \Delta\phi(\ell, \vec{E}_T^{\text{miss}}) > 0.6,$ $\Delta R(j_1, \ell) < 2.75,$ $\Delta R(bj_1, \ell) < 3,$	3382	0.08	0.72
$E_T^{\text{miss}} > 270$ GeV	2047	0.05	0.61
$E_T^{\text{miss}} / \sqrt{H_T} > 9 \sqrt{\text{GeV}}$	2042	0.05	0.99
$m_T > 130$ GeV	1982	0.05	0.97
$am_{T2} > 190$ GeV	1171	0.03	0.59
$m_{\text{top}} < 360$ GeV	642	0.02	0.55

Table 8.3: Yields and efficiencies for the SR_mix requirements on the DM+ tt EFT sample with $m_\chi = 100$ GeV. The second column contains the number of events in the sample after each requirement. The third column shows the cumulative efficiency of the requirements, while the forth column shows the efficiency of each requirement separately.

8.3.2 Selection of DM+ bb events

Events in the signal region SR1 are required to have one or two jets. One or both jets must be b -tagged, and the leading b jet must have $p_T > 100$ GeV. Events with at least one identified muon or electron are removed to suppress the background arising from leptonic decays of W and Z bosons. The missing transverse energy is required to exceed

300 GeV. The azimuthal angle between the directions of the jets and the missing transverse momentum is required to be above 1.0 rad, which removes a large portion of the QCD multi-jet background.

The efficiency of the SR1 event selection in the EFT DM+ bb sample with $m_\chi = 10$ GeV is shown in Table 8.4. The implementation of SR1 at Truth level has been validated by a comparison with the event counts and the efficiencies obtained using the reconstructed events for the search presented in Refs. [5, 6].

Requirement	$S_{\text{raw}}^{\text{Truth}}$	$S_{\text{raw}}^{\text{Truth}}/S_{\text{total}}^{\text{Truth}}$	relative to previous requirement
-	40000	1	-
No leptons	36171	0.90	0.90
$E_{\text{T}}^{\text{miss}} > 100$ GeV	21862	0.55	0.60
$1 \leq n_{\text{jets}} \leq 4$	21172	0.53	0.97
$\Delta\phi(j_i, \vec{E}_{\text{T}}^{\text{miss}}) > 1$	19606	0.49	0.93
Leading jet $p_{\text{T}} > 100$ GeV	12676	0.32	0.65
≥ 0 b jets	12676	0.32	1
Leading b jet $p_{\text{T}} > 100$ GeV	11774	0.29	0.93
$E_{\text{T}}^{\text{miss}} > 300$ GeV	744	0.02	0.06
< 3 jets	388	0.01	0.52

Table 8.4: Efficiencies for the SR1 requirements on the DM+ bb EFT sample with $m_\chi = 10$ GeV. The second column contains the number of events in the sample after each requirement. The third column shows the cumulative efficiency of the requirements, while the forth column shows the efficiency of each requirement separately.

8.4 Re-interpretation strategy

As previously mentioned, this study utilizes the Truth MC simulated samples, which contain generated events. The number of events $S_{\text{raw}}^{\text{Truth}}$ in the Truth samples satisfying the criteria of the SRs (see Section 8.3), is weighted to correspond to the integrated luminosity $L = 20 \text{ fb}^{-1}$ and normalized by the total number of events in the sample, $N_{\text{total}}^{\text{Truth}}$, to result in the number S^{Truth} , which in the following will be referred to as the expected number of truth signal events:

$$S^{\text{Truth}} = \frac{S_{\text{raw}}^{\text{Truth}}}{N_{\text{total}}^{\text{Truth}}} \cdot \sigma \cdot L \cdot f,$$

where σ is the cross section, and $f = 1$ is the generator filter efficiency. The expected number of truth signal event, S^{Truth} , is derived for the EFT sample ($S_{\text{EFT}}^{\text{Truth}}$) and for every sample corresponding to the point in the parameter grid of the simplified models with either a scalar or a pseudoscalar mediator.

The EFT analysis [5, 6] was performed using fully reconstructed events. For further calculations, the expected number of reconstructed background events, B^{Reco} , the systematic uncertainty on the background expectation, σ_B , and the expected number of reconstructed signal events in the EFT sample, $S_{\text{EFT}}^{\text{Reco}}$, are taken from Refs. [5, 6]. To be able to use the results of the EFT analysis, the number of truth signal events, S^{Truth} , has to be converted to the number of signal events that would be found after reconstruction, S^{Reco} . This is done for each point in the parameter grid using the formula:

$$S^{\text{Reco}} = \kappa \cdot S^{\text{Truth}}. \quad (8.1)$$

The acceptance κ is estimated as a ratio between the expected number of truth signal events in the EFT sample and the expected number of reconstructed signal events quoted in the EFT analysis papers [5, 6]:

$$\kappa = \frac{S_{\text{EFT}}^{\text{Reco}}}{S_{\text{EFT}}^{\text{Truth}}}. \quad (8.2)$$

The calculated value of κ is 0.653 for the DM+ tt sample and 0.58 for the DM+ bb sample.

A hypothesis test is performed in the exclusion formalism, deriving the CL_s value. To calculate the expected CL_s , the “observed” number of events is set to the expected number of background events. The models with $\text{CL}_s < 0.05$ are excluded at 95% confidence level. Additionally, the sensitivity significance introduced in Section 4.3.3 is calculated as:

$$\mathcal{S} = \frac{S^{\text{Reco}}}{\sqrt{S^{\text{Reco}} + B^{\text{Reco}} + \sigma_B^2}}. \quad (8.3)$$

To be conservative the numbers at the edge of the exclusion are considered not excluded.

8.5 Results

The significance of the sensitivity, $\mathcal{S}$, to DM+ tt production in the simplified models with a pseudoscalar and scalar mediator are shown in Figs. 8.1 and 8.2 respectively. The corresponding results for DM+ bb

production are shown in Figs. 8.3 and 8.4. The derived numerical values of $\mathcal{S}$ and CL_s for the DM+ tt signature are summarized in Table 8.5 for the simplified model with a pseudoscalar mediator, and in Table 8.6 for the simplified model with a scalar mediator. The values of $\mathcal{S}$ and CL_s for the DM+ bb signature are summarized in Table 8.7 for the simplified model with a pseudoscalar mediator, and in Table 8.8 for the simplified model with a scalar mediator.

The DM+ tt benchmarks with $m_\chi = 10$ GeV, $m_\phi \geq 50$ GeV for $g = 2$ and all the benchmarks with $m_\chi = 10$ GeV for $g = 3.5$ are excluded at 95% confidence level for both scalar and pseudoscalar mediators. If $m_\chi = 50$ GeV and $g = 3.5$, the DM+ tt production models with a mediator mass 95 and 200 GeV are excluded at 95% confidence level. If $m_\chi = 1$ GeV, the DM+ tt benchmarks with $m_\phi \leq 100$ GeV for $g = 2$ and $m_\phi \leq 300$ GeV for $g = 3.5$ are excluded at 95% confidence level for both scalar and pseudoscalar mediators. These points will thus do not need to be considered in further search at 13 TeV, while special attention should be paid to the region around $m_\chi = 1$ GeV, $m_\phi > 100$ for $g = 2$ and $m_\chi = 1$ GeV, $m_\phi > 300$ for $g = 3.5$, where the sensitivity to the signal is expected to be the highest. New benchmarks will be added in these regions to probe the models in the gaps between the excluded and the first not excluded points.

None of the DM+ bb models are found to be excluded by the hypothesis test in Run I. The sensitivity to all the benchmarks is very low ($\mathcal{S} \leq 0.18$ for $g = 3.5$ and $\mathcal{S} \leq 0.03$ for $g = 2$). This is explained by the fact that the signal region SR1 was optimized for the analysis under the EFT approach but not for the simplified model approach assumed in this study, and the SR requirements were found to be too tight for the considered models. Particularly, the requirement on E_T^{miss} rejects a big fraction of the signal events. Since the whole grid is available for discovery, new signal regions need to be optimized for the 13 TeV search to provide higher sensitivity to the target signatures in the simplified model approach.

m_χ	m_ϕ	$g = 2$			$g = 3.5$		
		σ [pb]	$\mathcal{S}$	CL_s	σ [pb]	$\mathcal{S}$	CL_s
1	10	0.4697 ± 0.0016	2.63	0.01	1.827 ± 0.006	6.23	0
1	20	0.4083 ± 0.0018	2.52	0.01	1.433 ± 0.007	5.67	0
1	50	0.2760 ± 0.0012	2.09	0.02	0.861 ± 0.004	4.53	0
1	100	0.1549 ± 0.0009	2.11	0.02	0.4391 ± 0.0016	4.28	0
1	200	0.0584 ± 0.0002	1.47	0.14	0.150 ± 0.007	2.97	0
1	300	$(243.0 \pm 1.2)10^{-4}$	0.91	0.34	0.0616 ± 0.0004	1.93	0.04
1	500	$(239.8 \pm 1.2)10^{-5}$	0.14	0.88	$(49.8 \pm 0.3)10^{-4}$	0.29	0.81
1	1000	$(128.7 \pm 0.5)10^{-6}$	0.01	0.98	$(298.0 \pm 1.6)10^{-6}$	0.04	0.98
1	5000	$(83.9 \pm 0.5)10^{-9}$	$0.5 \cdot 10^{-5}$	1	$(36.8 \pm 0.2)10^{-8}$	$2.3 \cdot 10^{-5}$	1
10	10	0.0529 ± 0.0003	0.66	0.51	0.495 ± 0.003	3.75	0
10	15	0.0666 ± 0.0003	0.82	0.39	0.621 ± 0.003	4.35	0
10	50	0.2791 ± 0.0011	2.09	0.02	0.868 ± 0.004	4.52	0
10	100	0.1562 ± 0.0006	1.97	0.04	0.438 ± 0.002	4.03	0
50	10	$(71.6 \pm 0.4)10^{-4}$	0.20	0.85	0.0677 ± 0.0003	1.51	0.11
50	50	$(88.7 \pm 0.4)10^{-4}$	0.23	0.81	0.0838 ± 0.0003	1.72	0.09
50	95	0.0345 ± 0.0002	0.73	0.46	0.3244 ± 0.0013	4.04	0
50	200	0.0581 ± 0.0003	1.43	0.14	0.1506 ± 0.0007	2.91	0
50	300	$(240.4 \pm 1.2)10^{-4}$	0.88	0.38	0.0605 ± 0.0003	1.87	0.06
150	10	$(49.8 \pm 0.2)10^{-5}$	0.027	0.97	$(469.0 \pm 1.9)10^{-5}$	0.25	0.80
150	200	$(90.5 \pm 0.4)10^{-5}$	0.049	0.97	$(85.3 \pm 0.4)10^{-4}$	0.43	0.69
150	295	$(83.5 \pm 0.5)10^{-4}$	0.34	0.76	$(79.7 \pm 0.6)10^{-3}$	2.31	0.01
150	500	$(186.3 \pm 0.8)10^{-5}$	0.11	0.91	$(357.0 \pm 1.7)10^{-5}$	0.20	0.84
150	5000	$(57.3 \pm 0.3)10^{-9}$	$4.5 \cdot 10^{-6}$	1	$(246.8 \pm 1.3)10^{-9}$	$1.9 \cdot 10^{-5}$	1
500	10	$(172.9 \pm 0.8)10^{-8}$	$1.8 \cdot 10^{-4}$	1	$(162.0 \pm 0.7)10^{-7}$	0.0016	0.99
500	500	$(256.4 \pm 1.2)10^{-8}$	$2.7 \cdot 10^{-4}$	1	$(235.9 \pm 1.2)10^{-7}$	0.0025	0.99
500	995	$(186.7 \pm 0.9)10^{-7}$	0.0018	0.99	$(46.42 \pm 0.2)10^{-6}$	0.0045	0.99
1000	10	$(392.0 \pm 1.8)10^{-11}$	$5.4 \cdot 10^{-7}$	1	$(366.8 \pm 1.5)10^{-10}$	$5.0 \cdot 10^{-6}$	1
1000	1000	$(61.43 \pm 0.2)10^{-10}$	$8.9 \cdot 10^{-7}$	1	$(55.7 \pm 0.3)10^{-9}$	$8.1 \cdot 10^{-6}$	1
1000	5000	$(235.0 \pm 1.1)10^{-12}$	$3.4 \cdot 10^{-8}$	1	$(83.1 \pm 0.4)10^{-11}$	$1.2 \cdot 10^{-7}$	1

Table 8.5: Exclusion test results for the DM+ $t\bar{t}$ pseudoscalar simplified model grid. Sensitivity $\mathcal{S}$ and CL_s for coupling $g = 2$ and 3.5.

m_χ	m_ϕ	$g = 2$			$g = 3.5$		
		σ [pb]	$\mathcal{S}$	CL_s	σ [pb]	$\mathcal{S}$	CL_s
1	10	22.81 ± 0.07	4.83	0	70.3 ± 0.3	9.18	0
1	20	11.69 ± 0.04	2.70	0.002	33.31 ± 0.13	5.31	0
1	50	3.130 ± 0.011	2.96	0	8.25 ± 0.03	5.47	0
1	100	0.691 ± 0.002	2.48	0.01	1.785 ± 0.007	4.65	0
1	200	0.0905 ± 0.0003	1.58	0.11	0.24210 ± 0.0007	3.24	0
1	300	$(241.3 \pm 0.9)10^{-4}$	0.82	0.39	0.06789 ± 0.0003	1.92	0.04
1	500	$(289.0 \pm 1.3)10^{-5}$	0.17	0.87	$(73.3 \pm 0.4)10^{-4}$	0.42	0.71
1	1000	$(129.1 \pm 0.5)10^{-6}$	0.01	0.98	$(330.8 \pm 1.3)10^{-6}$	0.03	0.97
1	5000	$(86.13 \pm 0.5)10^{-9}$	$5.0 \cdot 10^{-6}$	1	$(374.9 \pm 1.6)10^{-9}$	$2.2 \cdot 10^{-5}$	1
10	10	0.4277 ± 0.0016	0.84	0.39	4.013 ± 0.018	4.47	0
10	15	0.543 ± 0.002	1.17	0.22	5.111 ± 0.019	5.65	0
10	50	3.169 ± 0.012	2.73	0.003	8.51 ± 0.04	5.17	0
10	100	0.684 ± 0.002	1.96	0.04	1.752 ± 0.006	3.78	0
50	10	$(74.8 \pm 0.3)10^{-4}$	0.14	0.87	0.0701 ± 0.0003	1.11	0.24
50	50	$(92.4 \pm 0.3)10^{-4}$	0.15	0.87	0.0866 ± 0.0003	1.20	0.21
50	95	$(270.6 \pm 1.2)10^{-4}$	0.32	0.80	0.2542 ± 0.0010	2.16	0.02
50	200	0.0864 ± 0.0002	1.44	0.14	0.2229 ± 0.0008	2.92	0
50	300	$(228.8 \pm 0.8)10^{-4}$	0.84	0.39	0.0598 ± 0.0003	1.86	0.05
150	10	$(189.6 \pm 0.9)10^{-6}$	0.010	0.98	$(178.4 \pm 0.8)10^{-5}$	0.10	0.91
150	200	$(300.8 \pm 1.2)10^{-6}$	0.018	0.97	$(282.4 \pm 1.2)10^{-5}$	0.17	0.87
150	295	$(108.1 \pm 0.5)10^{-5}$	0.058	0.97	$(101.5 \pm 0.4)10^{-4}$	0.50	0.64
150	500	$(184.2 \pm 0.8)10^{-5}$	0.12	0.89	$(416.7 \pm 1.9)10^{-5}$	0.26	0.81
150	5000	$(375.6 \pm 1.9)10^{-10}$	$3.3 \cdot 10^{-6}$	1	$(160.4 \pm 1.0)10^{-9}$	$1.4 \cdot 10^{-5}$	1
500	10	$(48.0 \pm 0.2)10^{-8}$	$5.4 \cdot 10^{-5}$	1	$(452.0 \pm 1.7)10^{-8}$	$5.0 \cdot 10^{-4}$	1
500	500	$(66.5 \pm 0.3)10^{-8}$	$7.7 \cdot 10^{-5}$	1	$(62.4 \pm 0.3)10^{-7}$	$7.2 \cdot 10^{-4}$	1
500	995	$(372.9 \pm 1.7)10^{-8}$	$3.8 \cdot 10^{-4}$	1	$(144.4 \pm 0.6)10^{-7}$	0.0015	0.99
1000	10	$(76.4 \pm 0.3)10^{-11}$	$1.1 \cdot 10^{-7}$	1	$(71.7 \pm 0.3)10^{-10}$	$1.0 \cdot 10^{-6}$	1
1000	1000	$(1137.0 \pm 0.4)10^{-11}$	$1.6 \cdot 10^{-7}$	1	$(105.0 \pm 0.6)10^{-10}$	$1.5 \cdot 10^{-6}$	1
1000	5000	$(65.8 \pm 0.3)10^{-12}$	$1.0 \cdot 10^{-8}$	1	$(236.5 \pm 1.1)10^{-12}$	$3.7 \cdot 10^{-8}$	1

Table 8.6: Exclusion test results for the DM+ tt scalar simplified model grid. Sensitivity $\mathcal{S}$ and CL_s for coupling $g = 2$ and 3.5.

m_χ	m_ϕ	$g = 2$			$g = 3.5$		
		σ [pb]	$\mathcal{S}$	CL_s	σ [pb]	$\mathcal{S}$	CL_s
1	100	0.732 ± 0.003	0.033	0.98	1.878 ± 0.008	0.085	0.96
1	200	0.1013 ± 0.0005	0.028	0.99	0.2671 ± 0.0012	0.072	0.98
1	300	$(243.0 \pm 1.1)10^{-4}$	0.0146	0.99	0.0666 ± 0.0003	0.039	0.98
1	500	$(188.0 \pm 1.0)10^{-5}$	0.0037	0.99	$(53.5 \pm 0.3)10^{-4}$	0.011	0.99
1	1000	$(57.1 \pm 0.3)10^{-6}$	0.00023	1	$(195.2 \pm 0.9)10^{-6}$	0.00081	1
1	5000	$(54.5 \pm 0.3)10^{-9}$	$5.4 \cdot 10^{-8}$	1	$(240.9 \pm 1.4)10^{-9}$	$2.4 \cdot 10^{-7}$	1
10	10				5.731 ± 0.019	0.13	0.94
10	15	0.861 ± 0.003	0.019	1	8.04 ± 0.03	0.18	0.92
10	50	3.558 ± 0.014	0.080	0.97			
50	10	$(169.1 \pm 0.6)10^{-4}$	0.0019	1	0.1580 ± 0.0006	0.018	1.01
50	50	$(222.2 \pm 0.7)10^{-4}$	0.0027	1	0.2086 ± 0.0007	0.026	0.99
50	95	$(124.1 \pm 0.5)10^{-3}$	0.0084	0.99	1.159 ± 0.005	0.079	0.972
50	300	$(261.4 \pm 1.0)10^{-4}$	0.016	0.99	0.0692 ± 0.0003	0.042	0.984
150	10	$(288.0 \pm 1.0)10^{-6}$	$4.0 \cdot 10^{-4}$	1	$(269.0 \pm 1.1)10^{-5}$	0.0038	1
150	200	$(574.0 \pm 1.8)10^{-6}$	$6.9 \cdot 10^{-4}$	1	$(537.0 \pm 1.8)10^{-5}$	0.0064	0.996
150	295	$(68.9 \pm 0.3)10^{-4}$	0.0057	1	0.0645 ± 0.0003	0.053	0.984
150	500	$(166.7 \pm 0.7)10^{-5}$	0.0035	1	$(369.0 \pm 1.4)10^{-5}$	0.0076	0.996
150	5000	$(190.0 \pm 0.8)10^{-10}$	$6.3 \cdot 10^{-8}$	1	$(83.5 \pm 0.3)10^{-9}$	$2.8 \cdot 10^{-7}$	1
500	10	$(285.1 \pm 0.9)10^{-9}$	$2.60 \cdot 10^{-6}$	1	$(265.9 \pm 1.2)10^{-8}$	$2.4 \cdot 10^{-5}$	1
500	500	$(427.8 \pm 1.7)10^{-9}$	$3.81 \cdot 10^{-6}$	1	$(400.8 \pm 1.4)10^{-8}$	$3.6 \cdot 10^{-5}$	1
500	995	$(374.6 \pm 1.7)10^{-8}$	$2.85 \cdot 10^{-5}$	1	$(91.9 \pm 0.3)10^{-7}$	$6.9 \cdot 10^{-5}$	1
1000	10	$(45.18 \pm 0.2)10^{-11}$	$6.81 \cdot 10^{-9}$	1	$(423.0 \pm 1.8)10^{-11}$	$6.4 \cdot 10^{-8}$	1
1000	1000	$(70.78 \pm 0.2)10^{-11}$	$1.06 \cdot 10^{-8}$	1	$(64.9 \pm 0.3)10^{-10}$	$9.7 \cdot 10^{-8}$	1
1000	5000	$(274.6 \pm 0.9)10^{-13}$	$4.4 \cdot 10^{-10}$	1	$(103.5 \pm 0.4)10^{-12}$	$1.6 \cdot 10^{-9}$	1

Table 8.7: Exclusion test results for the DM+ bb pseudoscalar simplified model grid. Sensitivity $\mathcal{S}$ and CL_s for coupling $g = 2$ and 3.5.

m_χ	m_ϕ	$g = 2$			$g = 3.5$		
		σ [pb]	$\mathcal{S}$	CL_s	σ [pb]	$\mathcal{S}$	CL_s
1	10	11.9 ± 0.04	0	1	40.25 ± 0.15	0	1
1	20	8.43 ± 0.03	0	1	25.27 ± 0.09	0	1
1	50	3.009 ± 0.010	0	1	7.985 ± 0.03	0	1
1	100	0.737 ± 0.003	0.03	0.99	1.889 ± 0.008	0.085	0.96
1	200	0.1016 ± 0.0005	0.01	0.99	0.2678 ± 0.0011	0.030	0.97
1	300	$(243.0 \pm 1.1)10^{-4}$	0.02	1.01	0.0668 ± 0.0003	0.055	0.98
1	500	$(188.0 \pm 1.0)10^{-5}$	0.003	1	$(53.6 \pm 0.3)10^{-4}$	0.0095	0.99
1	1000	$(57.14 \pm 0.3)10^{-6}$	0.0003	1	$(195.1 \pm 0.8)10^{-6}$	0.00097	1
1	5000	$(54.4 \pm 0.3)10^{-9}$	$5.8 \cdot 10^{-8}$	1	$(241.0 \pm 1.4)10^{-9}$	$2.6 \cdot 10^{-7}$	1
10	10	0.3904 ± 0.0014	0.009	0.99	3.658 ± 0.013	0.08	0.97
10	15	0.4903 ± 0.0017	0	1	4.563 ± 0.017	0	1
10	50	3.030 ± 0.011	0	1	8.34 ± 0.04	0	1
10	100	0.735 ± 0.003	0.03	0.99	1.889 ± 0.007	0.09	0.96
50	10	$(81.8 \pm 0.3)10^{-4}$	0.0018	1	0.0770 ± 0.0003	0.017	1.01
50	50	$(101.4 \pm 0.4)10^{-4}$	0.0018	1	0.0956 ± 0.0003	0.017	1.01
50	95	$(300.4 \pm 1.0)10^{-4}$	0.0023	1	0.2814 ± 0.0011	0.022	0.998
50	200	0.0981 ± 0.0003	0.031	0.98	0.2504 ± 0.0010	0.079	0.972
50	300	$(227.6 \pm 0.9)10^{-4}$	0.016	1.01	0.0576 ± 0.0002	0.041	0.982
150	10	$(112.3 \pm 0.4)10^{-6}$	0.00016	1	$(105.6 \pm 0.5)10^{-5}$	0.0015	1
150	200	$(191.6 \pm 0.7)10^{-6}$	0.00028	1	$(181.1 \pm 0.6)10^{-5}$	0.0027	1
150	295	$(85.4 \pm 0.3)10^{-5}$	0.00089	1	$(80.2 \pm 0.3)10^{-4}$	0.0083	0.99
150	500	$(99.8 \pm 0.4)10^{-5}$	0.0023	1	$(211.1 \pm 0.8)10^{-5}$	0.0049	1
150	5000	$(124.2 \pm 0.5)10^{-10}$	$5.2 \cdot 10^{-8}$	1	$(54.2 \pm 0.3)10^{-9}$	$2.3 \cdot 10^{-7}$	1
500	10	$(79.2 \pm 0.3)10^{-9}$	$7.7 \cdot 10^{-7}$	1	$(73.89 \pm 0.4)10^{-8}$	$7.2 \cdot 10^{-6}$	1
500	500	$(111.2 \pm 0.5)10^{-9}$	$1.1 \cdot 10^{-6}$	1	$(104.4 \pm 0.4)10^{-8}$	$1.0 \cdot 10^{-5}$	1
500	995	$(66.4 \pm 0.4)10^{-8}$	$5.5 \cdot 10^{-6}$	1	$(243.8 \pm 0.9)10^{-9}$	$2.0 \cdot 10^{-5}$	1
1000	10	$(88.0 \pm 0.4)10^{-12}$	$1.5 \cdot 10^{-9}$	1	$(82.1 \pm 0.3)10^{-11}$	$1.4 \cdot 10^{-8}$	1
1000	1000	$(131.2 \pm 0.5)10^{-12}$	$2.1 \cdot 10^{-9}$	1	$(120.3 \pm 0.5)10^{-11}$	$1.9 \cdot 10^{-8}$	1
1000	5000	$(73.7 \pm 0.3)10^{-13}$	$1.2 \cdot 10^{-10}$	1	$(266.1 \pm 1.1)10^{-13}$	$4.3 \cdot 10^{-10}$	1

Table 8.8: Exclusion test results for the DM+ bb scalar simplified model grid. Sensitivity $\mathcal{S}$ and CL_s for coupling $g = 2$ and 3.5.

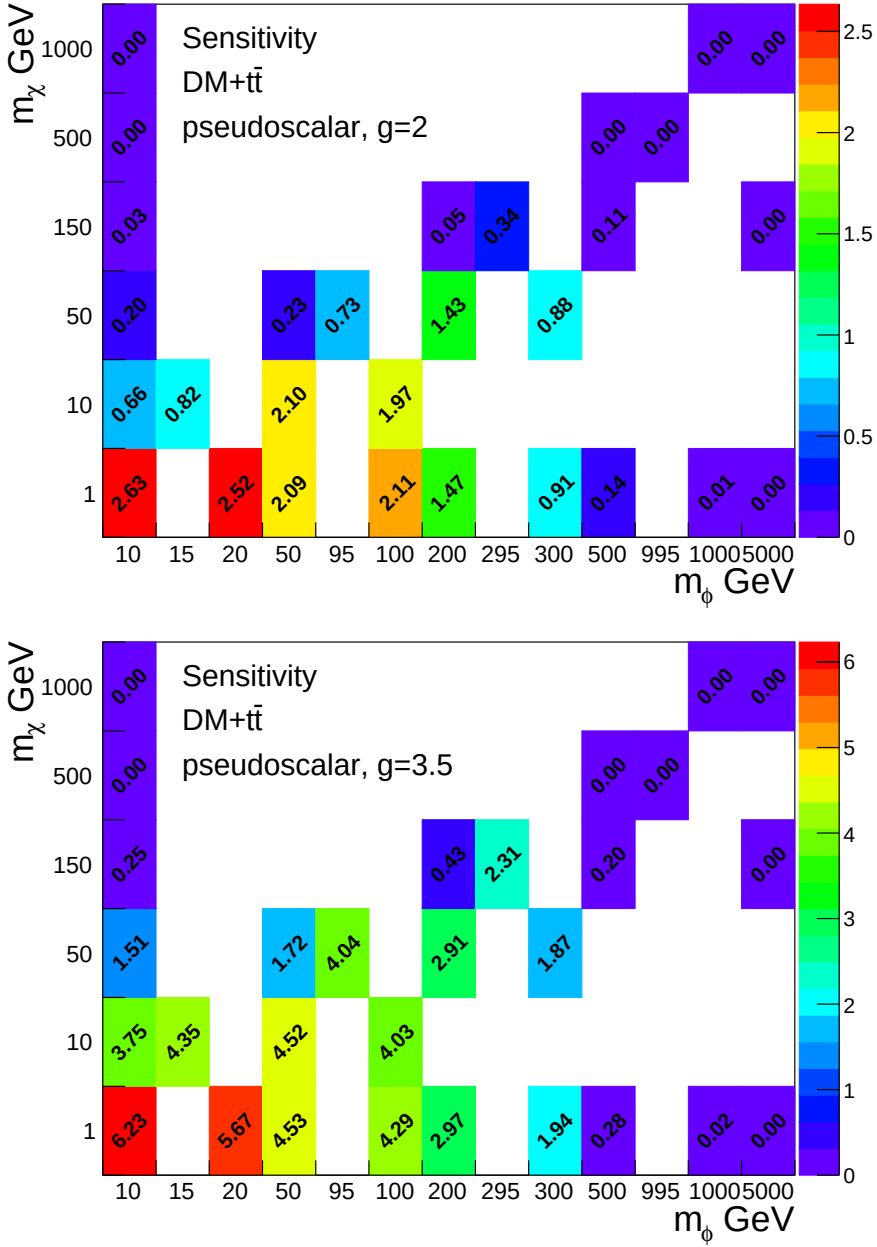


Figure 8.1: Significance, $\mathcal{S}$, of the sensitivity to DM+ $t\bar{t}$ production in the simplified models with pseudoscalar mediator and coupling $g = 2$ (top) and $g = 3.5$ (bottom).

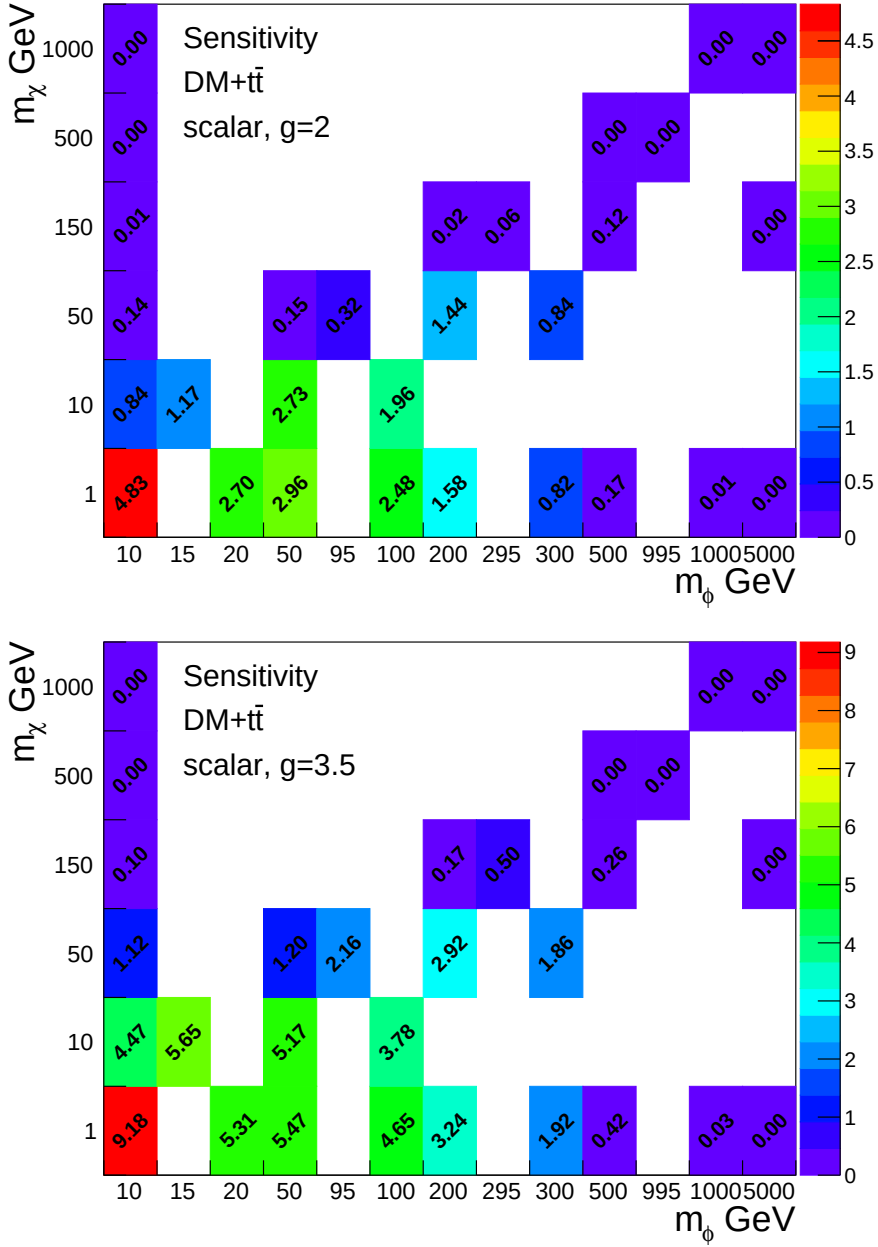


Figure 8.2: Significance, $\mathcal{S}$, of the sensitivity to DM+ $t\bar{t}$ production in the the simplified models with scalar mediator and coupling $g = 2$ (top) and $g = 3.5$ (bottom).

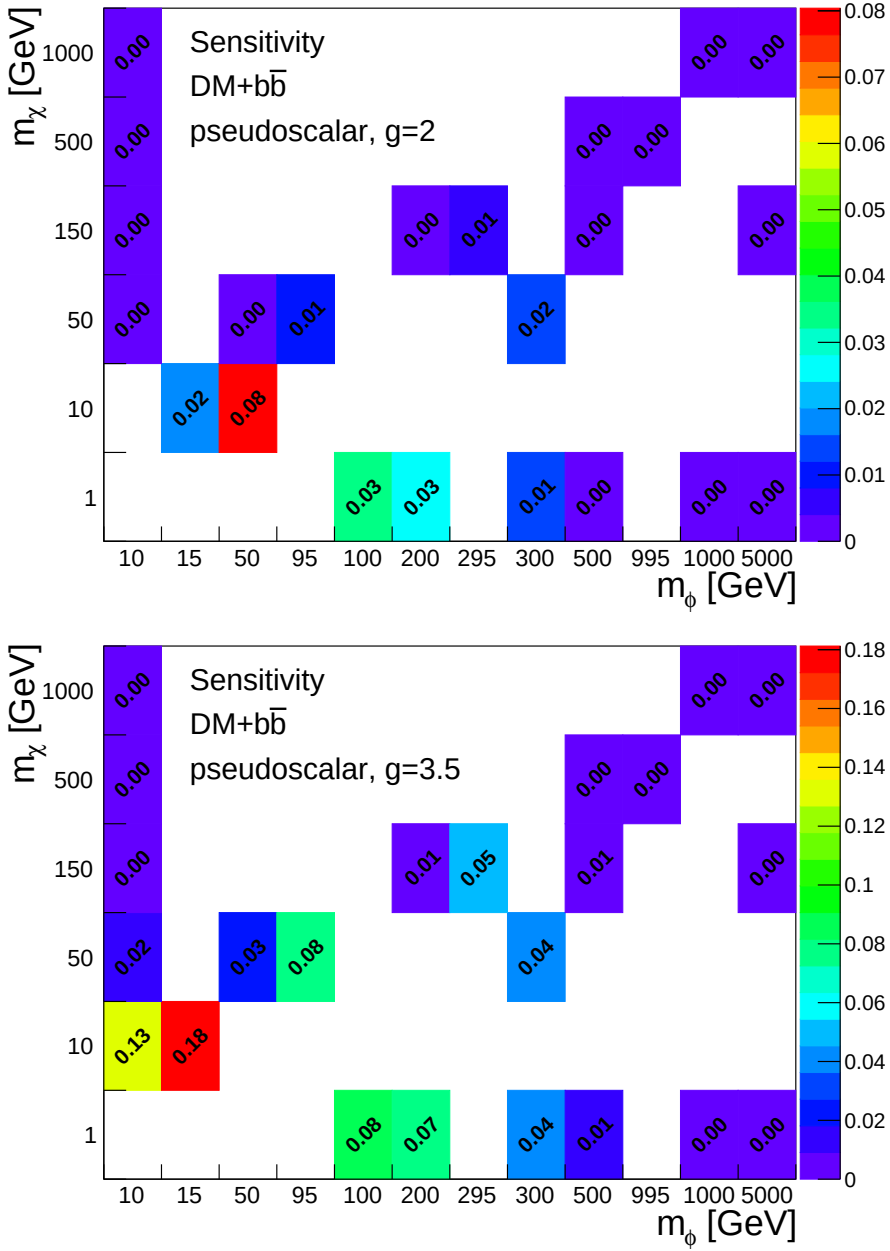


Figure 8.3: Significance, $\mathcal{S}$, of the sensitivity to DM+ $b\bar{b}$ production in the simplified models with pseudoscalar mediator and coupling $g = 2$ (top) and $g = 3.5$ (bottom).

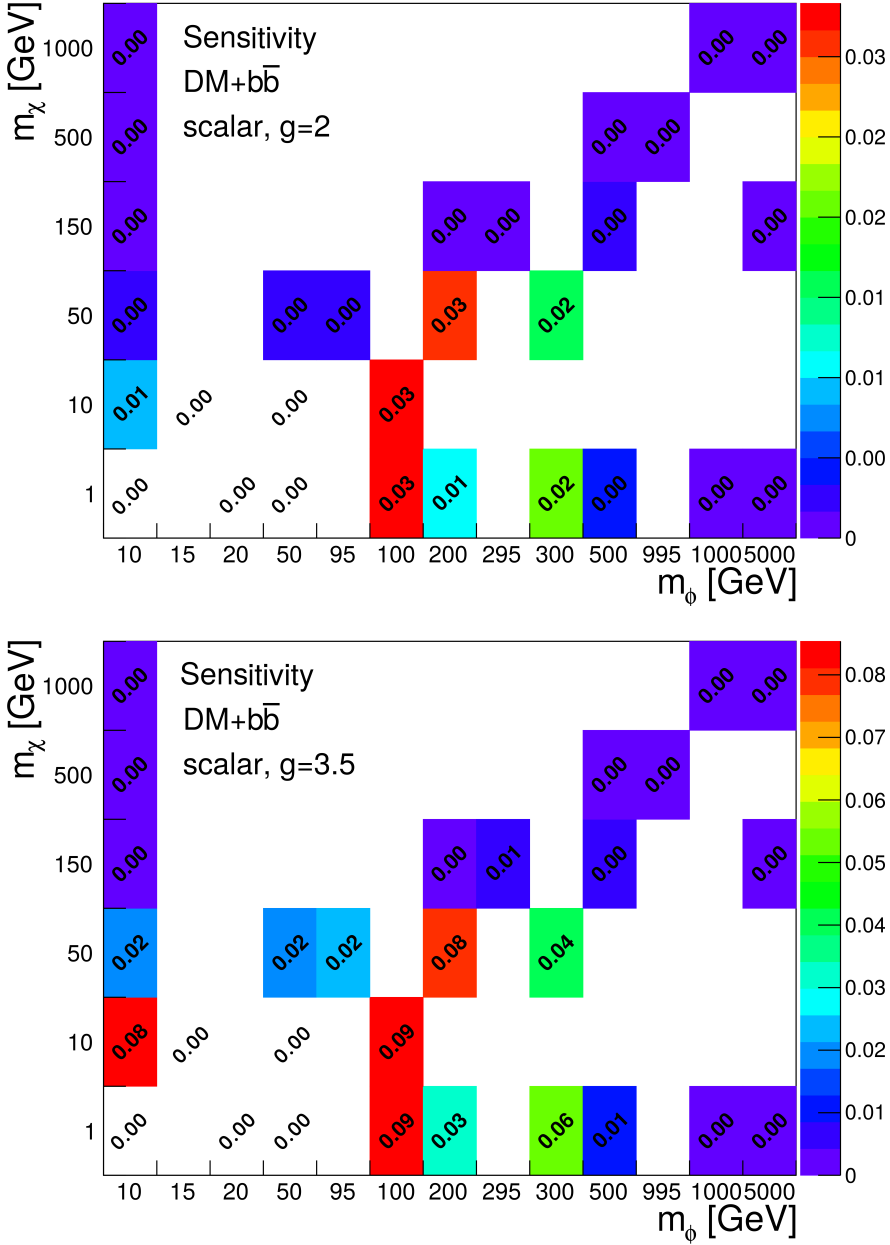


Figure 8.4: Significance, $\mathcal{S}$, of the sensitivity to DM+ $b\bar{b}$ production in the the simplified models with scalar mediator and coupling $g = 2$ (top) and $g = 3.5$ (bottom).

9 DM search at $\sqrt{s} = 13$ TeV

9.1 Motivation and models

The search presented in this chapter is published in Ref. [4]. It is based on the entire sample of pp -collision data collected in 2015 and 2016 at a centre-of-mass energy $\sqrt{s} = 13$ TeV in Run II, corresponding to an integrated luminosity of 36.1 fb^{-1} . Two 1-dimensional grids of the signal model parameters are tested. In the first grid the DM particle mass is assumed to be light, $m_\chi = 1$ GeV. The considered mediator masses are 10, 20, 50, 100, 200, 300, 500, 1000 and 5000 GeV. The second grid is produced by scanning the DM candidate mass at fixed mediator mass of $m_\phi = 10$ GeV. The considered DM candidate masses are 10, 50, 150, 500 and 1000 GeV. The aim of the analysis is to search for DM pair production via a spin-0 mediator in association with a $t\bar{t}$ pair. In case of non-discovery some models are expected to be excluded at 95% C.L., and an upper limit on the production cross section for each point of the parameter grid can be set. This analysis is a continuation of a search based on the partial 2016 data set, corresponding to 13.2 fb^{-1} , presented in Ref. [2]. Since an excess of 3.3σ was observed in the SR DM_low (here referred to as DM_low_loose), this SR is included in the new search together with two new SRs, which have been optimized for this search: DM_low targeting models with low mediator mass and DM_high targeting models with high mediator mass. Taking into account previous results [2], two benchmark models have been chosen for optimization:

- $(m_\phi, m_\chi, g_{\chi,q}) = (20 \text{ GeV}, 1 \text{ GeV}, 1),$
- $(m_\phi, m_\chi, g_{\chi,q}) = (300 \text{ GeV}, 1 \text{ GeV}, 2).$

9.2 Simulated samples

In order to model the signal and background processes the following samples of MC simulated events are used. Signal samples of DM+ $t\bar{t}$ events

with one extra parton are generated with MADGRAPH5_AMC@NLO interfaced with PYTHIA8 for parton shower and hadronization, and using the NNPDF3.0LO PDF set. The couplings of the mediator to the DM and to the SM particles are set to 1, as the kinematics of the decay do not depend strongly on this choice and therefore the cross section can be scaled to probe the other allowed values of the coupling. The signal events are simulated in AtlasFast II, while the background samples are processed with the full simulation of the ATLAS detector [66]. The $t\bar{t}$ and single-top samples are generated with POWHEG using the CT10 PDF set and interfaced to PYTHIA6 for parton showering and hadronization. The $t\bar{t}V$ samples are generated with MADGRAPH interfaced to PYTHIA8. Additional SHERPA $t\bar{t}V$ samples are used to evaluate systematic uncertainties. The W +jets and diboson samples are generated with SHERPA, using the NNPDF3.0 NNLO and CT10 PDF sets, respectively. The MC events are reweighted to match the simulated distribution of the number of interactions per bunch crossing to that measured in data.

9.3 Physics object identification

The analysis described in this chapter exploits *baseline* and *signal* physics objects (electrons, muons etc.) passing either loose or tight requirements. Baseline objects are utilized in computing the missing transverse momentum, as well as in the overlap removal procedure (Sec. 9.3.2). The baseline leptons are used to veto events with zero or more than one lepton. Signal objects are utilized in the signal selections.

9.3.1 Object reconstruction

Baseline electrons are reconstructed in the region $|\eta| < 2.47$ as described in Section 4.2.4. They are required to have $p_T > 5$ GeV and to satisfy the “VeryLooseLH” identification criteria defined in Ref. [134]. Signal electrons must, in addition to all the baseline requirements, also have $p_T > 25$ GeV, satisfy the “LooseAndBLayerLH” identification criteria [134] and have impact parameter significances that satisfy $|d_0|/\sigma_{d_0} < 5$ and $|z_0 \sin \theta| < 0.5$ mm. Signal electrons are isolated from other activity in the EM or ID using the loose isolation requirement [79], which is based on information from ID tracks and does not depend on the electron p_T .

Standalone MS muons, combined muons as well as calo-tagged muons are reconstructed as described in Sec. 4.2.6. Baseline muons are required to have $|\eta| < 2.7$, $p_T > 4$ GeV and to satisfy the “Loose” identification criteria described in Ref. [93]. Signal muons must, in addition to all the baseline requirements, have $p_T > 25$ GeV, satisfy the “Medium” identification criteria defined in Ref. [93] and have $|d_0|/\sigma_{d_0} < 3$ and

$|z_0 \sin \theta| < 0.5$ mm. Signal muons are required to be isolated according to criteria similar to those used for signal electrons, but the isolation criteria are dependent on the muon p_T . Minor mis-modelling of the electron and muon identification and reconstruction in the MC samples is corrected using dedicated scale factors derived from $Z \rightarrow \ell\ell$ data samples.

Jets are built from topological clusters measured in the calorimeters using the anti- k_t algorithm with a jet radius parameter of $R = 0.4$ (Section 4.2.5). Contributions from pile-up are subtracted using the jet area method [47]. The jet energy is calibrated to account for the detector response effects and additional jet energy scale corrections are applied in data (Section 4.2.5). Baseline jets are required to have $p_T > 20$ GeV, while signal jets must have $p_T > 25$ GeV and $|\eta| < 2.5$. Signal jets with p_T below 60 GeV residing within $|\eta| < 2.4$ must satisfy the jet vertex tagger criterion, $JVT > 0.59$, to reject jets originating from pile-up. Identification of b -jets is done with the MV2c10 b -tagging algorithm [135, 136] at a working point providing 77% b -tagging efficiency in simulated $t\bar{t}$ events. Scale factors reflecting the differences in b -tagging efficiencies between data and MC are applied to simulated events.

Hadronically decaying τ leptons are reconstructed using the loose identification criteria described in Ref. [137, 138] and calibrated to the correct energy scale [137]. The τ candidates are required to have one or three associated tracks with total electric charge opposite to the signal electron or muon, $p_T > 20$ GeV and $|\eta| < 2.5$.

Hadronically decaying top candidates are reconstructed using all the signal jets in the event with the iterative reclustering algorithm described in Section 7.5.

The missing transverse momentum is computed as the negative vector sum of the transverse momenta of baseline objects (electrons, muons and jets) and a soft term built from high-quality ID tracks (Section 4.2.7).

9.3.2 Overlap removal

An overlap removal procedure is applied to avoid labelling the same detector signature as more than one object. The procedure checks for overlap between pairs of baseline objects in several steps, shown by the columns in Tab. 9.1. A pair of objects meet the matching condition if they either have a shared track, are ghost-matched [139], or satisfy a requirement on the minimal distance ΔR between them. For example, in the first step, if a baseline electron has a shared track with a calo-tagged baseline muon, the muon is removed, while the electron (as stated in the “Precedence” row) is retained. If the requirement in the “Condition” row

is not met, then both matched objects are kept. Each step is applied to the objects which survived the previous steps.

Step number	1	2	3	4	5
Object 1	e	e	μ	j	e
Object 2	μ	j	j	ℓ	τ
Matching criteria	shared track	$\Delta R < 0.2$	ghost-matched	$\Delta R < \min \left(0.4, 0.04 + \frac{10}{p_T/\text{GeV}} \right)$	$\Delta R < 0.1$
Condition	calo-tagged μ	jet not b tagged	jet not b tagged and $\left(n_{\text{track}}^{\text{jet}} < 3 \text{ or } \frac{p_T^\mu}{p_T^{\text{jet}}} > 0.7 \right)$	–	–
Precedence	e	e	μ	j	e

Table 9.1: Overlap removal procedure for physics objects. The first row shows the order of the steps applied. The types of overlapping objects are given in the second and third rows: electron (e), muon (μ), electron or muon (ℓ), jet (j), and hadronically decaying tau lepton (τ). The third and forth rows specify the matching criteria and the condition which objects 1 and 2 have to meet to be considered overlapping. The last row shows the object which is retained, while the other object is discarded [4].

9.4 Event pre-selection

Events used in this analysis are collected using a set of unprescaled E_T^{miss} triggers. Each trigger accepts events with E_T^{miss} above a given threshold that depends on the data-taking period. The selected events are required to have $E_T^{\text{miss}} > 230$ GeV, which ensures that all the period-dependent triggers are fully efficient. The primary vertex in the event is required have at least two associated tracks with $p_T > 400$ MeV. At least four signal jets and exactly one signal lepton must be present in the event and no additional baseline leptons. To suppress QCD multi-jet events with misidentified or non-prompt leptons and mismeasured E_T^{miss} , the transverse mass of the signal lepton and the missing transverse momentum, m_T , is required to be more than 30 GeV and the azimuthal angle between the E_T^{miss} and each of the two leading jets must be $|\Delta\phi(j_i, E_T^{\text{miss}})| > 0.4$, $i \in \{1, 2\}$. A τ -veto $m_{T2}^\tau > 80$ GeV is applied to remove events with hadronic τ lepton candidates.

Events containing a jet that does not pass the loose jet cleaning criteria are removed to suppress detector noise and non-collision backgrounds [140, 141]. As seen in Fig. 9.1 the data are found to be in good agreement with the background MC predictions after the pre-selection.

9.5 Signal regions

Optimization of the new SRs is done using signal samples generated for the benchmarks with a scalar mediator, assuming an integrated luminosity of $L = 36.5 \text{ fb}^{-1}$. The figure of merit used for optimization is the expected discovery significance defined by equation 4.14, where the systematic error is conservatively estimated to be 20% of the total number of expected background events. The signal region selections are optimized with the following iterative algorithm:

1. All discriminant variables are ranked according to the figure of merit that can be achieved by cutting on them.
2. The highest ranked variable is chosen and a cut maximizing the figure of merit is applied.

These two steps are repeated until no significant improvement in the figure of merit can be achieved. After every iteration at least 10 events of each type of background must be present to ensure that the statistics available in the MC simulated sample is not too low. The resulting signal selections for DM_low and DM_high, together with DM_low_loose are summarized in Table 9.2. All the three SRs put tight requirements on the E_T^{miss} and m_T . DM_low and DM_high require at least one reconstructed hadronic top candidate with a mass of more than 130 GeV.

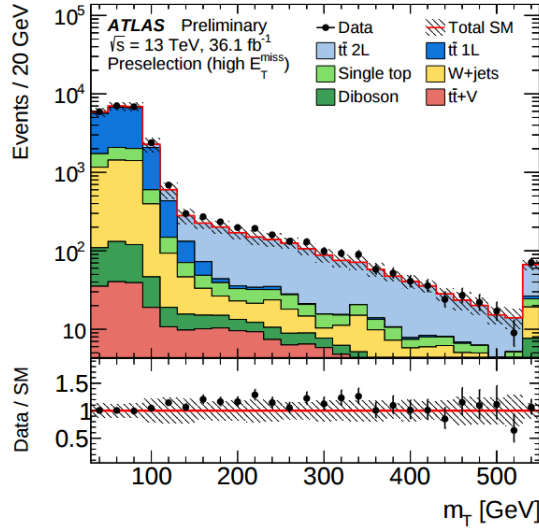


Figure 9.1: The m_T distribution at the pre-selection level. The background predictions are normalized to the theoretical cross sections. Statistical and experimental uncertainties are shown by the hashed area around the total SM prediction and the gray band in the Data/SM ratio panel. The last bin includes overflow [4].

DM_low sets an additional requirement on the p_T of the leading b jet. The tt background is further reduced by the am_{T2} cut and the angular $\Delta\phi(E_T^{\text{miss}}, j_i)$ cuts. The main backgrounds in the SRs are $ttZ(\rightarrow \nu\nu)$, dileptonic tt , and W +heavy flavor processes. The expected numbers of background and signal events (pre-fit yields) in DM_low, DM_high and DM_low_loose are listed in Table 9.3 and the contributions from the different background components are shown in Fig. 9.2. The E_T^{miss} distribution after applying all the SR requirements except for the requirement on the E_T^{miss} itself is shown in Fig. 9.3. Unless the background estimates are explicitly said to “pre-fit”, the background contributions are scaled with normalization factors, which are obtained from a simultaneous likelihood fit (see Section 9.7).

	DM_low_loose	DM_low	DM_high
Number of (jets, b jets)	$(\geq 4, \geq 1)$	$(\geq 4, \geq 1)$	$(\geq 4, \geq 1)$
Leading jet p_T [GeV]	> 60	> 120	> 125
Second jet p_T [GeV]	> 60	> 85	> 75
Third jet p_T [GeV]	> 40	> 65	> 65
Fourth jet p_T [GeV]	> 25	> 25	> 25
Leading b jet p_T [GeV]	–	> 60	–
E_T^{miss} [GeV]	> 300	> 320	> 380
m_T [GeV]	> 120	> 170	> 225
$H_{T,\text{sig}}^{\text{miss}}$	14	14	–
am_{T2} [GeV]	> 140	> 160	190
$\Delta\phi(\vec{E}_T^{\text{miss}}, \ell)$	> 0.8	> 1.2	> 1.2
$\min(\Delta\phi(\vec{E}_T^{\text{miss}}, j_i), i \in \{1, 4\})$	> 1.4	> 1.0	> 1.0
mass of the top candidate [GeV]	–	> 130	> 130

Table 9.2: Event selections defining the DM_low, DM_high and DM_low_loose signal regions. The common event pre-selection defined in Section 9.4 is applied beforehand.

	DM_low	DM_high	DM_low_loose
$t\bar{t}$ 1L	0.07 ± 0.06	0.00 ± 0.00	2.66 ± 1.71
$t\bar{t}$ 2L	2.07 ± 0.21	0.69 ± 0.10	11.49 ± 0.90
W +jets	3.03 ± 1.02	1.52 ± 0.21	11.81 ± 1.48
Single top	0.62 ± 0.13	0.35 ± 0.10	2.76 ± 0.38
$t\bar{t} + V$	6.32 ± 0.39	4.06 ± 0.31	13.02 ± 0.50
Diboson	0.98 ± 0.15	0.66 ± 0.11	3.55 ± 0.25
Total SM	13.08 ± 1.13	7.28 ± 0.42	45.30 ± 2.53
Signal	16.37 ± 2.50	14.20 ± 1.24	27.24 ± 3.04

Table 9.3: Expected number of events (pre-fit) in the SRs for 36.1 fb^{-1} . The uncertainty quoted is statistical only. The last row shows the expected number of signal events for the model with $(m_\phi, m_\chi, g_{\chi,q}) = (300 \text{ GeV}, 1 \text{ GeV}, 2)$ in DM_high and $(20 \text{ GeV}, 1 \text{ GeV}, 1)$ in DM_low and DM_low_loose.

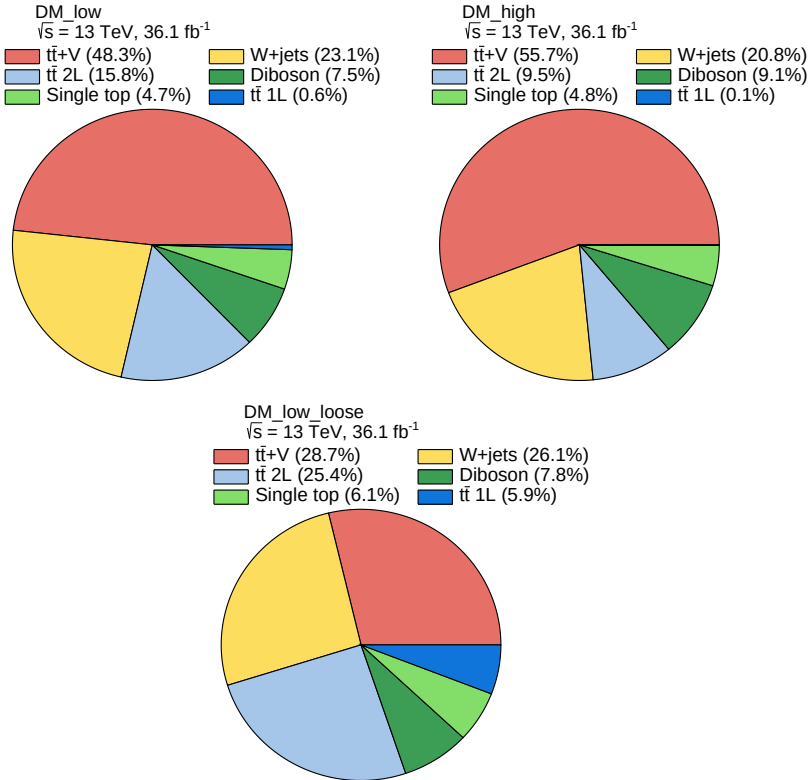


Figure 9.2: Breakdown of the individual SM contributions to the signal regions DM_low (top left), DM_high (top right) and DM_low_loose (bottom).

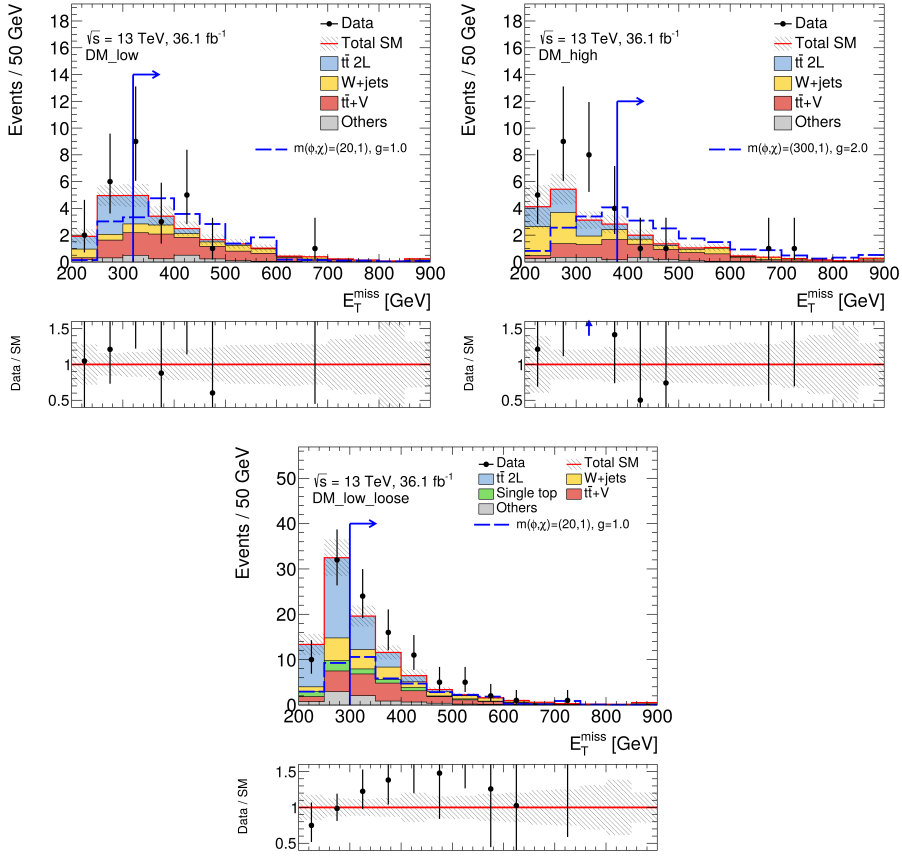


Figure 9.3: Distribution of the E_T^{miss} after applying all cuts of the SR DM_low (top left), DM_high (top right) and DM_low_loose (bottom), except for the cut on E_T^{miss} itself, for which the cut value is indicated by the arrow.

9.5.1 Expected performance

The expected discovery significance of the SRs is shown in Figs. 9.4 and 9.5 as a function of luminosity given 10%, 20% or 30% systematic uncertainty on the background estimation. The significance in DM_low and DM_high is computed for the benchmark points for which they are optimized: $(m_\phi, m_\chi, g) = (20 \text{ GeV}, 1 \text{ GeV}, 1)$ and $(300 \text{ GeV}, 1 \text{ GeV}, 2)$, while the significance in DM_low_loose is computed for both benchmark points. Comparing Figs. 9.4 and 9.5 one can see that the newly optimized SRs are expected to perform better than DM_low_loose for discovery. Non of them reaches 5σ significance and are therefore not able to reach a *discovery*, although all the SRs reach 3σ significance, meaning that it is potentially possible to obtain an *evidence* of new physics using these SRs.

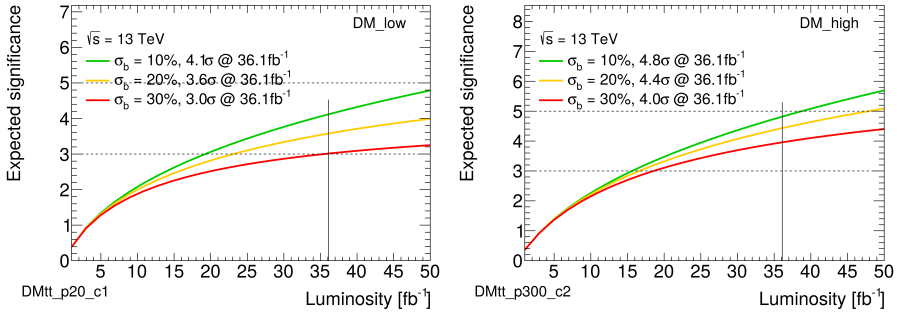


Figure 9.4: Expected discovery significance for the benchmark models as a function of luminosity for DM_low (left) and DM_high (right).

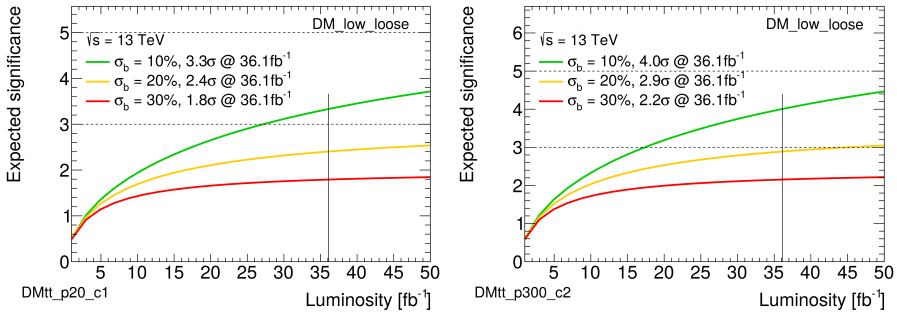


Figure 9.5: Expected discovery significance for benchmarks $(m_\phi, m_\chi, g_{q,\chi}) = (20 \text{ GeV}, 1 \text{ GeV}, 1)$ and $(300 \text{ GeV}, 1 \text{ GeV}, 2)$ as a function of luminosity for DM_low_loose.

9.6 Background and validation regions

To estimate the main background processes each of them is enhanced in a dedicated CR. To validate the estimations of the $t\bar{t}$ and W +jets backgrounds, VRs are built from the corresponding CRs by modifying some of the requirements. Table 9.4 matches each dominant background process to the name of its CR and VR.

Enriched in events	CR name	VR name
semileptonic $t\bar{t}$	T1LCR	T1LVR
dileptonic $t\bar{t}$	T2LCR	T2LVR
W +jets	WCR	WVR
single top (Wt)	STCR	-
$t\bar{t}Z(\rightarrow \nu\nu)$	TZCR	-

Table 9.4: Nomenclature of the control and validation regions.

To estimate the contribution of the $t\bar{t}$ background in DM_low and DM_high, two CRs are defined: T1LCR for the semileptonic $t\bar{t}$ background and T2LCR for the dileptonic $t\bar{t}$ background (which includes cases when the identified lepton originates from τ decay), while for DM_low_loose there is a single TCR enriched in $t\bar{t}$ events.

The CRs and VRs associated with DM_low_loose (except for TZCR) are the same as in Ref. [2] with the only difference that the requirement $E_T^{\text{miss}} > 200$ GeV in TCR and STCR is changed to $E_T^{\text{miss}} > 230$ GeV, to account for the E_T^{miss} trigger threshold increase in late 2016. For DM_low and DM_high the CRs are defined according to the following strategy, similar to that used for other analysis in Ref. [4]. The jet p_T requirements in the CRs and VRs associated to DM_low and DM_high are kept the same as in the SR selections, given in Table 9.2. The requirements on E_T^{miss} and $H_{T,\text{sig}}^{\text{miss}}$ are relaxed and some angular requirements are removed to increase statistics in the CRs.

The CRs and VRs are defined in windows of m_T . In T1LCR and WCR m_T is required to be within a window around the W -boson mass, from 30 to 90 GeV. In T1LVR associated with DM_low or DM_high (as well as TVR associated with DM_low_loose) and W +jets validation region, in WVR the m_T window is shifted to 90-120 GeV, between that of the corresponding CRs and the upper bound set by the SRs. In STCR the m_T window is extended to cover the range from 30 to 120 GeV in order to increase the available statistics. The upper bound at 120 GeV prevents the STCR purity from degrading due to the contribution of dileptonic $t\bar{t}$ events. The price for this extension is the absence of a dedicated VR. The background estimation in STCR is validated using the other VRs and CRs containing a significant single top contribution.

In T2LCR and T2LVR m_T has to be above the W -boson mass endpoint, since in the dileptonic tt events the second neutrino contributes to the m_T calculation.

The presence of a hadronic top quark candidate with mass above 130 GeV (“top-tagging”) is required in T1LCR, while it is vetoed in T2LCR, WCR and STCR to reduce the potential signal contamination and improve the purity of the CRs. In T2LVR the top veto is inverted to the requirement of a hadronic top quark with mass above 130 GeV. While the dileptonic tt events with one lost lepton are suppressed in the SRs by requiring large am_{T2} (mostly above the top-quark mass), these events are selected in T2LCR by requiring low am_{T2} . The requirement on the am_{T2} is tightened in T2LVR associated with DM_high, as this significantly reduces the contamination of potential signal. The am_{T2} variable is also powerful at discriminating the dileptonic tt events from the single-top and the W +jets events. In the single-top and W +jets events the mass of the Wb system, which does not come from an on-shell top quark, is typically higher than the top quark mass in the phase space selected by this analysis. Hence, STCR and WCR are characterized by large am_{T2} . The lower STCR bound on am_{T2} is set as high as 200 GeV to reduce contamination of semileptonic tt events, while WCR keeps the same am_{T2} requirement as in the SRs. The single-top events often have a second b -jet within the acceptance. This fact is used to reduce the W +jets contamination and increase the purity of STCR by requiring two b -tagged jets in the event.

In the semileptonic tt events values of am_{T2} can exceed the top-quark mass, when one of the two b -jet candidates used in the am_{T2} calculation is a mistagged c jet from the hadronic W decay. In this case these two b -jets candidates originate from the same top quark, and ΔR between them tends to be smaller than for Wt events. Since STCR selects events with large am_{T2} values, such semileptonic tt events can contribute to STCR. To remove them from STCR, a requirement of a large ΔR between the two leading b jets is placed. Two processes contribute at LO to W +jets with at least one b jet: $qb \rightarrow Wbq'$, where the W boson originates from ISR, and $qq' \rightarrow Wbb$. In the latter process two b jets are produced from the gluon splitting, therefore the radial distance between them tends to be small. WCR requires $\Delta R(b_1, b_2) < 1.2$ if more than one b jet is present in the event, which makes WCR orthogonal to STCR.

The purity of WCR is increased by the requirement that the lepton in the event is positively charged. Due to the asymmetry in the production of W^+ over W^- events at pp colliders, the lepton in the W +jets events tends to be positively charged. The requirement of large E_T^{miss} increases this effect, as neutrinos from decays of the mostly left-handed

W^+ are preferentially emitted in the same direction as the W^+ . The requirements on lepton charge and $|\Delta\phi(j_i, \vec{E}_T^{\text{miss}})|$ is absent in T2LVR associated with DM_high to increase the number of events entering the VR.

The requirements on m_T , am_{T2} , the hadronic top quark candidates (in DM_low and DM_high) and the number of b jets ensure that the CRs are orthogonal to each other and to the corresponding VRs and SRs. The expected potential signal contamination of the CRs does not exceed 11%.

The ttZ production process, where the Z boson decays to two neutrinos, is the dominant background in this analysis. It is irreducible, so its contribution to the SRs has to be estimated with data-driven techniques, using samples of a process that can mimic the $ttZ(\rightarrow \nu\nu)$, e.g. $ttZ(\rightarrow \ell\ell)$ or $tt\gamma$. In this analysis the $ttZ(\rightarrow \ell\ell)$ samples are exploited to construct a CR enriched with $ttZ(\rightarrow \nu\nu)$ events (TZCR), and the $tt\gamma$ samples are used as a cross check. The TZCR selects events with at least four jets, one of which is b -tagged, and puts the same requirements on the p_T of the four leading jets as in the corresponding SR. Exactly three loose leptons must be present in the event and at least one of them must satisfy the tight criteria. Two of the leptons are required to have opposite charge and the same flavour, and the mass of the dilepton system must be within the window $81 \text{ GeV} < m(\ell\ell) < 101 \text{ GeV}$ around the Z -boson mass.

The kinematic distributions in Fig. 9.6 show good agreement between the observed data and the MC SM predictions. The background contributions are scaled with normalization factors, which are obtained from a simultaneous likelihood fit to data, described in Section 9.7.

Table 9.5 summarizes the definitions of the CRs and VRs associated with the SRs DM_low, DM_high and DM_low_loose. The expected numbers of background and signal events in these CRs and VRs are shown in Tables 9.6 and 9.7. Several kinematic distributions in the VRs are displayed in Fig. 9.7.

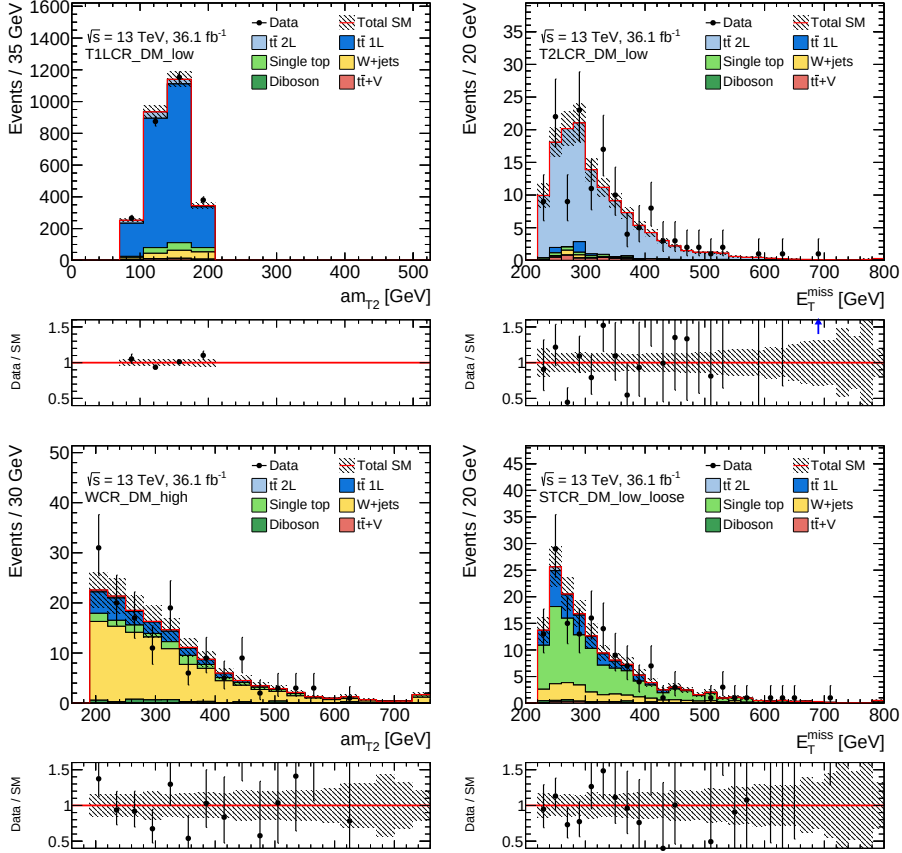


Figure 9.6: Distribution of am_{T2} (left) and E_T^{miss} (right) after applying all cuts of the T1LCR (top left) and T2LCR (top right) associated with DM_low; WCR associated with DM_high (bottom left) and STCR associated with DM_low_loose (bottom right). Only statistical uncertainties are displayed. The last bin includes the overflow.

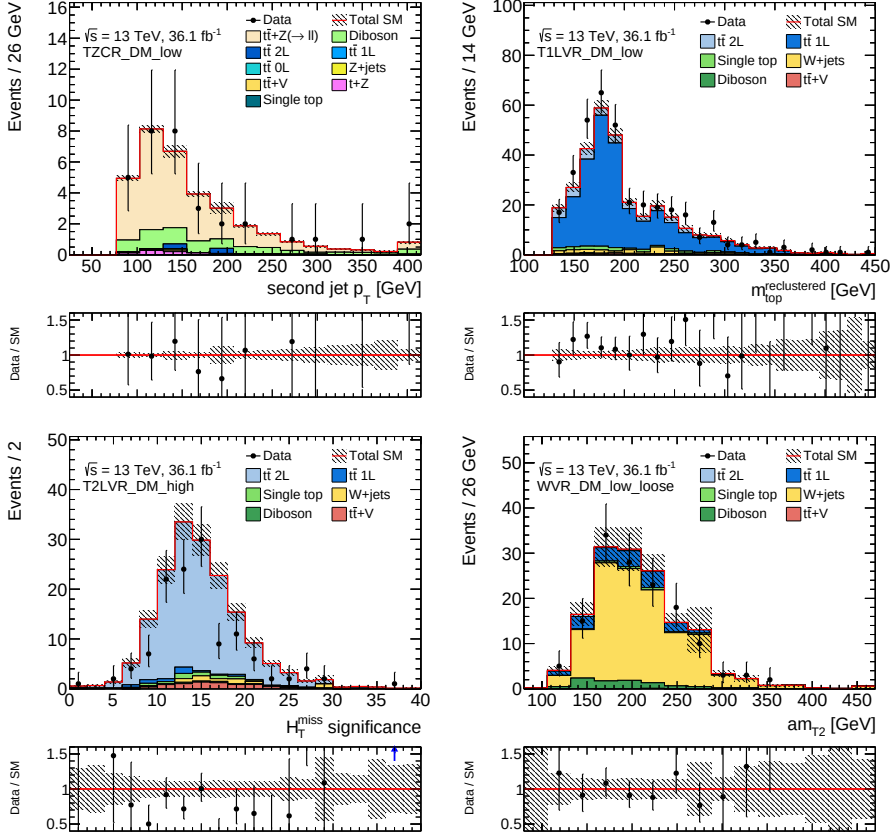


Figure 9.7: Distribution of the second leading jet p_T in TZCR associated with DM_low (top left), the re-clustered hadronic top mass in T1LVR associated with DM_low (top right), H_T^{miss} in T2LVR associated with DM_high (bottom left) and am_{T2} in WVR associated with DM_low_loose (bottom right) in the observed data and simulations. The background contributions in the VRs are scaled with the NFs, while that in TZCR are scaled with the theoretical cross section. Only statistical uncertainties are displayed. The last bin includes the overflow.

	pre-selection				
trigger	$E_{\text{T}}^{\text{miss}} > 230 \text{ GeV}$				
lepton	exactly one signal lepton (e, μ), no additional baseline leptons				
jets	at least 4 signal jets, $ \Delta\phi(E_{\text{T}}^{\text{miss}}, j_{1,2}) > 0.4$				
m_{T} [GeV]	> 30				
τ veto	veto events with a hadronic τ with $m_{\text{T}2}^{\tau} < 80 \text{ GeV}$				
	DM_low	T1LCR/VR	T2LCR/VR	WCR/VR	STCR
jets p_{T} [GeV]	$(> 120, > 85, > 65, > 60)$				
num. of b jets	≥ 1	≥ 1	≥ 1	≥ 1	≥ 2
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 320	> 250	> 230	> 250	> 250
m_{T} [GeV]	> 170	$[30, 90]/[90, 120]$	> 120	$[30, 90]/[90, 120]$	$[30, 120]$
$H_{\text{T},\text{sig}}^{\text{miss}}$	> 14	> 10	> 10	> 10	> 10
$m_{\text{top}}^{\text{had}}$ [GeV]	> 130	> 130	veto/ > 130	veto	veto
$am_{\text{T}2}$ [GeV]	> 160	< 200	< 160	> 160	> 200
$\Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, \ell)$	> 1.2	-	> 1.2	-	-
$ \Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, j_i) $	> 1.0	-	-	-	-
$\Delta R(b_1, b_2)$	-	-	-	< 1.2 or 1 b -jet	> 1.2
lepton charge	-	-	-	$= +1$	-
	DM_high	T1LCR/VR	T2LCR/VR	WCR/VR	STCR
jets p_{T} [GeV]	$(> 125, > 75, > 65, > 25)$				
num. of b jets	≥ 1	≥ 1	≥ 1	≥ 1	≥ 2
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 380	> 280	> 280	> 280	> 280
m_{T} [GeV]	> 225	$[30, 90]/[90, 120]$	> 120	$[30, 90]/[90, 120]$	$[30, 120]$
$m_{\text{top}}^{\text{had}}$ [GeV]	> 130	> 130	veto/ > 130	veto	veto
$am_{\text{T}2}$ [GeV]	> 190	< 200	$< 200 / < 190$	> 190	> 200
$\Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, \ell)$	> 1.2	-	> 1.2	-	-
$ \Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, j_i) $	> 1.0	> 1.0	-	$> 1.0/-$	-
$\Delta R(b_1, b_2)$	-	-	-	< 1.2 or 1 b -jet	> 1.2
lepton charge	-	-	-	$= +1/-$	-
	DM_low_loose	TCR/VR		WCR/VR	STCR
jets p_{T} [GeV]	$(> 60, > 60, > 40, > 25)$				
num. of b jets	≥ 1	≥ 1		$= 0$	≥ 2
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 300	> 230		> 230	> 230
m_{T} [GeV]	> 120	$[30, 90]/[90, 120]$		$[30, 90]/[90, 120]$	$[30, 120]$
$H_{\text{T},\text{sig}}^{\text{miss}}$	> 14	> 8		> 8	> 8
$am_{\text{T}2}$ [GeV]	> 140	$[100, 200]$		> 100	> 200
$\Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, \ell)$	> 0.8	> 0.8		> 0.8	-
$ \Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, j_i) $	> 1.4	> 1.4		> 1.4	> 1.4
$\Delta R(b_1, b_2)$	-	-		-	> 1.8

Table 9.5: Overview of the common event pre-selection and the event selections defining the SRs DM_low, DM_high and DM_low_loose and the associated CRs and VRs.

DM_low	T1LCR	T2LCR	WCR	STCR
$t\bar{t}$ 1L	2401 ± 13	3.1 ± 1.8	73.9 ± 2.4	26.8 ± 1.3
$t\bar{t}$ 2L	90.4 ± 2.1	114.5 ± 3.1	8.07 ± 0.55	4.47 ± 0.54
W +jets	134.5 ± 3.7	1.77 ± 0.77	194.3 ± 4.5	27.6 ± 1.2
Single top	115.2 ± 3.8	2.90 ± 0.40	34.9 ± 1.7	44.9 ± 1.5
$t\bar{t} + V$	21.46 ± 0.73	3.33 ± 0.32	1.58 ± 0.20	1.00 ± 0.17
Diboson	12.6 ± 1.5	0.450 ± 0.060	14.8 ± 1.5	1.59 ± 0.41
Total SM	2776 ± 14	126.1 ± 3.7	327.7 ± 5.6	106.4 ± 2.4
p20_c1_g1	57.3 ± 7.1	14.4 ± 3.0	2.8 ± 1.1	3.3 ± 1.3
DM_low	T1LVR	T2LVR	WCR	
$t\bar{t}$ 1L	259.3 ± 4.8	14.3 ± 1.4	10.4 ± 1.1	
$t\bar{t}$ 2L	30.7 ± 1.3	136.0 ± 3.4	3.25 ± 0.36	
W +jets	14.9 ± 1.7	-2.2 ± 4.2	20.3 ± 1.5	
Single top	12.2 ± 1.1	3.72 ± 0.53	5.8 ± 1.0	
$t\bar{t} + V$	4.33 ± 0.35	6.08 ± 0.39	0.220 ± 0.080	
Diboson	1.45 ± 0.36	0.82 ± 0.11	1.41 ± 0.30	
Total SM	322.8 ± 5.3	158.7 ± 5.6	41.3 ± 2.2	
p20_c1_g1	21.8 ± 3.8	31.1 ± 4.9	0.210 ± 0.090	
DM_high	T1LCR	T2LCR	WCR	STCR
$t\bar{t}$ 1L	208.3 ± 3.6	3.5 ± 1.8	18.6 ± 1.3	25.5 ± 1.1
$t\bar{t}$ 2L	6.40 ± 0.53	111.6 ± 2.6	1.64 ± 0.24	4.33 ± 0.49
W +jets	54.0 ± 2.2	2.75 ± 0.61	91.6 ± 2.8	26.5 ± 1.0
Single top	20.3 ± 1.3	3.85 ± 0.41	13.7 ± 1.0	45.1 ± 1.5
$t\bar{t} + V$	2.35 ± 0.23	4.02 ± 0.35	0.48 ± 0.10	0.93 ± 0.17
Diboson	4.36 ± 0.96	1.10 ± 0.10	4.48 ± 0.75	2.37 ± 0.73
Total SM	295.8 ± 4.6	126.8 ± 3.3	130.5 ± 3.4	104.7 ± 2.3
p300_c1_g2	1.15 ± 0.27	8.53 ± 0.78	0.45 ± 0.19	0.93 ± 0.22
DM_high	T1LVR	T2LVR	WCR	
$t\bar{t}$ 1L	17.4 ± 1.1	3.84 ± 0.86	1.82 ± 0.30	
$t\bar{t}$ 2L	2.61 ± 0.33	122.9 ± 2.8	0.48 ± 0.13	
W +jets	4.91 ± 0.52	4.95 ± 0.97	8.38 ± 0.79	
Single top	1.93 ± 0.30	4.93 ± 0.60	1.84 ± 0.35	
$t\bar{t} + V$	0.53 ± 0.15	7.61 ± 0.45	0.150 ± 0.050	
Diboson	0.30 ± 0.16	1.75 ± 0.17	0.41 ± 0.13	
Total SM	27.6 ± 1.3	146.0 ± 3.2	13.08 ± 0.94	
p300_c1_g2	0.53 ± 0.25	17.2 ± 1.2	0.18 ± 0.11	

Table 9.6: Expected number of events (pre-fit) in the CRs and VRs associated with DM_low (top) and DM_high (bottom) for 36.1 fb^{-1} . Only the statistical uncertainty of the MC samples is given. The last rows of the tables show the expected number of signal events for the models with $(m_\phi, m_\chi, g_{\chi,q}) = (20 \text{ GeV}, 1 \text{ GeV}, 1)$ in DM_low and $(300 \text{ GeV}, 1 \text{ GeV}, 2)$ in DM_high.

DM_low_loose	TCR	WCR	STCR
$t\bar{t}$ 1L	80.6 ± 3.1	26.4 ± 2.9	24.5 ± 1.6
$t\bar{t}$ 2L	3.46 ± 0.60	1.03 ± 0.28	1.91 ± 0.36
W +jets	33.7 ± 2.9	$280. \pm 10.$	24.4 ± 1.2
Single top	10.3 ± 1.8	3.87 ± 0.55	69.5 ± 1.8
$t\bar{t} + V$	0.46 ± 0.11	0.130 ± 0.040	1.95 ± 0.20
Diboson	1.42 ± 0.47	8.9 ± 1.2	1.80 ± 0.50
Total SM	130.0 ± 4.7	$320. \pm 11.$	124.0 ± 2.8
p20_c1_g1	2.9 ± 1.4	0.55 ± 0.51	2.08 ± 0.74
DM_low_loose	TVR	WVR	
$t\bar{t}$ 1L	38.3 ± 3.4	14.9 ± 1.6	
$t\bar{t}$ 2L	7.72 ± 0.82	1.40 ± 0.29	
W +jets	10.6 ± 1.3	123.0 ± 8.4	
Single top	2.69 ± 0.38	1.79 ± 0.38	
$t\bar{t} + V$	0.78 ± 0.12	0.160 ± 0.070	
Diboson	0.59 ± 0.16	9.2 ± 1.6	
Total SM	60.7 ± 3.8	150.5 ± 8.7	
p20_c1_g1	3.1 ± 1.2	0.77 ± 0.47	

Table 9.7: Expected number of events (pre-fit) in the CRs and VRs associated with DM_low_loose for 36.1 fb^{-1} . Only the statistical uncertainty of the MC samples is given. The last rows of the tables show the expected number of signal events for the models with $(m_\phi, m_\chi, g_{\chi,q}) = (20 \text{ GeV}, 1 \text{ GeV}, 1)$ in DM_low_loose.

9.7 Simultaneous fit

9.7.1 Likelihood fit

For each SR a likelihood fit is performed in the associated bins: SR, T1LCR, T2LCR (or TCR), WCR, STCR, TZCR and the corresponding VRs. In each bin i a probability density function (PDF) $\mathcal{P}_i$ is constructed based on a Poisson term $P(n_i^{\text{obs}} | \lambda_i(\mu_{\text{sig}} \cdot \vec{n}_{\text{sig}} + \vec{n}_{\text{bkg}}, \vec{\theta}))$, where n_i is the number of observed events in bin i and λ_i is the Poisson expectation, which depends on the signal strength parameter μ_{sig} , the expected number of signal events $\vec{n}_{\text{sig}}$, the normalized background predictions n_{bkg} and nuisance parameters $\vec{\theta}$, that model the systematic uncertainties. The signal strength μ_{sig} in this analysis represents a ratio between the DM production cross section and the simplified model expectation of the DM production cross section. It is taken to be 0 when testing the background only hypothesis and 1 when testing the signal-plus-background hypothesis.

All systematic uncertainties that can affect the signal and background expectation are factorized to independent sources. The impact of each systematic uncertainty j is modelled by a nuisance parameter θ_j , that is allowed to vary according to a PDF, usually the standard Gaussian dis-

tribution. For the nominal value $\theta_j^0 = 0$, and for $\pm 1\sigma$ (“up” and “down”) variations of the systematic uncertainty $\theta_j = \pm 1$, where 1σ means one standard deviation. The constraints on the systematic uncertainties are implemented by the PDF term

$$C_{\text{sys}}(\vec{\theta}^0, \vec{\theta}) = \prod_j G(\theta_j^0 - \theta_j), \quad (9.1)$$

where $\vec{\theta}^0 = \{\theta_1^0, \theta_2^0, \dots, \theta_j^0\}$ are the central values around which $\vec{\theta}$ are varied. The nuisance parameters are treated as uncorrelated, and the total uncertainty on the fitted total background in the SRs, CRs and VRs is computed, properly taking into account the correlation matrix between the individual uncertainties.

A likelihood function is built as the product of Poisson probabilities for the bins and the term describing the systematic uncertainties:

$$\begin{aligned} L(\vec{n}^{\text{obs}}, \vec{\theta}^0 | \mu_{\text{sig}} \cdot \vec{n}_{\text{sig}}, \vec{n}_{\text{bkg}}, \vec{\theta}) &= \mathcal{P}_{\text{SR}} \cdot \mathcal{P}_{\text{CRs}} \cdot C_{\text{sys}} = \\ \mathcal{P}(n_{\text{SR}}^{\text{obs}} | \lambda(\mu_{\text{sig}} \cdot \vec{n}_{\text{sig}}, \vec{n}_{\text{bkg}}, \vec{\theta})) &\times \\ \prod_{i \in \text{CRs}} \mathcal{P}(n_i^{\text{obs}} | \lambda_i(\mu_{\text{sig}} \cdot \vec{n}_{\text{sig}}, \vec{n}_{\text{bkg}}, \vec{\theta})) &\cdot C_{\text{sys}}(\vec{\theta}^0, \vec{\theta}) \end{aligned} \quad (9.2)$$

The p -values and CL_s (see Section 4.3.2 for details) are evaluated in the profile likelihood fit. The profile likelihood ratio is constructed as

$$q(\mu_{\text{sig}}) = \frac{L(\mu_{\text{sig}}, \hat{\vec{\theta}}(\mu_{\text{sig}}))}{L(\hat{\mu}_{\text{sig}}, \hat{\vec{\theta}})}, \quad (9.3)$$

where the maximum likelihood estimates $\hat{\vec{\theta}}$ and $\hat{\mu}_{\text{sig}}$ are the values of the parameters $\vec{\theta}$ and μ_{sig} that maximize the likelihood function $L(\mu_{\text{sig}}, \vec{\theta})$.

The $\hat{\vec{\theta}}$ is the conditional maximum likelihood estimate that equals the value of $\vec{\theta}$ which maximizes the likelihood function for a given μ_{sig} , and is often called the profiled value of $\vec{\theta}$. The profile likelihood ratio can take values $0 \leq q(\mu_{\text{sig}}) \leq 1$. The values close to 1 show good agreement between data and the expectation for the assumed μ_{sig} value.

The hypothesis test is performed using the one-sided profile likelihood ratio $t_{\mu_{\text{sig}}}$ as test statistic [100]:

$$t_{\mu_{\text{sig}}} = \begin{cases} -2 \ln q(\mu_{\text{sig}}), & \hat{\mu}_{\text{sig}} \leq \mu_{\text{sig}} \\ 0, & \hat{\mu}_{\text{sig}} > \mu_{\text{sig}} \end{cases} \quad (9.4)$$

This test statistic is constructed so that only data fluctuating downward ($\hat{\mu}_{\text{sig}} \leq \mu_{\text{sig}}$) would be considered in the calculations, when setting upper

limits. The data that fluctuate upwards ($\hat{\mu}_{\text{sig}} > \mu_{\text{sig}}$) can not represent less or equal compatibility with the hypothesized μ_{sig} , hence these data are disregarded in this case and $t_{\mu_{\text{sig}}} = 0$.

9.7.2 Fit configurations

Three types of fit configuration are used in this analysis: background-only fit, exclusion (model-dependent) and discovery (model-independent) fit. All of them are implemented in the HistFitter software framework [128].

The **background-only fit** is done without any assumption on a signal model, using only the simulated background samples and the data samples. Only the CRs are used in this fit and they are assumed to be free of any signal contamination. This fit configuration serves to derive the *transfer factors* (TFs) to extrapolate the MC predictions of the dominant background processes in the dedicated CRs into the VRs and to the SR by constraining the fit parameters, which correspond to the background *normalization factors* (NFs). In order to compute the background normalization factors μ_p , the number of events N_p^{CR} of a background process p in the CR, obtained from the MC simulation (pre-fit number), is used to fit the number of events observed in data in this region:

$$N_{\text{data}}^{\text{CR}} = \sum_p \mu_p \cdot N_p^{\text{CR}}, \quad (9.5)$$

where the CRs are T1LCR, T2LCR or T3LCR for DM_low_loose, WCR, STCR and TZCR; and the summation is done over the dominant background processes: the semileptonic and dileptonic $t\bar{t}$ backgrounds for DM_low and DM_high or the $t\bar{t}$ background for DM_low_loose, the single top background, the W +jets and the $t\bar{t}Z$ backgrounds. To account for the presence of the (minor) diboson background, that is not estimated in a dedicated CR, the number of diboson events normalized by the theoretical cross section is subtracted from the right sides of equations 9.5. In the background-only fit configuration there are five free parameters μ_p for the new SRs (DM_low and DM_high) and four free parameters for DM_low_loose, corresponding to each type of dominant background. To estimate the expected background contribution $N_{p,\text{exp}}^{\text{R}}$ in the validation or the signal region R, the pre-fit number of events N_p^{R} of the background process p in this region is scaled by the corresponding NF:

$$N_{p,\text{exp}}^{\text{R}} = \mu_p \cdot N_p^{\text{R}} \equiv N_{p,\text{exp}}^{\text{CR}} \cdot \left[\frac{N_p^{\text{R}}}{N_p^{\text{CR}}} \right]. \quad (9.6)$$

The ratio appearing in the square brackets is defined as the transfer factor.

The **discovery fit** tests the background-only hypothesis and sets **model-independent** limits on the number of potential signal events in the SR. The signal region and all CRs associated with it are included in the fit simultaneously, but instead of using signal samples a “dummy signal” prediction with one signal event is added. The signal in this fit configuration can contribute only to the SR. In presence of a signal, its contamination in the CRs is attributed to the background processes, thus the background can potentially be overestimated in the CRs as well as in the SR, which would make the fit configuration conservative, but that should not happen if the CRs are well-designed. The model-independent profile likelihood fit is performed two times: the background-only hypothesis test, when μ_{sig} is set to zero, and the one-sided hypothesis test, when μ_{sig} (and consequently the number of signal events) is floating but positive. The first fit allows to derive the p_b -value, which is the probability that the background fluctuates up to, or beyond, the observed number of events. The p_b -values are set to 0.5 if the number of observed events is less than the number of expected events. The second fit allows to set the observed and expected 95% confidence level upper limit on the number of non-SM events in the SR.

The **exclusion fit** tests the signal-plus-background hypothesis and derives exclusion limits on the tested signal model. It is performed for each point of the parameter grid. A signal strength parameter μ_{sig} is assigned to the signal sample. The signal region and all CRs associated with it are included in the fit simultaneously. The signal contribution in the SR and the CRs is taken into account as predicted by the signal model. The result of the exclusion test is expressed as a CL_s value, representing the probability that the observation is compatible with the signal-plus-background hypothesis. CL_s is computed with two different approaches. The *observed* CL_s value is derived when the observed data in the SRs are used in the calculation. The *expected* sensitivity of the analysis is derived by using the number of the expected number of background events in the SRs instead of the observed data. The signal model under consideration is excluded at 95% confidence level, if the CL_s value is below 0.05. Scanning over the signal strength parameter μ_{sig} , an upper limit on it is set to the value yielding $\text{CL}_s = 0.05$.

9.8 Systematic uncertainties

Systematic uncertainties are incorporated in the profile likelihood ratio as nuisance parameters constrained by standard Gaussian distribution.

Uncertainty of channel [%]	DM_low	DM_high	DM_low_loose
Total systematic uncert.	26.14	28.87	17.05
$t\bar{t}V$ modeling	14.6	17.7	8.9
W +jets modeling	4.4	4.9	2.7
$t\bar{t}2L$ hard scatter. modeling	2.5	2.5	4.9
MC statistical uncertainties	8.6	5.7	5.6
$t\bar{t} + Z$ fitted normalization	17.5	20.7	8.7
W +jets fitted normalization	3.9	4.3	2.3
$t\bar{t}2L$ fitted normalization	1.7	1.2	6.2
Pile-up reweighting uncert.	1.2	5.5	4.5
Jet energy scale	8.3	4.6	0.53
tagging efficiency for c jets	5.4	2.8	3.5
Jet energy resolution	3.1	1.8	5.6

Table 9.8: The impact of the main sources of systematic uncertainty on the total predicted background yield (in %), obtained in the background-only fits, in each SRs. Since the individual sources can be correlated, the total systematic uncertainty can be different from their sum in quadrature.

From a technical point of view, evaluation of some uncertainties require production of separate samples, in which the parameter of interest is varied, and then the background TFs, obtained by running the analysis on the nominal and varied samples, are compared. For all systematic variations, histograms for nominal and varied samples are built in Hist-Fitter, so that the fit is only performed once, taking into account all the systematic variations. In most cases production of separate samples is not needed, as varied histograms can be built from the nominal by applying weights. Table 9.8 summarises the contributions of the dominant sources of systematic uncertainty for the three SRs.

9.8.1 Experimental systematic uncertainties

The main sources of experimental systematic uncertainties are briefly discussed in this section.

- **JES**

Three nuisance parameters representing the impact of various JES uncertainty components are included in the final fit. JES is the dominant experimental uncertainty in this analysis.

- **JER**

The uncertainty on the measurement of the jet energy resolution (JER) is derived using techniques described in [92] by smearing the jet energy in simulations according to the 1σ variation on the

resolution.

- **E_T^{miss} soft term**

The uncertainty associated with E_T^{miss} soft term reconstruction is assessed by varying the scale of the "soft" tracks that are not associated to hard reconstructed objects, described by the last term of equation 4.3 for the E_T^{miss} calculation.

- **Flavor tagging**

The uncertainty on the modelling of the b -tagging efficiency is estimated by varying the efficiency correction factors for b and c jets as well as the mistag rate correction factor within their uncertainties.

- **Other uncertainties**

The experimental uncertainties associated to the modelling of the lepton energy scales, energy resolutions, reconstruction and identification efficiencies, the modelling of pile-up and the integrated luminosity are found to be negligible.

9.8.2 Theoretical systematic uncertainties

Since the contributions of $t\bar{t}$, single top, W +jets and $t\bar{t}V$ processes are estimated in dedicated CRs, the uncertainties on the modelling of these processes affect only the extrapolation from the CR to the SR and to the other CRs. The following sources of systematic uncertainties related to the theoretical calculations are considered in the analysis.

- **Cross section**

The uncertainty on the theoretical cross section of the major background processes is not relevant for the analysis, since their normalizations are obtained from the fit using the CRs. However, the diboson samples are normalized by the predicted cross section, and the uncertainty on it was assessed.

- **MC generator**

The uncertainty on the choice of MC event generator is estimated for every background process by comparing samples produced with different generators.

- **Fragmentation/hadronization modelling**

Two different hadronization models (cluster and string models) are implemented in HERWIG and PYTHIA. The effects of these two mechanisms on the background estimation is assessed as a systematic uncertainty.

- **Additional radiation variation**

The uncertainty is calculated as the difference between the nominal samples and the samples designed to encompass some or all (depending on the generator) of the following effects:

- variable amount of parton shower (initial and final state) radiation produced by the generator;
- choice of renormalisation and factorization scales;
- choice of matching parameter between the matrix element and the parton shower;
- variation of the scale used for the resummation of soft gluon emission [142] (QSF variations).

- **PDF**

The cross sections of processes in proton-proton collision are derived using the PDF functions that are not calculable from the first principles but are determined experimentally with an uncertainty. This effect is either included in the cross section uncertainty or absorbed in the CR NF. The systematic uncertainty due to the choice of the PDF set in the MC generator gives a small effects on the background acceptance.

- **$t\bar{t}$ and single top interference effect**

Some of the Feynman diagrams beyond LO, that contribute to the Wt production can be interpreted as $t\bar{t}$ production at LO with subsequent decay of the t into a bW pair [143]. A large increase of the cross section of these diagrams occurs in the resonant kinematic region, where the invariant mass of the Wb -system approaches the top quark mass. Inclusive $WWb\bar{b}$ events are generated and compared with the sum of the resonant $t\bar{t}$ and Wt processes to evaluate the uncertainty arising from this interference.

Signal uncertainties

The production cross sections for the DM signal models are computed at NLO in the MadGraph generator. Uncertainties on the k-factors (the ratio of the NLO to LO cross section values) are estimated by comparing with the k-factors computed in PYTHIA, and combined (summed up in quadrature) with uncertainties on the values of the renormalization and factorization scales, and choice of the PDF set. The NLO cross sections, k-factors and uncertainties on them are displayed in Appendix G in Tab. A.3 of the samples generated for the models with a scalar or

pseudoscalar mediator. The breakdown of the systematic uncertainties in all the bins of the fit can be found in Appendix H for each SR.

9.9 Results

The background-only fit to data is performed using the MC (pre-fit) background yields in the CRs to obtain the background NFs. The NFs are presented in Table 9.9 and turn out to be close to 1 in all cases. The expected background yields in the SRs and VRs are derived by ap-

SR	DM_low	DM_high	DM_low_loose
$t\bar{t}1l$	0.95 ± 0.04	1.08 ± 0.14	1.13 ± 0.21
$t\bar{t}2l$	1.06 ± 0.12	1.19 ± 0.13	
W +jets	1.04 ± 0.18	1.08 ± 0.21	0.93 ± 0.10
single top	1.05 ± 0.35	0.94 ± 0.37	1.22 ± 0.27
$t\bar{t}Z$	1.06 ± 0.38	0.98 ± 0.38	1.10 ± 0.32

Table 9.9: The background normalization factors (NFs) obtained in the background-only fit [4].

plying the NF to the MC yields in the SRs and VRs using equation 9.6. The CRs are validated by comparing the expected (post-tag) background yields in the CRs and the VRs with the observed data. The SM predicted distributions in the CRs and the VRs agree well with the observed data, as seen e.g. from Figs. 9.6 and 9.7, which allows to unblind the data in the SRs. The MC expected and fitted numbers of the background events along with the observed numbers of events in DM_low, DM_high and DM_low_loose and the corresponding CRs and VRs are shown in Tables 9.11, 9.12 and 9.13. The discovery fit is performed in each SR, and the results are given in Table 9.10. No significant excess above the SM

SR	DM_low	DM_high	DM_low_loose
$p_b(\sigma)$	0.5(-)	0.5(-)	0.07 (1.5)
$N_{\text{non-SM}}^{\text{limit exp.}}$	11	7.2	23
$N_{\text{non-SM}}^{\text{limit obs.}}$	10	5.7	37

Table 9.10: The discovery fit results given by the expected and observed upper limits on the numbers of non-SM events, and the probabilities (represented by p_b values) under the background-only hypothesis to find a number of events equal or larger than the observed numbers of events [4].

expectation is observed in the SRs. The unblinded kinematic distributions in the SRs, some of which are presented in Fig. 9.8, indicate good compatibility between the observed data and the SM predictions. The largest excess of 1.5σ is observed in DM_low_loose, hence the excess of 3.3σ observed in Ref. [2] is not confirmed. In Fig. 9.9 the observed

numbers of events are compared with the SM background prediction in the SRs and the associated VRs.

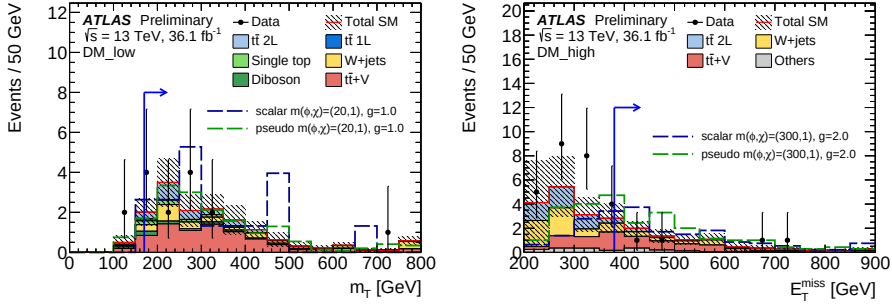


Figure 9.8: The m_T distribution in DM_low and the E_T^{miss} distributions in DM_high. The requirement on the displayed variable, indicated by the arrow, is not applied. The predicted SM background contributions are scaled with the NFs obtained from the corresponding CRs. The distributions predicted by the simplified models with coupling $g = 1$ are shown overlaid on the plots. The histogram labelled as “Others” represents the minor SM backgrounds that contribute less than 5% to the total SM background. The statistical and experimental uncertainties are shown by the hashed area around the total SM prediction. The last bin contains overflow [4].

Since no discovery is made, the model-dependent profile-likelihood fits are performed using the CL_s method. Exclusion limits at 95% confidence level are set on the signal strength, defined as a ratio $\mu_{\text{sig}} = \sigma/\sigma_{\text{th}}$, where σ is the measured signal cross section and σ_{th} is its theoretical value, calculated under the assumption of a simplified model with scalar or pseudoscalar mediator and unitary couplings. These limits can be considered as limits on the scaling factor that should be applied to the theoretical cross section in order to exclude the considered model. For each point of the parameter grid the SR providing the lowest expected CL_s value is chosen and the resulting best expected and observed exclusion limits are demonstrated in Fig. 9.10 as functions of the mediator mass (plots on the top) and the DM candidate mass (plots on the bottom). The solid black and the dashed red lines in Fig. 9.10 correspond to the observed and expected limits 95% CL limits. The yellow and the green bands show the experimental 1σ and 2σ uncertainties on the expected limit, while the blue line shows the signal strength scaled up and down by 1σ of theoretical uncertainties, assuming $g = 1$. The benchmarks with high mediator and DM candidate masses are omitted in the figure to properly display the interesting region, where the limits are close to the theoretical cross section. Table 9.14 contain the numerical values of the expected and observed upper limits on μ_{sig} and σ

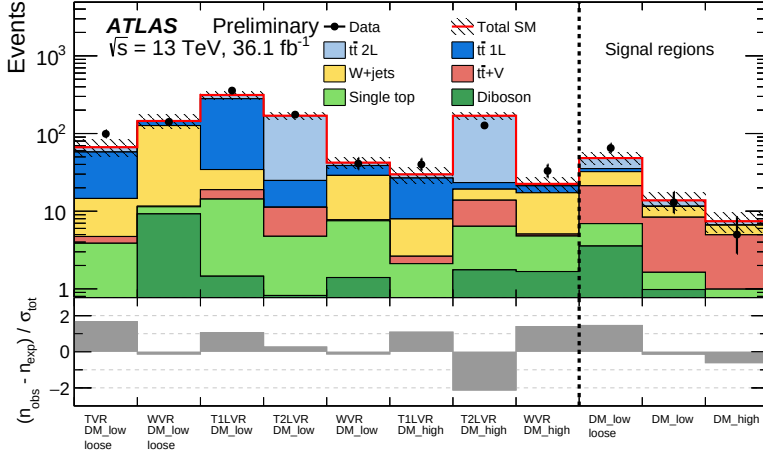


Figure 9.9: Comparison of the observed data (n_{obs}) with the predicted SM background (n_{exp}) in the DM_low, DM_high and DM_low_loose signal regions and the associated VRs. The background predictions are obtained using the background-only fit configuration, and the hashed area around the SM prediction includes all uncertainties. The bottom panel shows the difference between data and the predicted SM background divided by the total uncertainty (σ_{tot}) [4].

together with the theoretical cross section σ_{th} for the full set of the models with scalar and pseudoscalar mediator assuming unitary couplings. The best observed limit upper limits are set for the simplified model with $m_\chi = 1$ GeV and m_ϕ below 300 GeV. The simplified models with a scalar (pseudoscalar) mediator mass of up to 65 GeV (220 GeV) are excluded at 95% CL, assuming unitary couplings. Even though DM_low and DM_high are optimized for discovery, they show a significant improvement in exclusion compared to the SRs used in the previous search for the same signature [2].

		T1LVR	T2LVR	WVR	DM_low	
Observed events		357	175	41	13	
Fitted bkg events	$t\bar{t}1l$	246 ± 34	13.7 ± 5.5	9.9 ± 2.4	0.07 ± 0.03	
	$t\bar{t}2l$	32.7 ± 4.2	145 ± 16	3.47 ± 0.91	2.21 ± 0.58	
	W +jets	15.5 ± 4.3	0.00 ± 0.00	21.1 ± 5.5	3.2 ± 1.3	
	single top	12.9 ± 4.8	3.9 ± 1.3	6.1 ± 2.5	0.65 ± 0.57	
	$t\bar{t}Z$	4.6 ± 1.5	6.5 ± 2.4	0.23 ± 0.11	6.72 ± 3.2	
	diboson	1.45 ± 0.54	0.82 ± 0.28	1.40 ± 0.87	0.98 ± 0.33	
	Total	313 ± 37	170 ± 16	42.2 ± 6.4	13.8 ± 3.6	
MC exp. SM events	$t\bar{t}1l$	259.28	14.32	10.35	0.07	
	$t\bar{t}2l$	30.68	135.95	3.25	2.07	
	W +jets	14.88	0.00	20.28	3.03	
	single top	12.17	3.72	5.80	0.62	
	$t\bar{t}Z$	4.33	6.08	0.22	6.32	
	diboson	1.45	0.82	1.41	0.98	
	Total	322.79	160.89	41.29	13.08	
		T1LCR	T2LCR	WCR	STCR	ttZCR
Observed events		2674	134	335	109	36
Fitted bkg events	$t\bar{t}1l$	2280 ± 78	3.0 ± 1.7	70 ± 14	25.6 ± 5.7	0.00 ± 0.00
	$t\bar{t}2l$	96 ± 24	122 ± 12	8.6 ± 2.1	4.8 ± 1.4	0.33 ± 0.05
	W +jets	140 ± 29	1.9 ± 1.0	202 ± 28	28.8 ± 5.2	0.00 ± 0.00
	single top	121 ± 52	3.1 ± 1.6	37 ± 14	$47. \pm 14.$	0.00 ± 0.00
	$t\bar{t}Z$	22.8 ± 7.9	3.5 ± 1.2	1.68 ± 0.65	1.07 ± 0.38	25.7 ± 9.0
	diboson	12.6 ± 4.1	0.45 ± 0.17	14.9 ± 3.8	1.60 ± 0.83	6.06 ± 0.89
	Total	2674 ± 52	134 ± 12	334 ± 18	109 ± 10	36.0 ± 6.0
MC exp. SM events	$t\bar{t}1l$	2401.50	3.14	73.99	26.84	0.00
	$t\bar{t}2l$	90.42	114.54	8.07	4.47	0.33
	W +jets	134.50	1.77	194.27	27.60	0.00
	single top	115.24	2.90	34.91	44.88	0.00
	$t\bar{t}Z$	21.46	3.33	1.58	1.00	24.12
	diboson	12.56	0.45	14.84	1.59	6.05
	Total	2775.69	126.13	327.66	106.38	34.45

Table 9.11: The numbers of observed events in DM_low and the associated CRs and VRs together with the expected fitted and pre-fit number of background events for 36.1 fb^{-1} . Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty.

		T1LVR	T2LVR	WVR	DM_high	
Observed events		40	127	33	5	
Fitted bkg events	$t\bar{t}1l$	18.8 ± 4.8	4.2 ± 1.6	4.0 ± 1.5	0.00 ± 0.00	
	$t\bar{t}2l$	3.10 ± 0.88	146 ± 16	1.26 ± 0.18	0.82 ± 0.27	
	W +jets	5.3 ± 2.0	5.4 ± 1.6	12.2 ± 3.7	1.64 ± 0.53	
	single top	1.81 ± 0.93	4.6 ± 2.0	3.1 ± 1.4	0.33 ± 0.16	
	$t\bar{t}Z$	0.52 ± 0.20	7.5 ± 2.8	0.28 ± 0.10	4.0 ± 2.0	
	diboson	0.30 ± 0.20	1.75 ± 0.55	1.7 ± 1.1	0.66 ± 0.21	
	Total	29.8 ± 7.0	169.41 ± 15.77	22.5 ± 5.0	7.4 ± 2.1	
MC exp. SM events	$t\bar{t}1l$	17.37	3.84	3.67	0.00	
	$t\bar{t}2l$	2.61	122.91	1.06	0.69	
	W +jets	4.91	4.95	11.26	1.52	
	single top	1.93	4.93	3.32	0.35	
	$t\bar{t}Z$	0.53	7.61	0.28	4.06	
	diboson	0.30	1.75	1.67	0.66	
	Total	27.63	146.00	21.26	7.28	
		T1LCR	T2LCR	WCR	STCR	ttZCR
Observed events		317	148	139	107	35
Fitted bkg events	$t\bar{t}1l$	225 ± 26	3.8 ± 2.3	20.1 ± 5.6	27.6 ± 9.2	0.00 ± 0.00
	$t\bar{t}2l$	7.6 ± 2.7	133 ± 13	1.95 ± 0.56	5.2 ± 1.4	0.330 ± 0.050
	W +jets	59 ± 15	3.0 ± 1.4	99 ± 15	28.7 ± 5.7	0.00 ± 0.00
	single top	19.1 ± 9.6	3.6 ± 1.9	12.8 ± 5.5	$42. \pm 16.$	0.00 ± 0.00
	$t\bar{t}Z$	2.30 ± 0.84	3.9 ± 1.4	0.47 ± 0.23	0.91 ± 0.37	24.2 ± 9.2
	diboson	4.4 ± 1.8	1.10 ± 0.39	4.5 ± 1.2	2.37 ± 0.91	6.29 ± 0.93
	Total	317 ± 18	148 ± 12	139 ± 12	107 ± 10	35.0 ± 5.9
MC exp. SM events	$t\bar{t}1l$	208.31	3.49	18.63	25.51	0.00
	$t\bar{t}2l$	6.40	111.58	1.64	4.33	0.33
	W +jets	54.03	2.75	91.55	26.48	0.00
	single top	20.31	3.85	13.67	45.09	0.00
	$t\bar{t}Z$	2.35	4.02	0.48	0.93	24.75
	diboson	4.36	1.10	4.48	2.37	6.29
	Total	295.77	126.79	130.45	104.71	35.51

Table 9.12: The numbers of observed events in DM_high and the associated CRs and VRs together with the expected fitted and pre-fit numbers of background events for 36.1 fb^{-1} . Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty.

		TVR	WVR	DM_low_ICHEP	
Observed events		99	141	65	
Fitted bkg events	$t\bar{t}$	52 ± 16	18.5 ± 8.0	16.0 ± 5.7	
	W +jets	9.9 ± 3.4	115 ± 23	11.0 ± 2.8	
	singletop	3.3 ± 2.8	2.2 ± 1.7	3.4 ± 1.3	
	$t\bar{t}Z$	0.86 ± 0.30	$0.18^{+0.18}_{-0.18}$	14.3 ± 5.9	
	diboson	$0.59^{+0.59}_{-0.59}$	9.2 ± 3.5	3.6 ± 1.3	
	Total	67 ± 17	145 ± 29	48.3 ± 8.2	
MC exp. SM events	$t\bar{t}$	46.06	16.33	14.15	
	W +jets	10.55	122.98	11.81	
	singletop	2.69	1.79	2.76	
	$t\bar{t}Z$	0.78	0.16	13.02	
	diboson	0.59	9.22	3.55	
	Total	60.67	150.47	45.30	

		TCR	WCR	STCR	ttZCR
Observed events		141	306	141	82
Fitted bkg events	$t\bar{t}$	95 ± 15	31 ± 13	29.8 ± 7.9	$0.59^{+0.60}_{-0.59}$
	W +jets	31.5 ± 7.7	261 ± 23	22.8 ± 6.4	0.00 ± 0.00
	singletop	12.6 ± 4.6	4.7 ± 2.5	84 ± 17	0.00 ± 0.00
	$t\bar{t}Z$	0.51 ± 0.30	0.15 ± 0.10	2.14 ± 0.57	60 ± 17
	diboson	1.42 ± 0.69	8.9 ± 3.2	1.80 ± 0.75	12.7 ± 2.0
	Total	141 ± 12	306 ± 17	141 ± 12	82.0 ± 9.0
MC exp. SM events	$t\bar{t}$	84.10	27.41	26.36	0.59
	W +jets	33.71	279.56	24.41	0.00
	singletop	10.32	3.87	69.48	0.00
	$t\bar{t}Z$	0.46	0.13	1.95	54.61
	diboson	1.42	8.94	1.80	12.73
	Total	130.01	319.93	124.00	76.47

Table 9.13: The numbers of observed events in DM_low_loose and the associated CRs and VRs together with the expected fitted and pre-fit background events for 36.1 fb^{-1} . Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty.

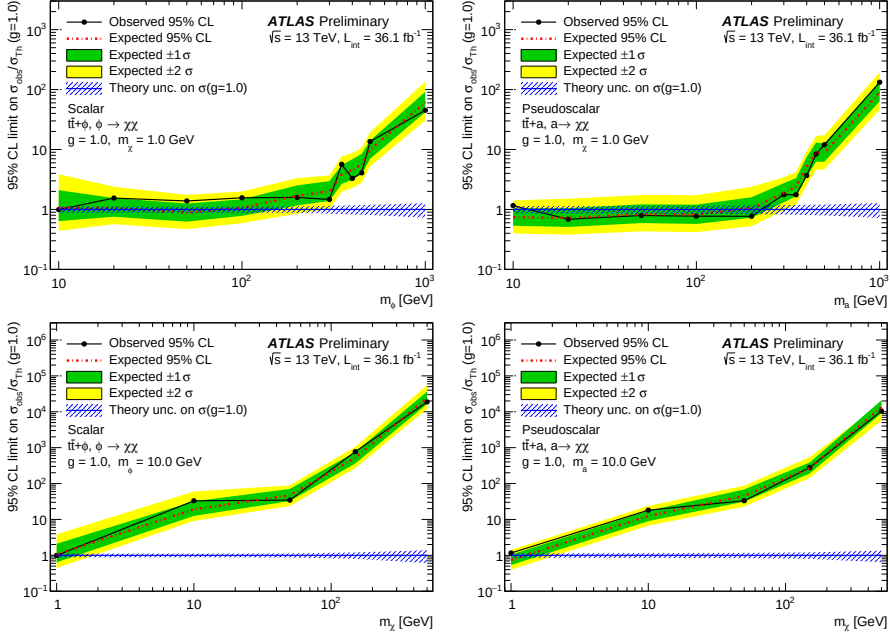


Figure 9.10: Upper limit on the ratio of the DM production cross section over the value predicted by the simplified model with a scalar (left) or a pseudoscalar (right) mediator, for a fixed DM candidate mass (top) or for a fixed mediator mass (bottom). The coupling of the mediator to the SM and to the DM particles is assumed to be $g = 1$. The scalar mediator mass is labelled m_ϕ , while the pseudoscalar mediator mass is m_a . Statistical and systematic uncertainties are included in the calculation. [4]

	m_χ	m_ϕ	best expect. SR	UL ^{obs}	UL ^{exp}	$\mu_{\text{sig}}^{\text{obs}}$	$\mu_{\text{sig}}^{\text{exp}}$	$\sigma_{\text{th}}^{\text{NLO}}$
scalar mediator	1	10	DM_low	19.48	20.69	0.99	1.06	19.61
	1	20	DM_low_loose	16.15	10.98	1.55	1.05	10.42
	1	50	DM_low_loose	4.05	2.73	1.38	0.93	2.94
	1	100	DM_low_loose	1.05	0.72	1.56	1.07	0.67
	1	200	DM_low	0.15	0.16	1.59	1.68	0.09
	1	300	DM_high	0.04	0.06	1.46	2.02	0.03
	1	350	DM_high	0.05	0.08	2.75	3.86	0.019
	1	400	DM_high	0.04	0.06	3.29	4.58	0.01
	1	450	DM_high	0.03	0.04	4.09	5.64	0.01
	1	500	DM_high	0.04	0.06	8.14	11.42	0.01
	1	1000	DM_high	0.02	0.02	45.09	61.09	0.00
	1	10	DM_low	19.48	20.69	0.99	1.06	19.61
	10	10	DM_low_loose	3.63	2.38	38.41	25.15	0.09
	50	10	DM_high	0.07	0.09	34.51	47.34	0.00
	150	10	DM_high	0.03	0.05	404.76	525.52	0.00
	500	10	DM_high	0.02	0.02	18756.70	24101.50	0.00
	1000	10	DM_high	0.01	0.01	0.00	0.00	0.00
pseudo-scalar mediator	1	10	DM_low	0.35	0.37	0.79	0.84	0.44
	1	20	DM_low	0.28	0.29	0.69	0.72	0.40
	1	50	DM_low	0.24	0.25	0.79	0.84	0.30
	1	100	DM_low	0.15	0.16	0.77	0.82	0.19
	1	200	DM_high	0.06	0.09	0.77	1.06	0.08
	1	300	DM_low	0.07	0.08	1.77	1.88	0.04
	1	350	DM_high	0.04	0.05	1.76	2.42	0.02
	1	400	DM_high	0.04	0.06	3.69	5.14	0.01
	1	450	DM_low	0.06	0.07	8.42	8.92	0.01
	1	500	DM_high	0.04	0.06	7.36	10.39	0.01
	1	1000	DM_low	0.04	0.04	98.60	104.53	0.00
	1	5000	DM_high	0.02	0.03	330923	427178	0.00
	1	10	DM_low	0.35	0.37	0.79	0.84	0.44
	10	10	DM_high	0.14	0.19	9.27	12.84	0.015
	50	10	DM_high	0.08	0.11	33.23	45.50	0.00
	150	10	DM_low	0.06	0.06	257.81	273.59	0.00
	500	10	DM_high	0.02	0.03	10506.50	13466.20	0.00
	1000	10	DM_high	0.01	0.01	445634	577676	0.00

Table 9.14: Results of the exclusion fit. The first two columns show the DM candidate mass and the mediator mass in [GeV]. The third column shows the SR providing the lowest expected CL_s value for the parameter grid point. In the forth and the fifth columns there are the observed and expected exclusion limits on the DM cross section production in association with a $t\bar{t}$ pair, in [pb], derived with this SR. The ratios of these values over the theoretical cross sections are presented in the sixth and the seventh columns. The last column displays the theoretical cross sections in [pb]. The assumed coupling is $g = 1$.

9.10 Conclusion

This chapter presents a search for DM pair production via a spin-0 mediator in association with $t\bar{t}$ pair using pp -collision data collected by the ATLAS detector in 2015 and 2016 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 36.1 fb^{-1} . The observed data in the SRs are compatible with the SM prediction. A small excess of 1.5σ is observed in the DM_low_loose SR. Upper limits are set on the production cross sections of various simplified models, assuming a unitary coupling of the mediator to the SM and to the DM particles.

10 Summary

Strong evidence for the presence of Dark Matter in the Universe is provided by various astrophysical observations. The Standard Model of particle physics is very successful in describing a vast range of observed particle physics phenomena and makes predictions with an impressive precision, yet it does not explain the nature of DM. With the energies available at the LHC it may be possible to produce DM particles from Standard Model particle interactions. The collider searches for DM are highly complementary to the direct and indirect DM detection experiments.

A large number of measurements and searches for new physics, including the searches for DM, performed with the ATLAS experiment at the LHC involve identification of jets that originate from b quarks. In order to identify b jets, various b -tagging algorithms are developed and used. The first study presented in this thesis aims to calibrate the performance of the MV1 b -tagging algorithm in order to correct for the potential mismodelling of the variables exploited by the algorithm. The calibration has been performed using MC simulated samples of multi-jet events and 8 TeV pp -collision data corresponding to an integrated luminosity of 20.1 fb^{-1} . The calibration technique is based on template fits, and has been applied to both calo-jets and track-jets. The presented method allows to perform the calibration for jets with transverse momenta up to 1200 GeV. The results of the calibration analysis are presented in the form of data-to-simulation b -tagging efficiency scale factors.

The second study presented in the thesis is based on the search for DM production in association with a pair of heavy flavour quarks at $\sqrt{s} = 8 \text{ TeV}$ under the EFT assumption. The results of this search have been re-interpreted under the assumption of simplified models with a spin-0 mediator. Benchmark models have been chosen to be used in the DM searches at $\sqrt{s} = 13 \text{ TeV}$.

The last part of this thesis presents a search for DM production in association with a pair of top quarks performed under the assumption of simplified models with a spin-0 mediator using data at $\sqrt{s} = 13 \text{ TeV}$. No excess over the background expectation has been found and 95%

CL upper limits have been set on the cross section of various simplifies models. Thus far, no direct observation of DM has been made, and its nature will therefore remain one of the most compelling mysteries in modern physics.

A Appendices

A $S_{d_0}^{t1}$ templates

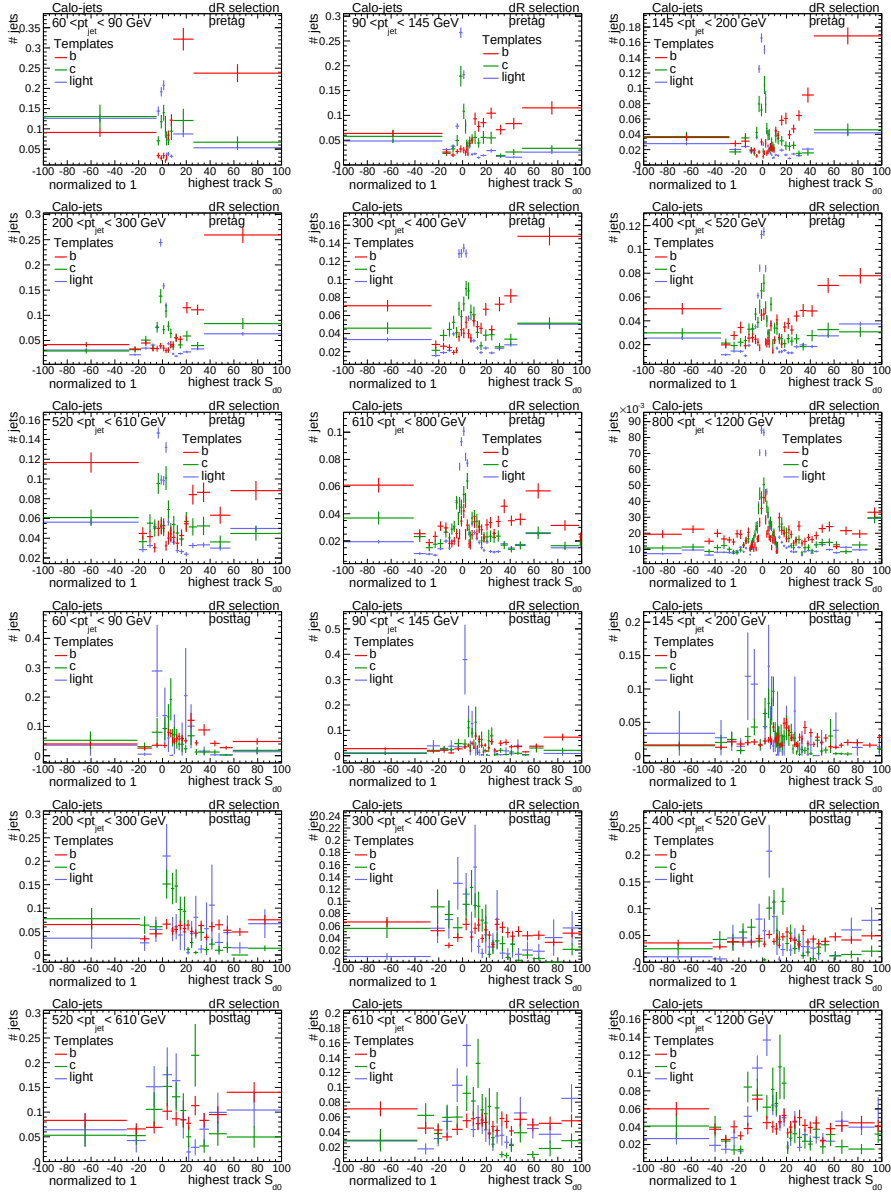


Figure A.1: Pretag (first nine) and posttag (last nine) b -, c - and light-jet templates for calo-jets for the dR selection in each jet p_T bin used in the fit.

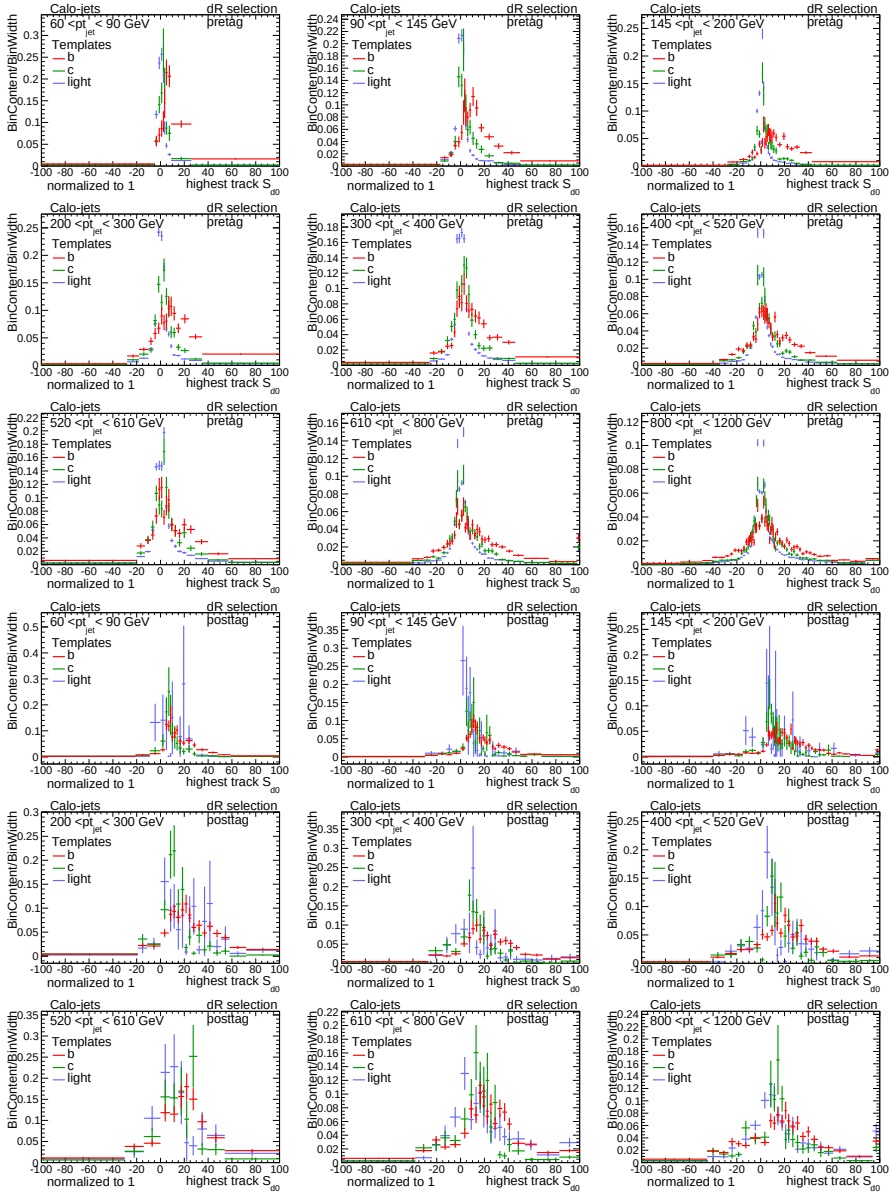


Figure A.2: Pretag (first nine) and posttag (last nine) b -, c - and light-jet templates for calo-jets for the dR selection in each jet p_T bin. The number of events in each bin of the templates is divided by the bin width.

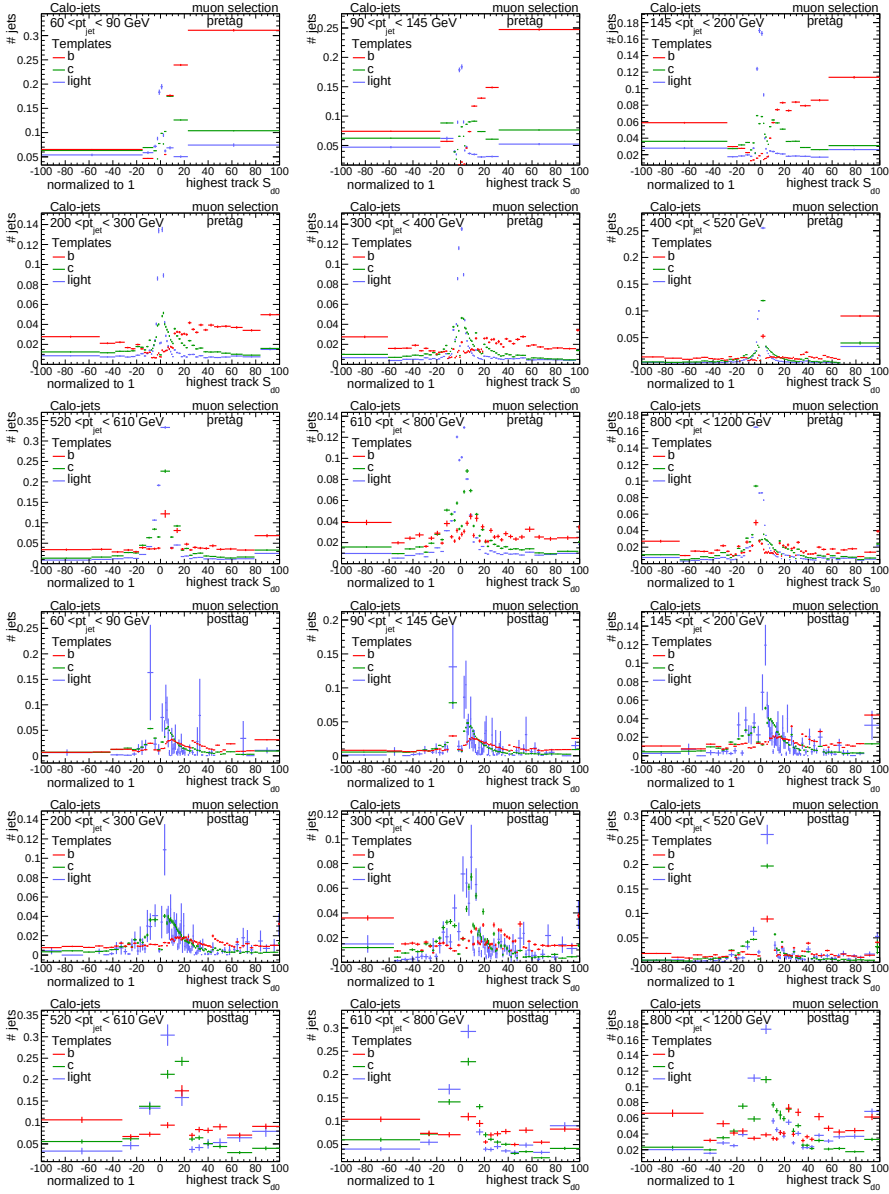


Figure A.3: Pretag (first nine) and posttag (last nine) b -, c - and light-jet templates for calo-jets for the muon-in-jet selection in each jet p_T bin used in the fit.

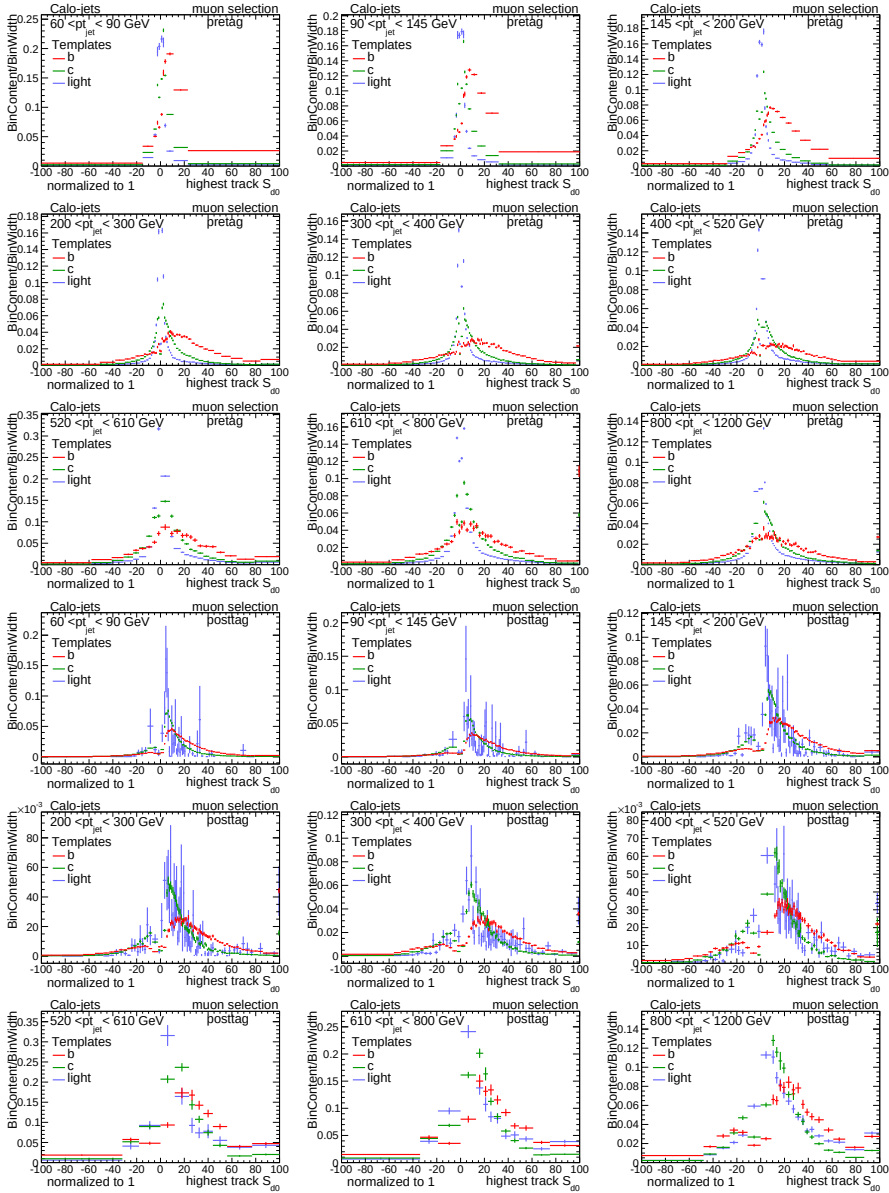


Figure A.4: Pretag (first nine) and posttag (last nine) b -, c - and light-jet templates for calo-jets for the muon-in-jet selection in each jet p_T bin. The number of events in each bin of the templates is divided by the bin width.

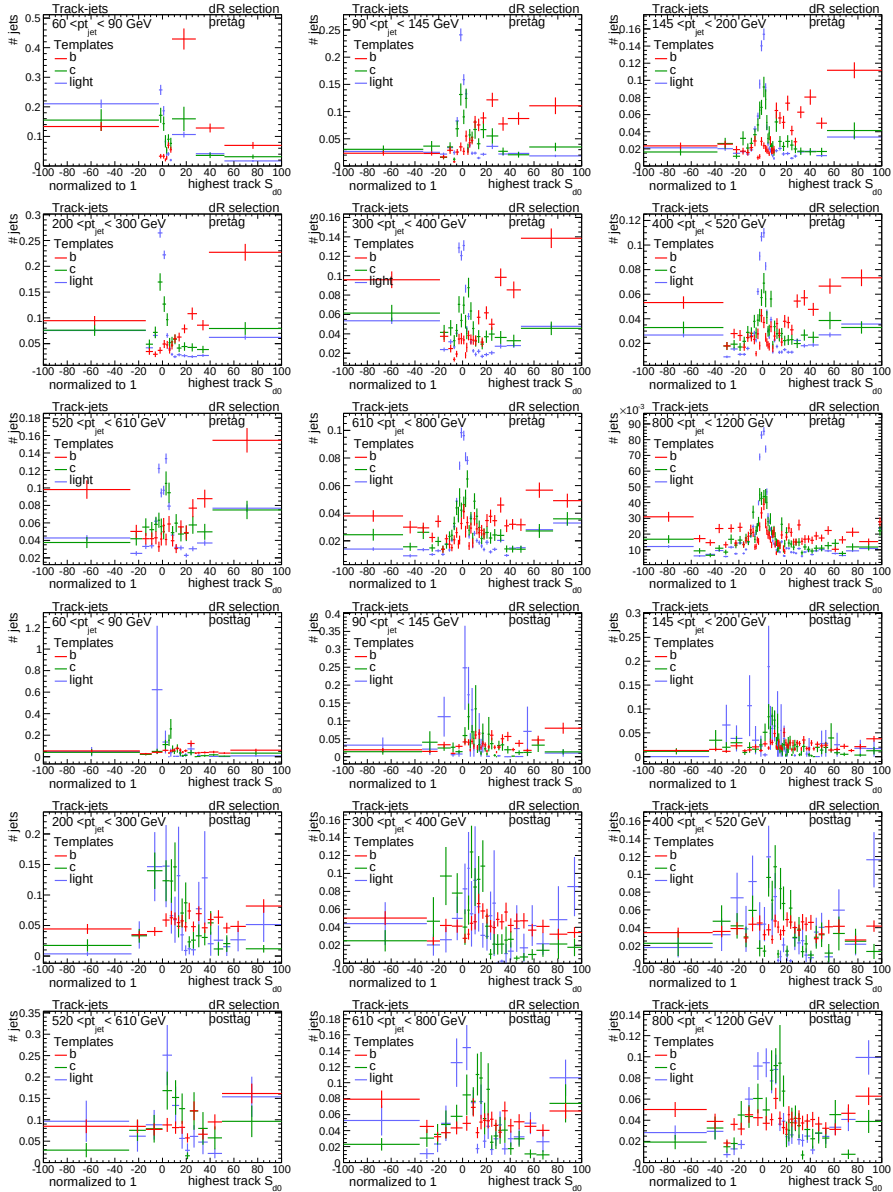


Figure A.5: Pretag (first nine) and posttag (last nine) b -, c - and light-jet templates for track-jets for the dR selection in each jet p_T bin used in the fit.

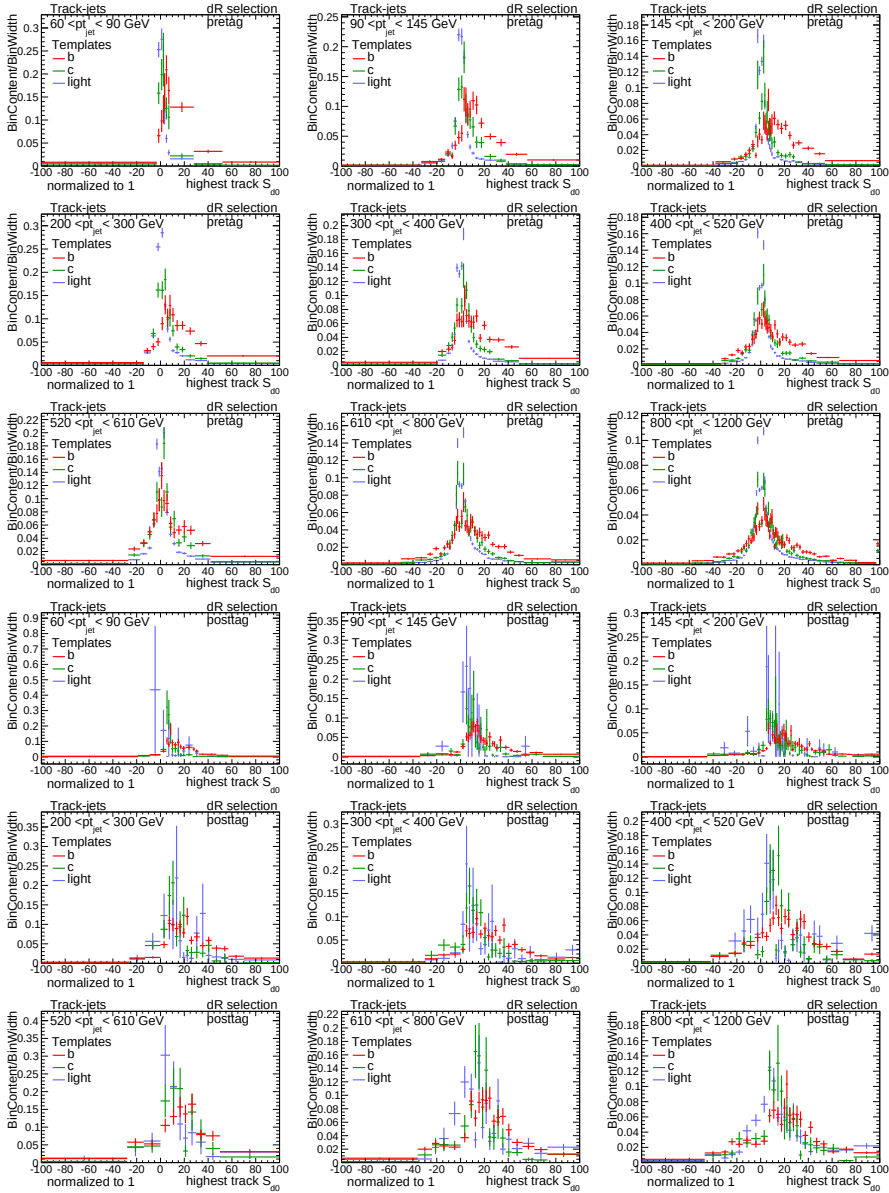


Figure A.6: Pretag (first nine) and posttag (last nine) b -, c - and light-jet templates for track-jets for the dR selection in each jet p_T bin. The number of events in each bin of the templates is divided by the bin width.

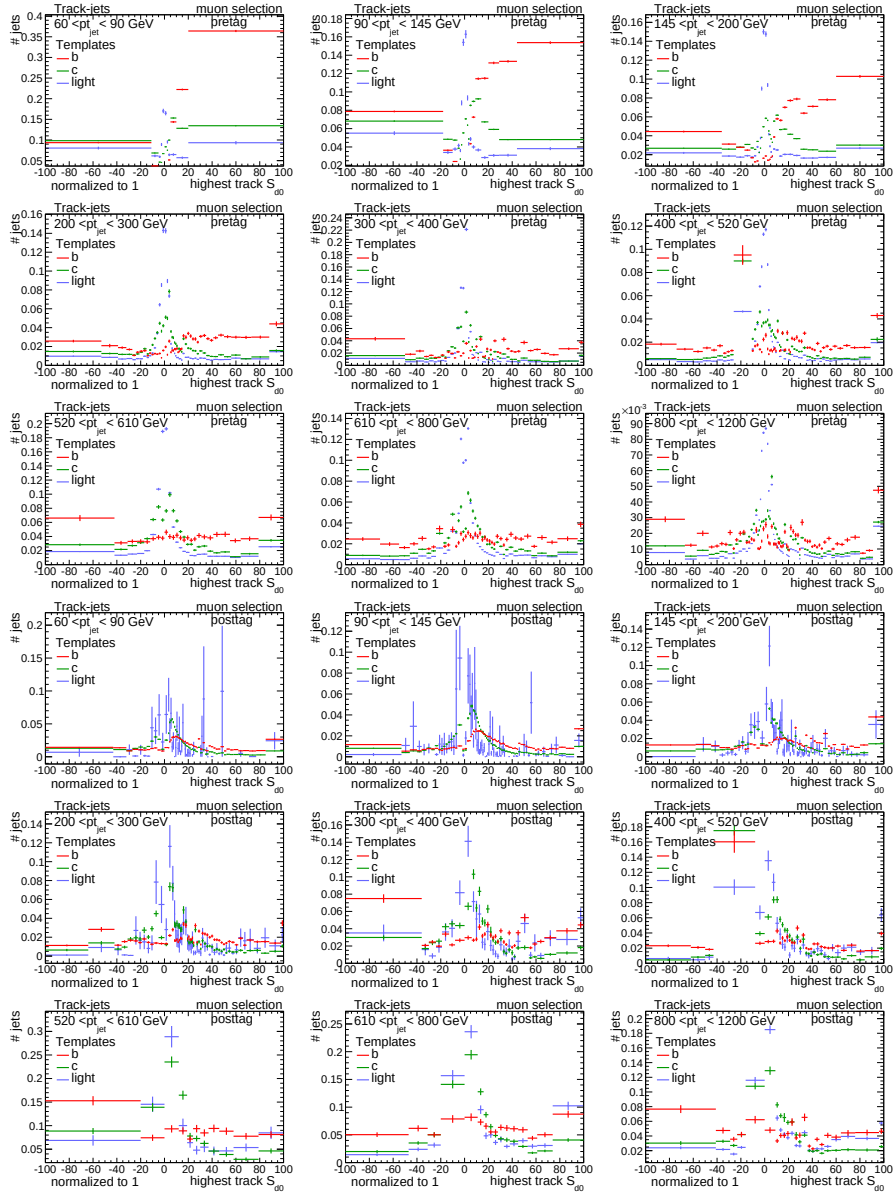


Figure A.7: Pretag (first nine) and posttag (last nine) b -, c - and light-jet templates for track-jets for the muon-in-jet selection in each jet p_T bin used in the fit.

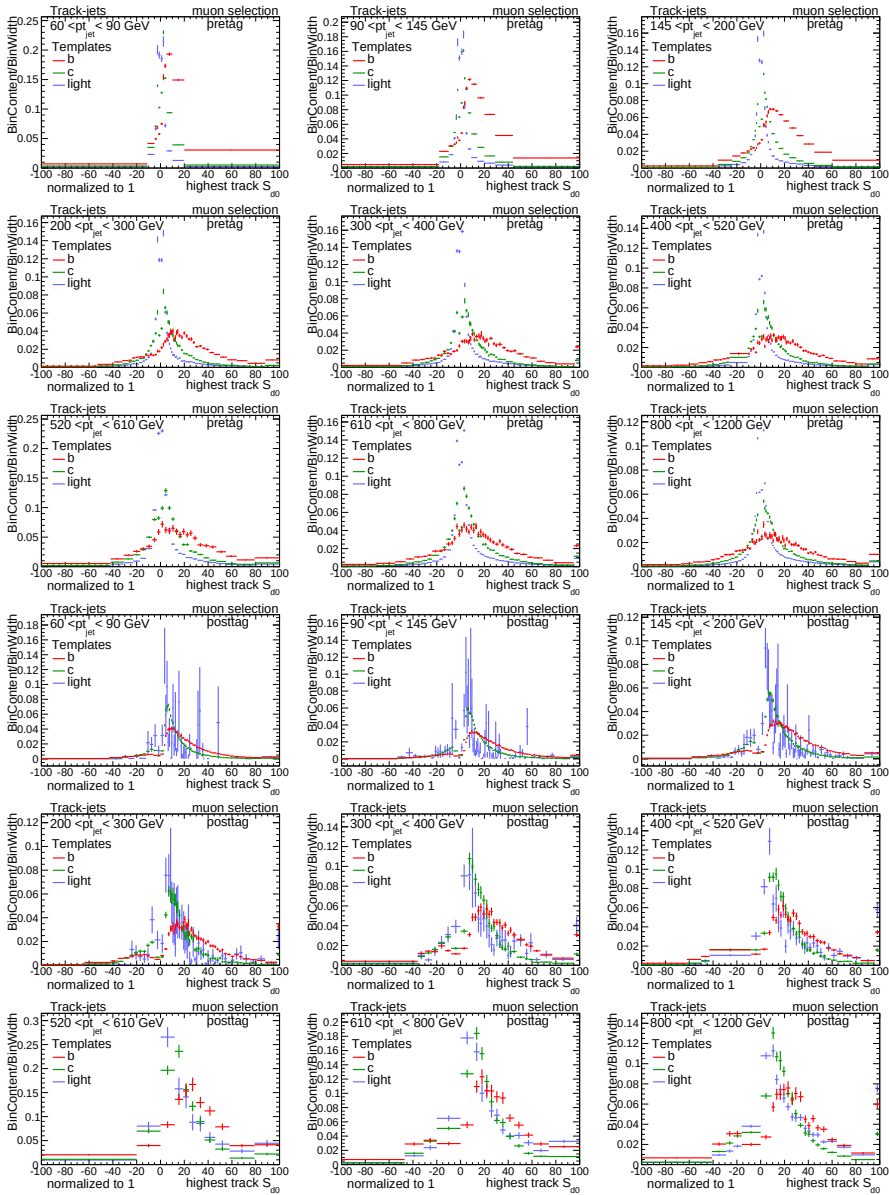


Figure A.8: Pretag (first nine) and posttag (last nine) b -, c - and light-jet templates for track-jets for the muon-in-jet selection in each jet p_T bin. The number of events in each bin of the templates is divided by the bin width.

B Template fits to $S_{d_0}^{t1}$

B.1 Calo-jets

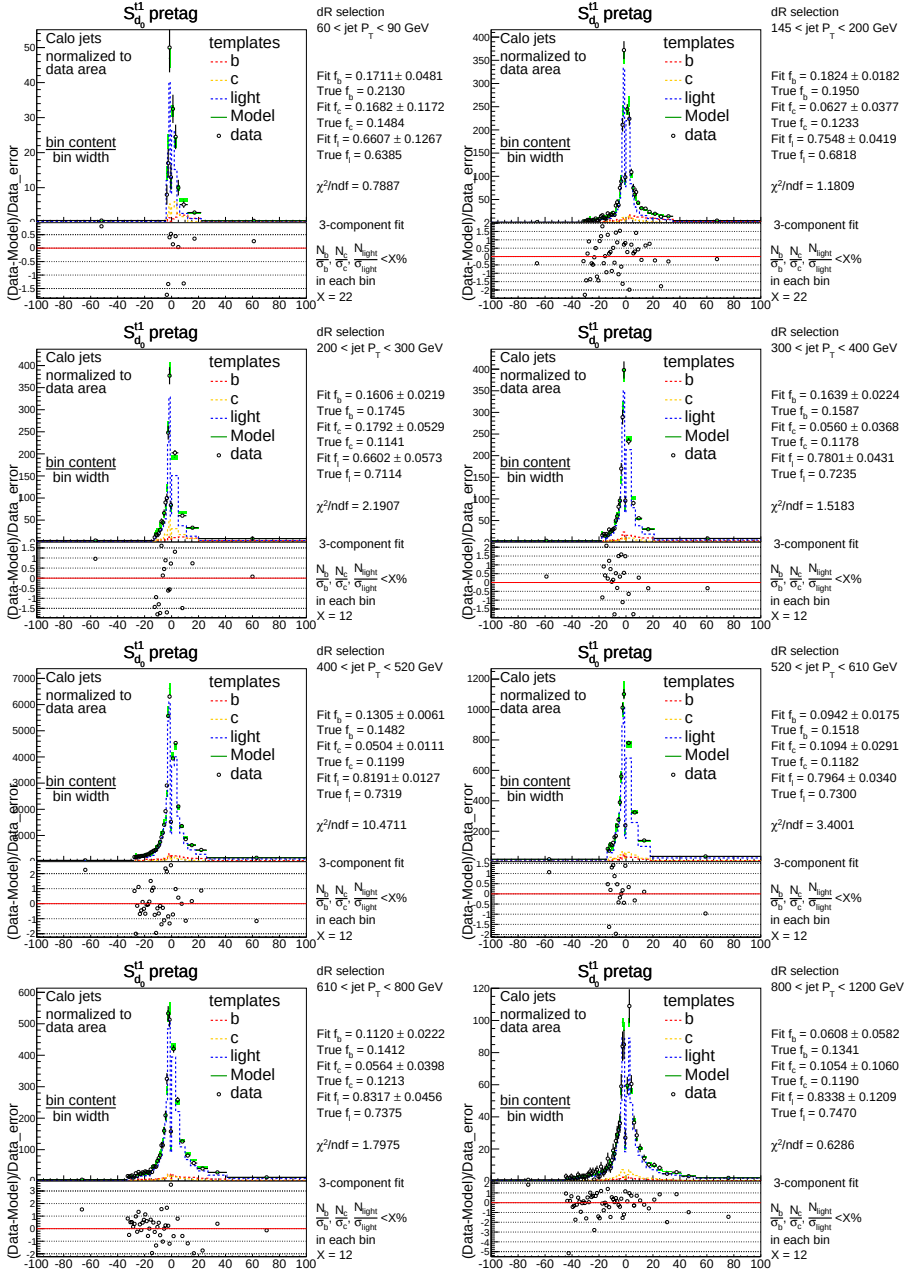


Figure A.9: Template fits to pretag $S_{d_0}^{t1}$ distribution of calo-jets for the dR selection. The filled green area corresponds to the model uncertainty.

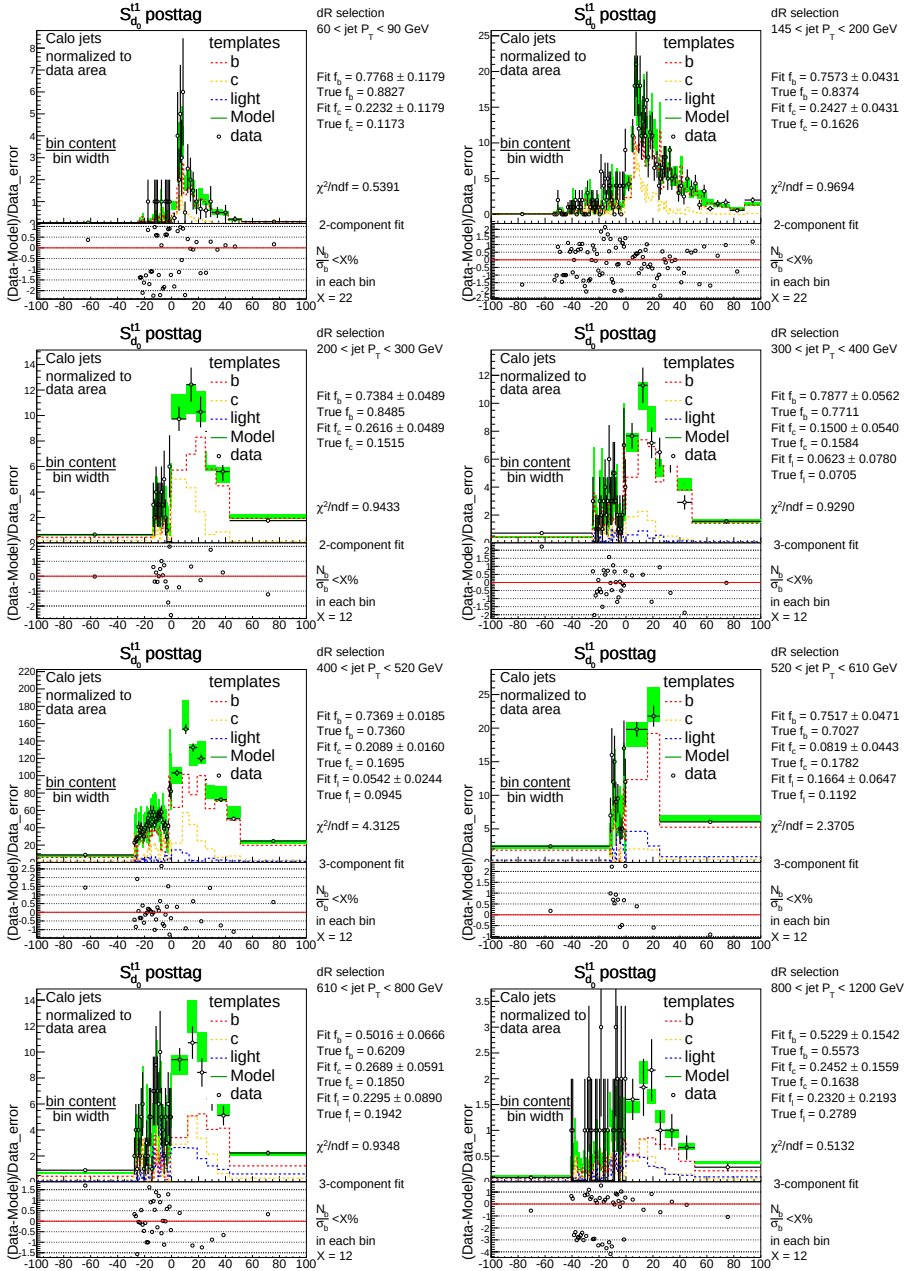


Figure A.10: Template fits to posttag $S_{d_0}^{t1}$ distribution of calo-jets for the dR selection. The filled green area corresponds to the model uncertainty.

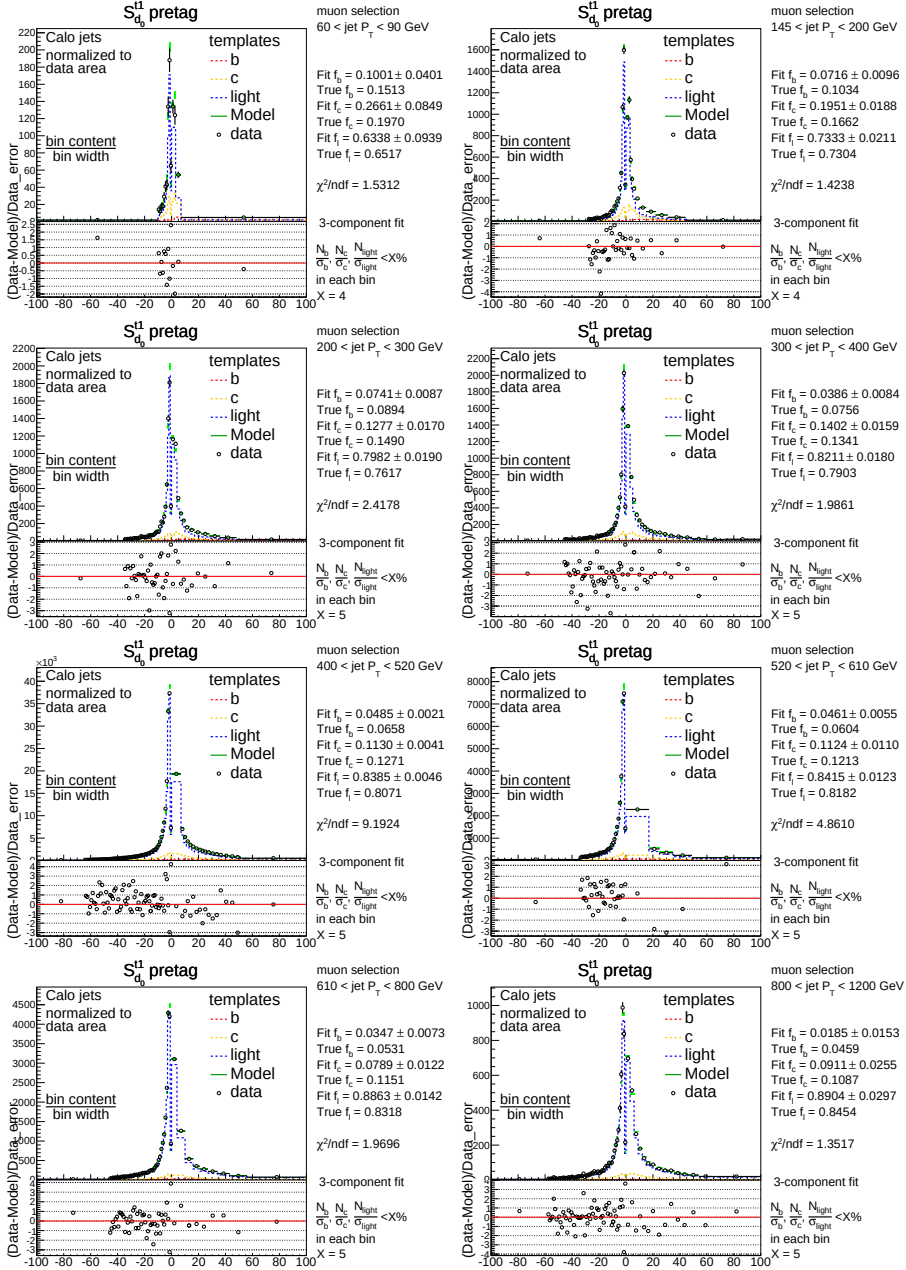


Figure A.11: Template fits to pretag $S_{d_0}^{t1}$ distribution of calo-jets for the muon-in-jet selection. The filled green area corresponds to the model uncertainty.

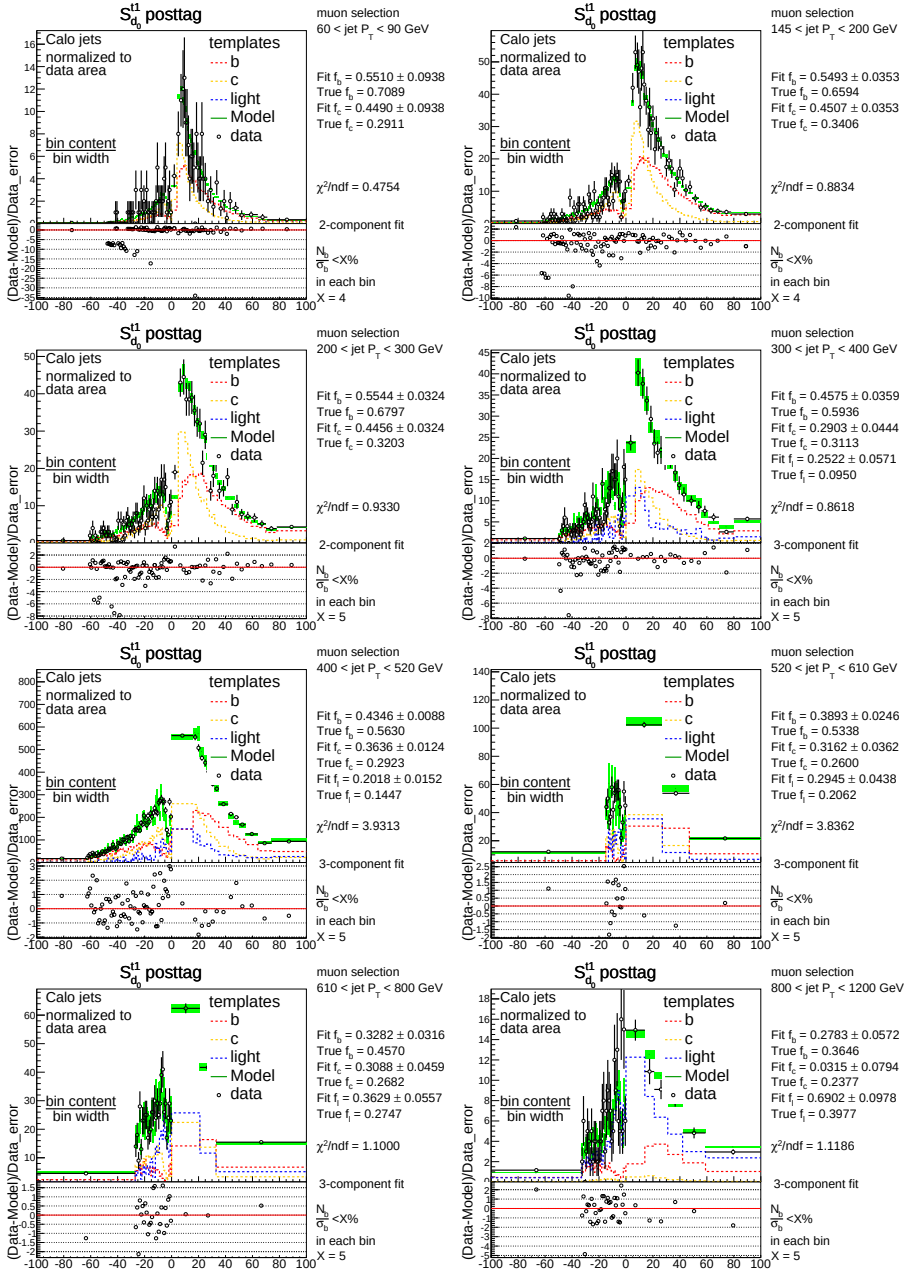


Figure A.12: Template fits to posttag $S_{d_0}^{t1}$ distribution of calo-jets for the muon-in-jet selection. The filled green area corresponds to the model uncertainty.

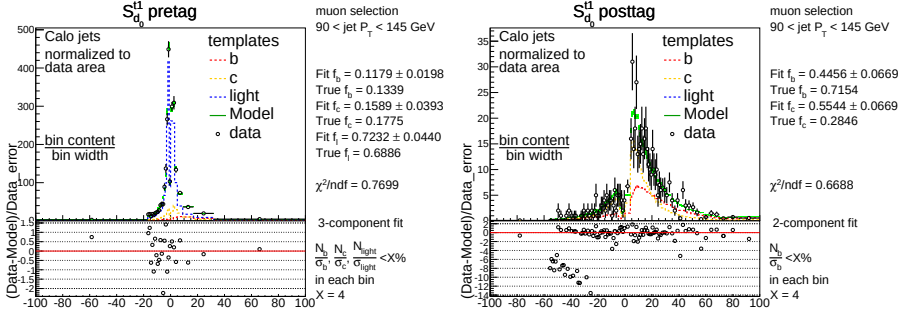


Figure A.13: Template fits to the pretag (left) and posttag (right) $S_{d_0}^{t1}$ distributions of calo-jets for the muon-in-jet selection in jet p_T region [90,145] GeV. The filled green area corresponds to the statistical model uncertainty.

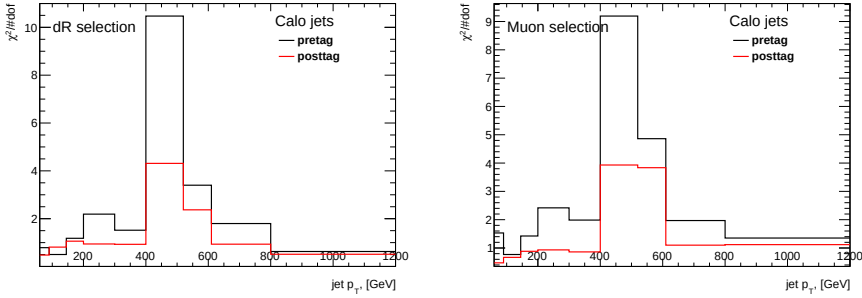


Figure A.14: χ^2 of template fits to the $S_{d_0}^{t1}$ distribution of calo-jets in data vs calo-jet p_T for the dR selection (left) and the muon-in-jet selection (right).

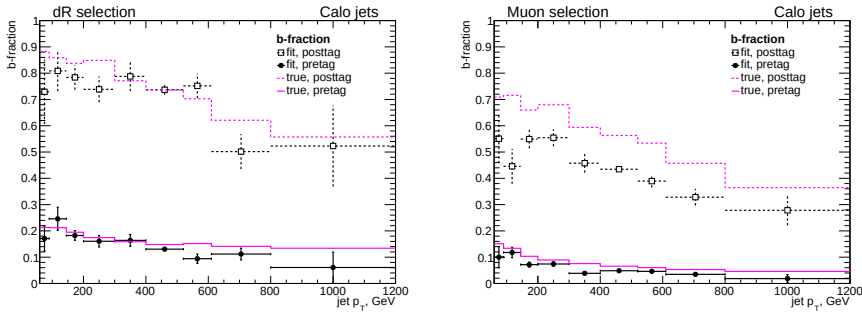


Figure A.15: Pretag and posttag b -jet fractions vs calo-jet p_T for the dR selection (left) and the muon-in-jet selection (right). The black markers show the b -jet fractions obtained from the template fits to the $S_{d_0}^{t1}$ distribution of calo-jets in data, and the expected b -jet fractions obtained from unfiltered MC samples are shown in magenta color.

B.2 Track-jets

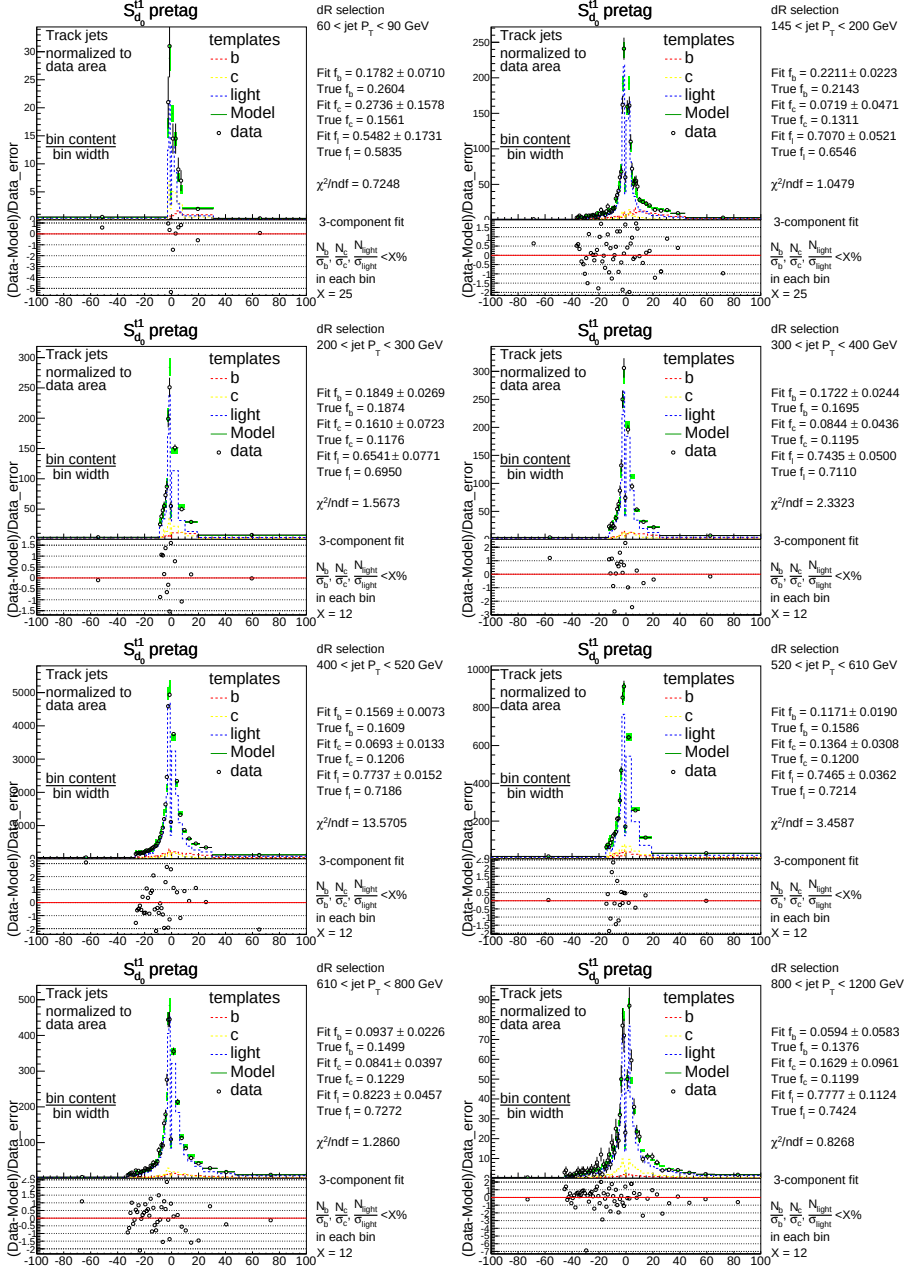


Figure A.16: Template fits to pretag $S_{d_0}^{t1}$ distribution of track-jets for the dR selection. The filled green area corresponds to the model uncertainty.

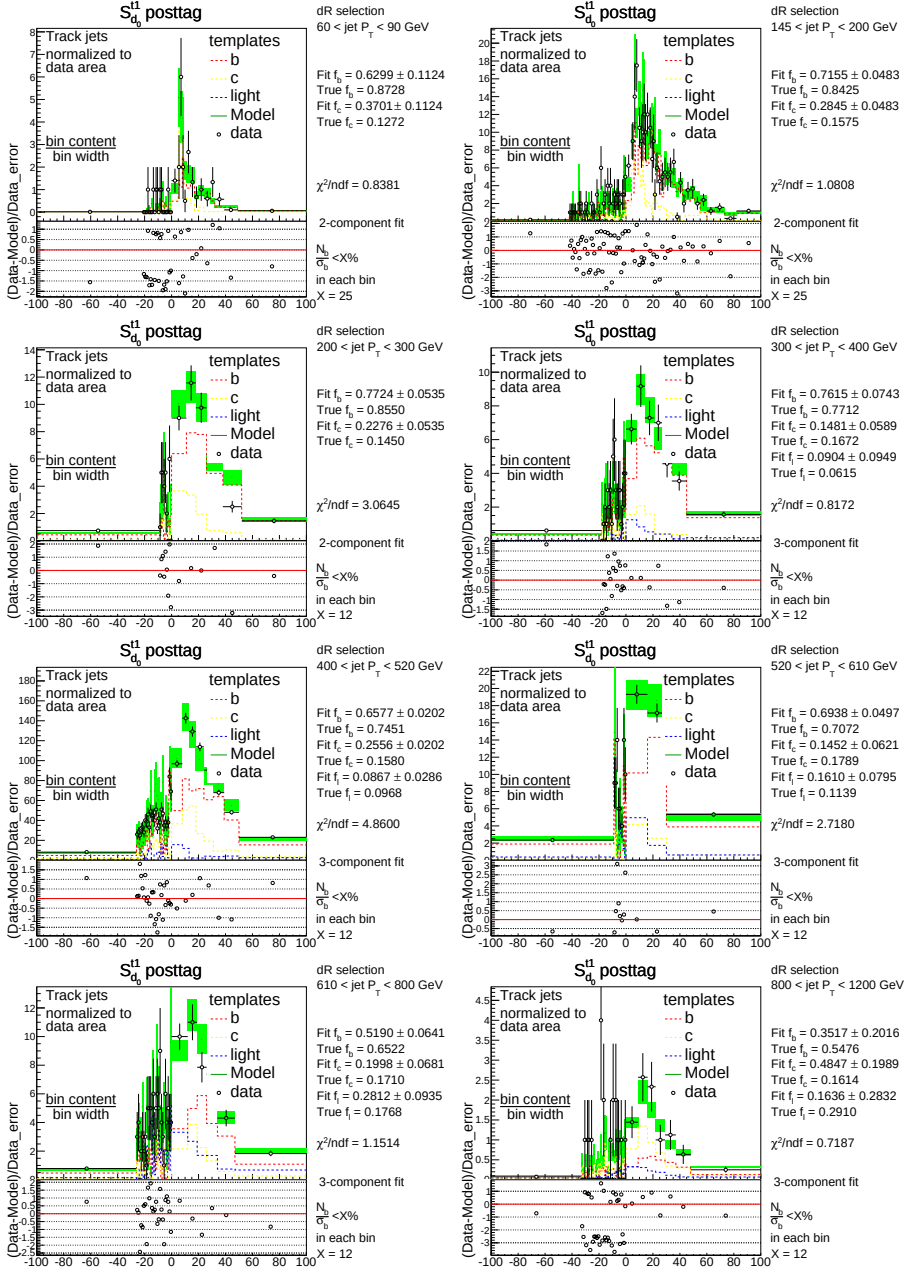


Figure A.17: Template fits to posttag $S_{d_0}^{t1}$ distribution of track-jets for the dR selection. The filled green area corresponds to the model uncertainty.

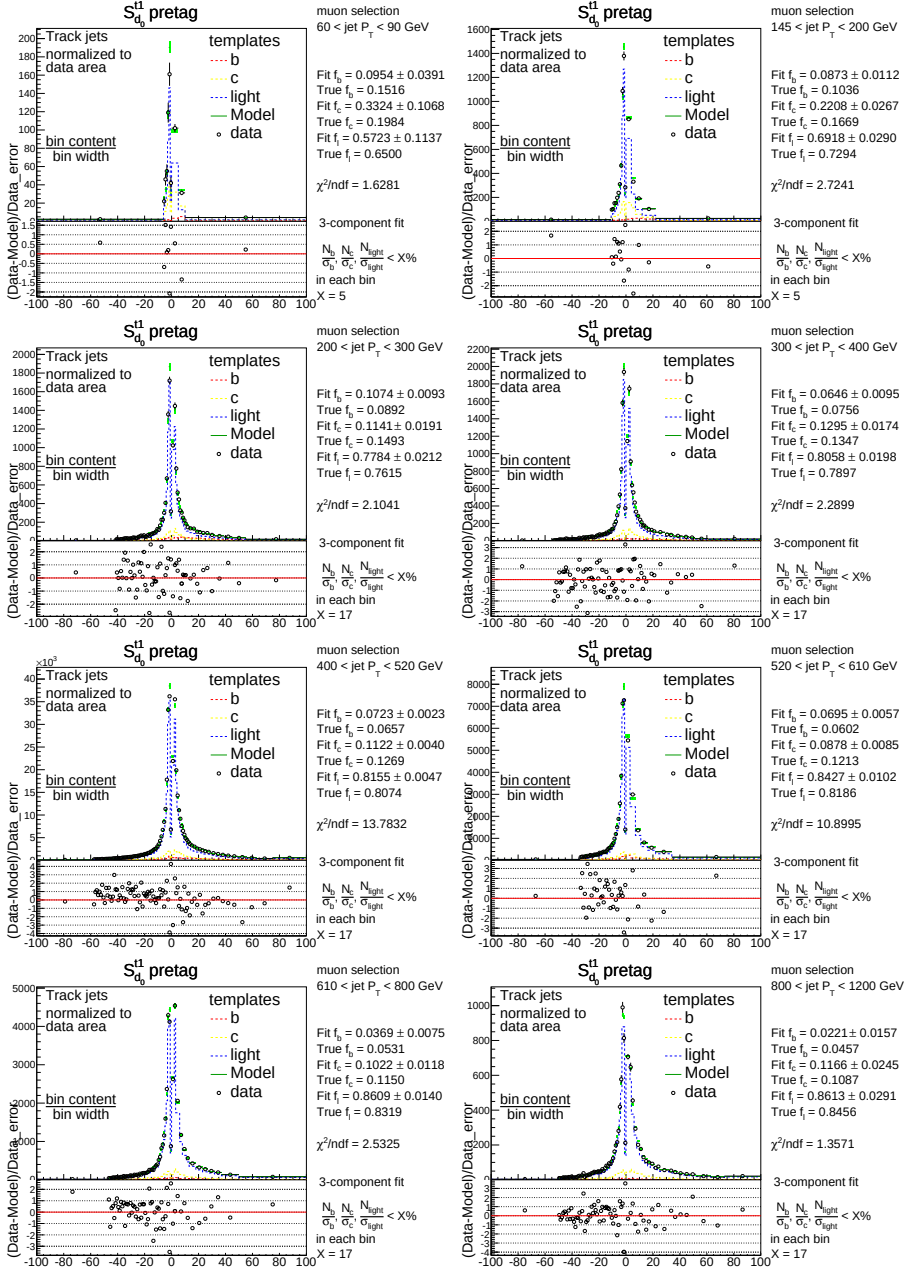


Figure A.18: Template fits to pretag $S_{d_0}^{t1}$ distribution of track-jets for the muon-in-jet selection. The filled green area corresponds to the model uncertainty.

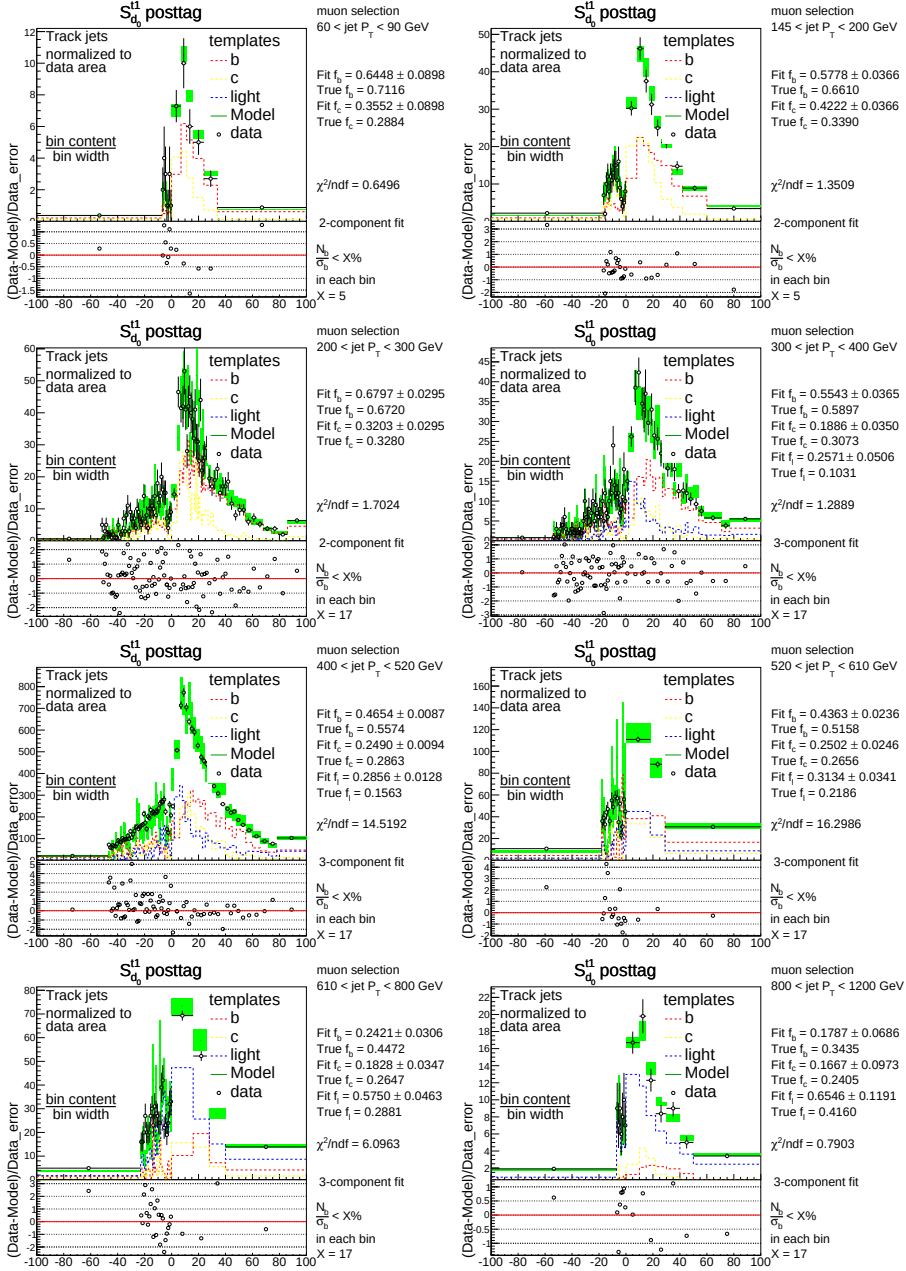


Figure A.19: Template fits to posttag $S_{d_0}^{t1}$ distribution of track-jets for the muon-in-jet selection. The filled green area corresponds to the model uncertainty.

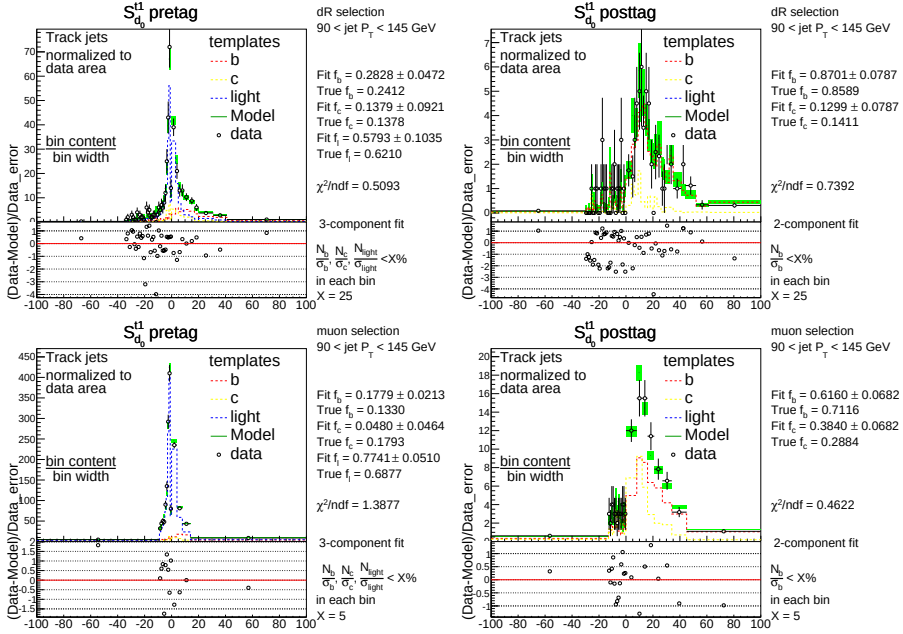


Figure A.20: Template fits to the pretag (left) and posttag (right) $S_{d_0}^{t1}$ distributions of calo-jets after the dR selection (top) or the muon-in-jet selection (bottom) in jet p_T region [90,145) GeV. The filled green area corresponds to the statistical model uncertainty.

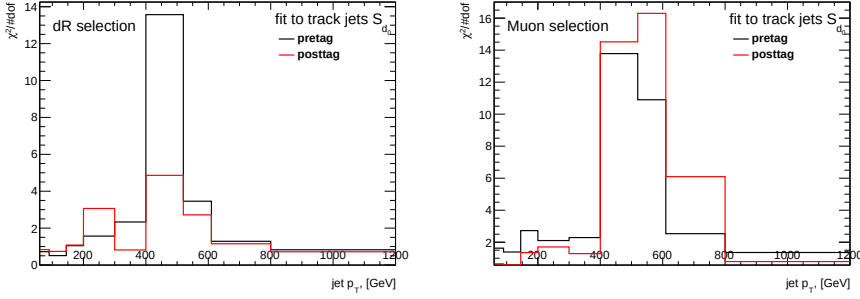


Figure A.21: χ^2 of template fits to the $S_{d_0}^{t1}$ distribution of track-jets in data vs calo-jet p_T for the dR selection (left) and the muon-in-jet selection (right).

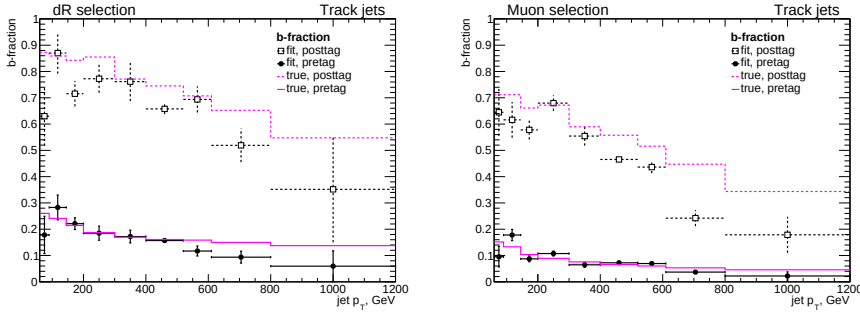


Figure A.22: Pretag and posttag b -jet fractions vs calo-jet p_T for the dR selection (left) and the muon-in-jet selection (right). The black markers show the b -jet fractions obtained from the template fits to the $S_{d_0}^{t1}$ distribution of track-jets in to data, and the expected b -jet fractions obtained from unfiltered MC samples are shown in magenta color.

C Pseudo-data experiments

A set of tests is performed, where the experimental data are replaced by pseudo-data generated from the templates. The flavour fractions (f^b , f^c and f^{light}) are chosen to be equal to the expected values from the unfiltered MC samples. To generate the pseudo-data the template histograms used for fitting PDF^b , PDF^c and $\text{PDF}^{\text{light}}$ are cloned as $\text{PDF}_{\text{pseu}}^b$, $\text{PDF}_{\text{pseu}}^c$ and $\text{PDF}_{\text{pseu}}^{\text{light}}$, and normalized to satisfy the equations:

$$\begin{aligned} \frac{\int \text{PDF}_{\text{pseu}}^b}{\int \text{PDF}_{\text{pseu}}^b + \int \text{PDF}_{\text{pseu}}^c + \int \text{PDF}_{\text{pseu}}^{\text{light}}} &= f^b, \\ \frac{\int \text{PDF}_{\text{pseu}}^c}{\int \text{PDF}_{\text{pseu}}^b + \int \text{PDF}_{\text{pseu}}^c + \int \text{PDF}_{\text{pseu}}^{\text{light}}} &= f^c, \\ \frac{\int \text{PDF}_{\text{pseu}}^{\text{light}}}{\int \text{PDF}_{\text{pseu}}^b + \int \text{PDF}_{\text{pseu}}^c + \int \text{PDF}_{\text{pseu}}^{\text{light}}} &= f^{\text{light}}. \end{aligned}$$

The clone histograms are then scaled to guarantee that the statistics in the pseudo-data is the same as in experimental data:

$$\int \text{PDF}_{\text{pseu}}^b + \int \text{PDF}_{\text{pseu}}^c + \int \text{PDF}_{\text{pseu}}^{\text{light}} = \int \text{data}.$$

The content of each bin i in the pseudo-data distribution is set to $N^i = N_b^i + N_c^i + N_{\text{light}}^i$, where N_b^i , N_c^i and N_{light}^i random numbers, each drawn from a Poisson distribution with a mean equal to the content of the corresponding bin i in either $\text{PDF}_{\text{pseu}}^b$, $\text{PDF}_{\text{pseu}}^c$ or $\text{PDF}_{\text{pseu}}^{\text{light}}$. The error of each bin i in the pseudo-data distribution is set to the square root of its content. The true b -, c - and light-jet fractions are calculated as $\sum_i N_b^i / \sum_i N^i$, $\sum_i N_c^i / \sum_i N^i$, and $\sum_i N_{\text{light}}^i / \sum_i N^i$. The starting values of the free parameters are set to the true fractions. The original templates PDF^b , PDF^c and $\text{PDF}^{\text{light}}$ are used to fit the generated pseudo-data. This procedure is repeated 1000 times. The difference between fitted and true b -jet fractions ($f_b^{\text{fit}} - f_b^{\text{true}}$) is shown in jet p_T bins in Fig. A.23 for the dR selection and in Fig. A.26 for the muon-in-jet selection. It has approximately Gaussian shape centered around zero. The pull $(f_b^{\text{fit}} - f_b^{\text{true}}) / \sigma_{f_b}^{\text{fit}}$ is shown in Fig. A.24 for the dR selection and in Fig. A.27 for the muon-in-jet selection. As expected, it follows the normal distribution. The fit error σ_{f_b} is shown in Fig. A.25 for the pretag dR selection and in Fig. A.28 for the pretag muon-in-jet selection.

By the described pseudo-data experiments the fit is shown to be unbiased.

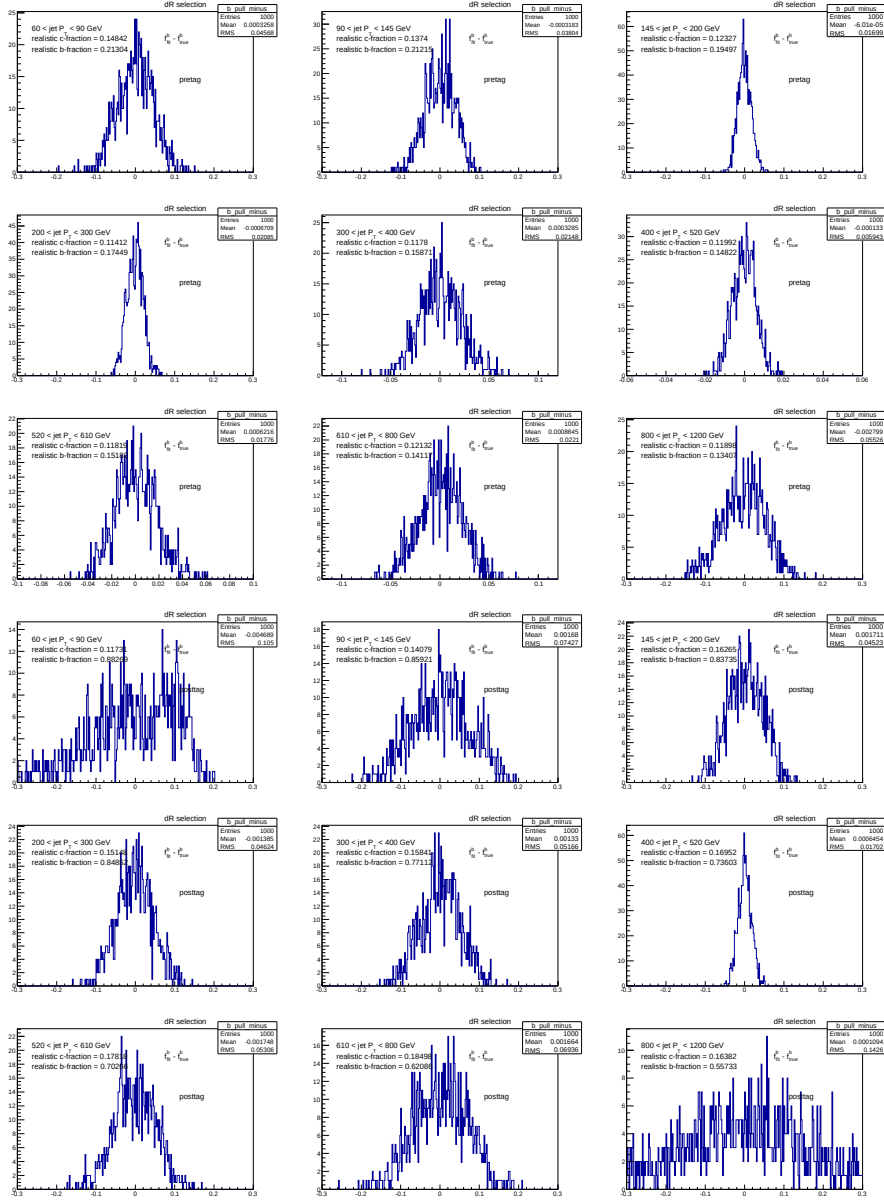


Figure A.23: The difference between fitted and true b -jet fractions ($f_b^{\text{fit}} - f_b^{\text{true}}$) in various jet p_T bins obtained in the pseudo-data experiments for the dR selection. The upper nine plots and the bottom nine plots correspond to the pretag and posttag fits, respectively.

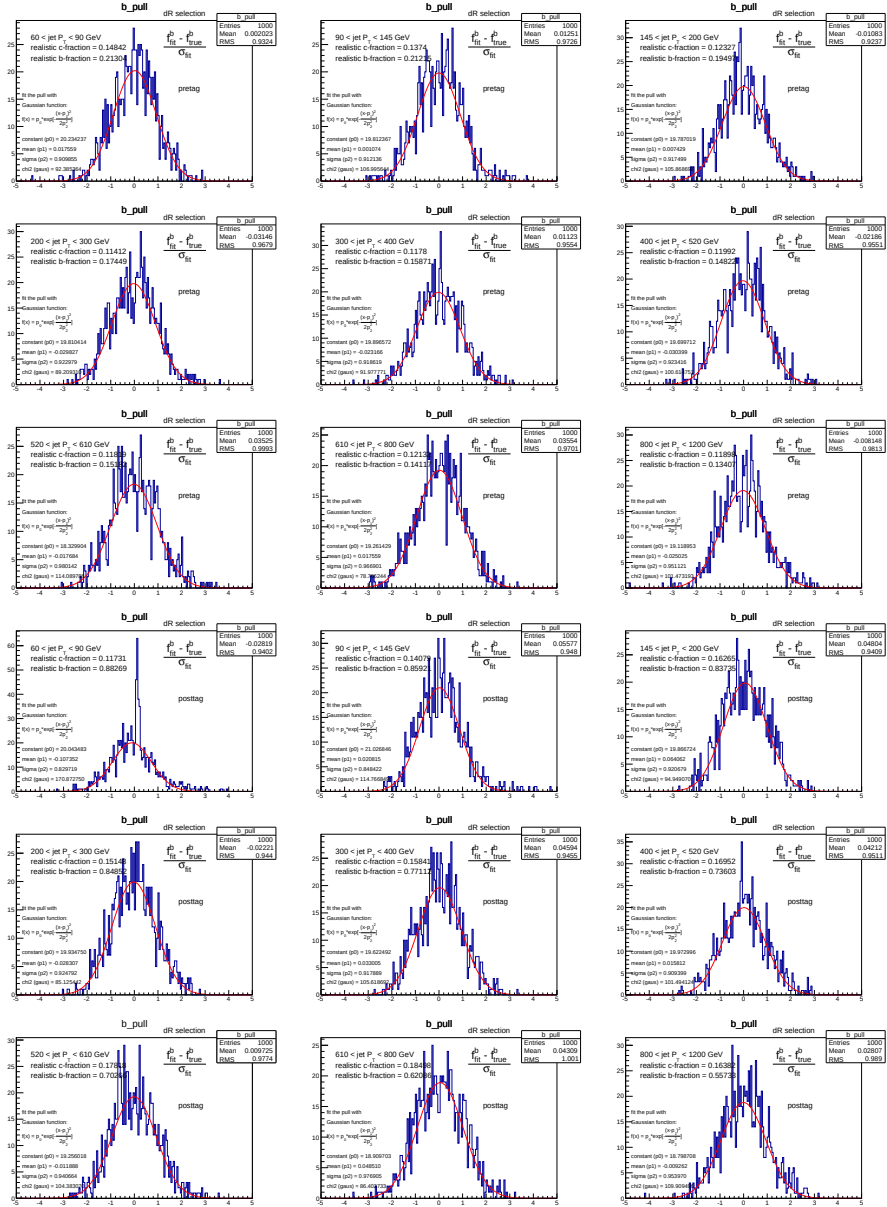


Figure A.24: The pull-distribution $(f_b^{\text{fit}} - f_b^{\text{true}})/\sigma_{f_b}^{\text{fit}}$ in various jet p_T bins obtained in the pseudo-data experiments for the dR selection. The upper nine plots and the bottom nine plots correspond to the pretag and posttag fits, respectively.

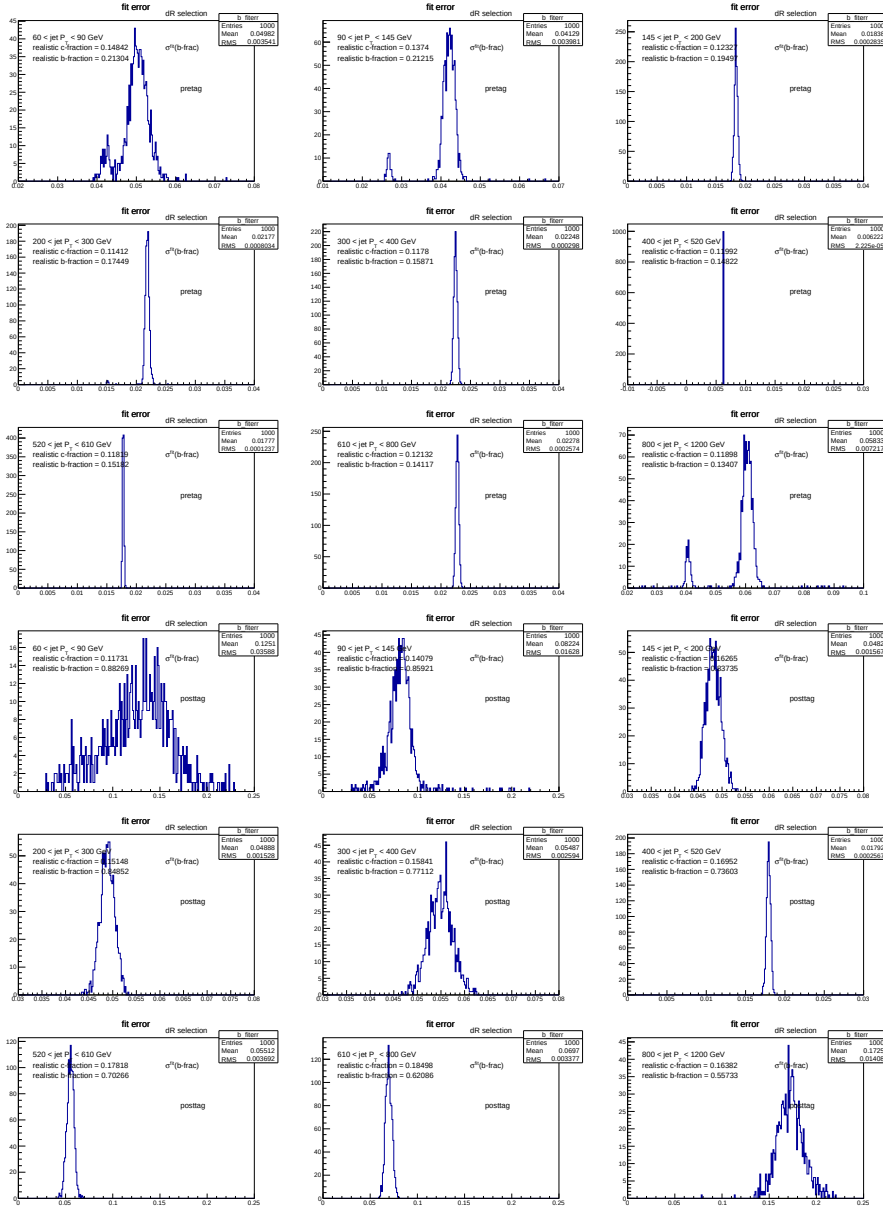


Figure A.25: The uncertainty σ_{f_b} on the fitted b fraction in various jet p_T bins, obtained in the pseudo-data experiments for the dR selection. The upper nine plots and the bottom nine plots correspond to the pretag and posttag fits, respectively.

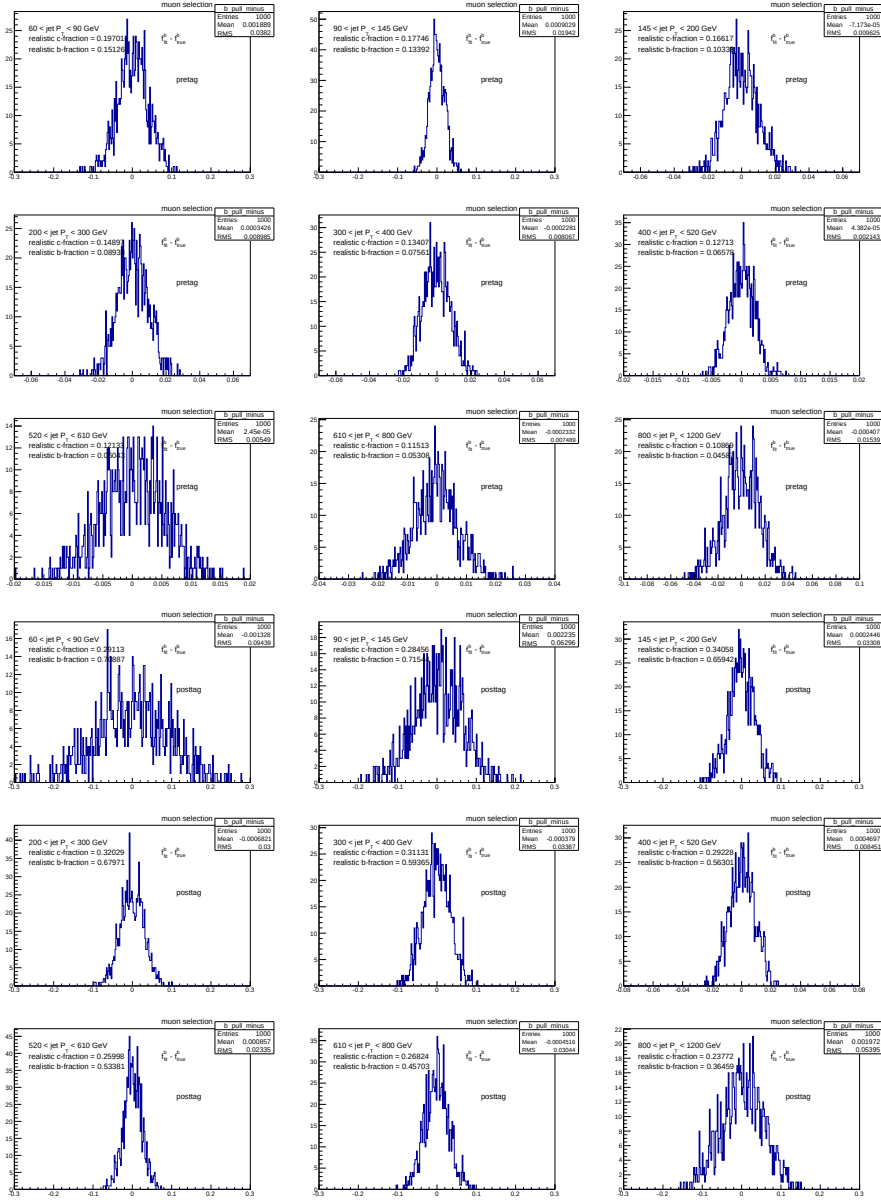


Figure A.26: The difference between fitted and true b -jet fractions ($f_b^{\text{fit}} - f_b^{\text{true}}$) in various jet p_T bins obtained in the pseudo-data experiments for the muon-in-jet selection. The upper nine plots and the bottom nine plots correspond to the pretag and posttag fits, respectively.

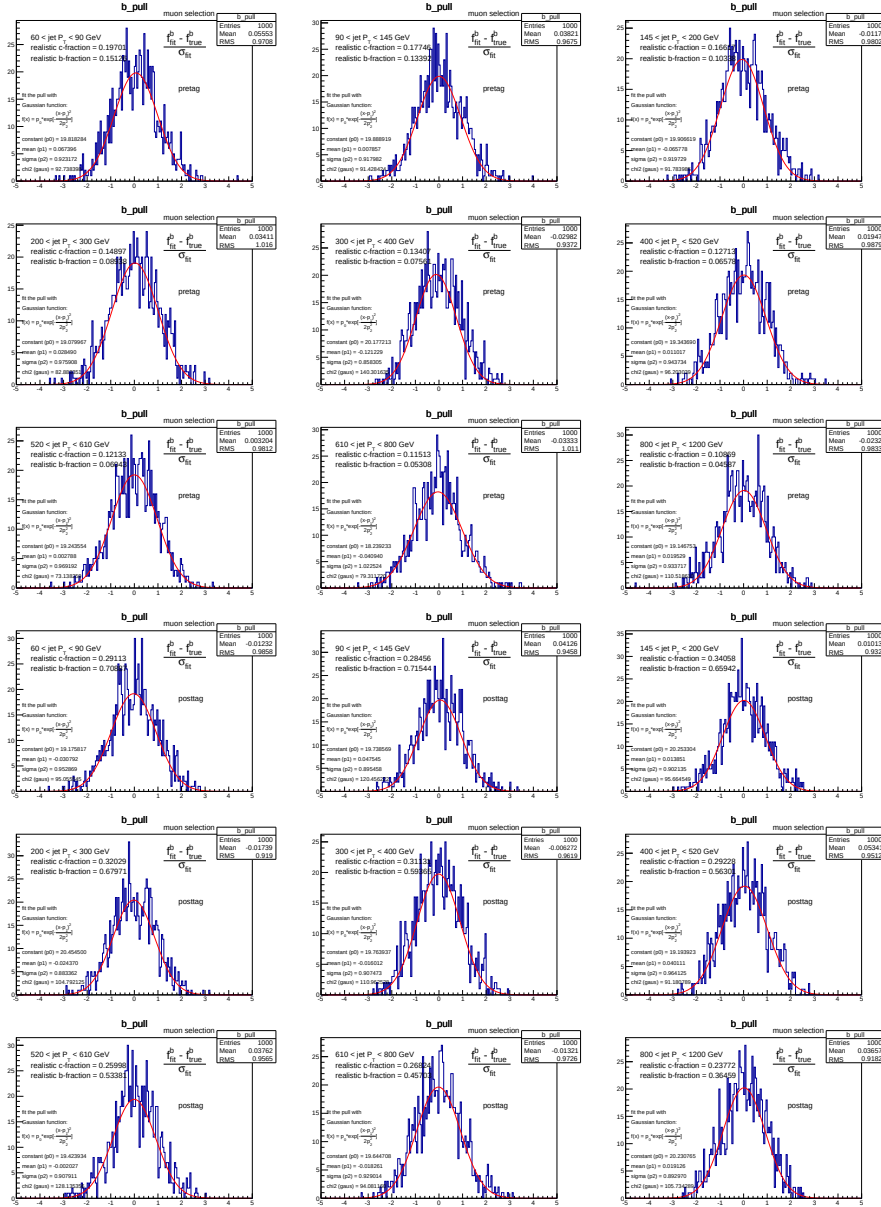


Figure A.27: The pull-distribution $(f_b^{\text{fit}} - f_b^{\text{true}})/\sigma_b^{\text{fit}}$ in various jet p_T bins obtained in the pseudo-data experiments for the muon-in-jet selection. The upper nine plots and the bottom nine plots correspond to the pretag and posttag fits, respectively.

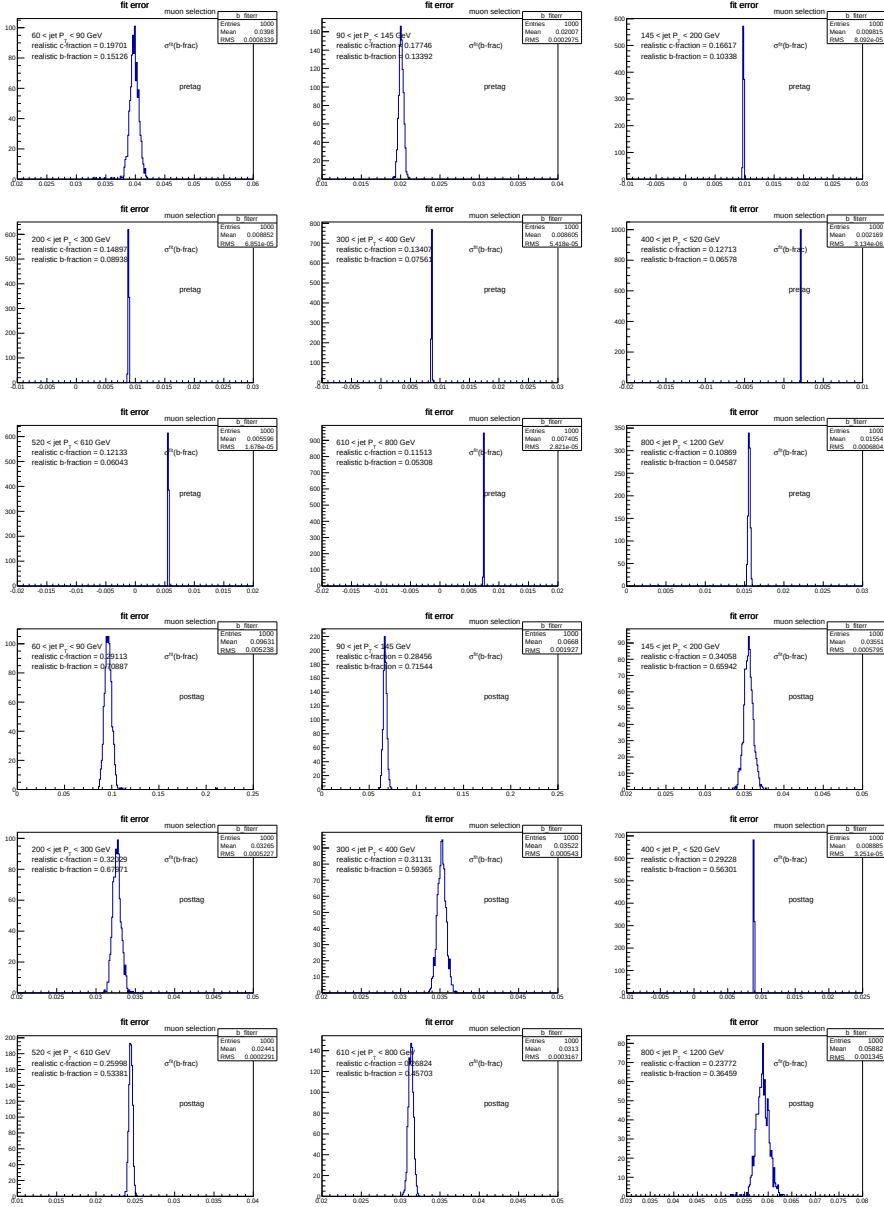


Figure A.28: The uncertainty σ_{f_b} on the fitted b fraction in various jet p_T bins, obtained in the pseudo-data experiments for the muon-in-jet selection. The upper nine plots and the bottom nine plots correspond to the pretag and posttag fits, respectively.

D Muon-in-jet selection

The b -tagging efficiency and the data-to-simulation scale factors vs calo-jet p_T for the muon-in-jet selection are presented in Fig. A.29. The left and the right plots are obtained by calibrating calo-jets and track-jets, respectively. The fits are found to be unstable, which is reflected in the large differences between the b fractions obtained from the fit in neighboring p_T bins. The presumption that the instability could be a statistical effect was rejected due to the fact that the number of event in the sample for the dR selection is even less than for the muon-in-jet selection. The b purity in the samples for the muon-in-jet selection is lower, and this might cause a fit bias. However, the pseudo-data experiments based on the same statistics do not show a bias. In the sample for the muon-in-jet selection the fraction of b jets with two b hadrons inside is larger than in the dR sample. Therefore, the fit might be more sensitive to the modelling of the fraction of $g \rightarrow b\bar{b}$ events. To check whether the source of the fit instability could be a bad modelling of the gluon splitting, 4-component fits are done, where an additional template is built using jets with two b hadrons inside. The fit results do not confirm the presumption. Moreover, the estimated $g \rightarrow b\bar{b}$ systematic uncertainty is not large (see Section 6.5.5), so the effect can likely not explain the issue in the muon-in-jet selection. Due to the stability issues, the results obtained with the muon-in-jet selection only serve as a cross-check.

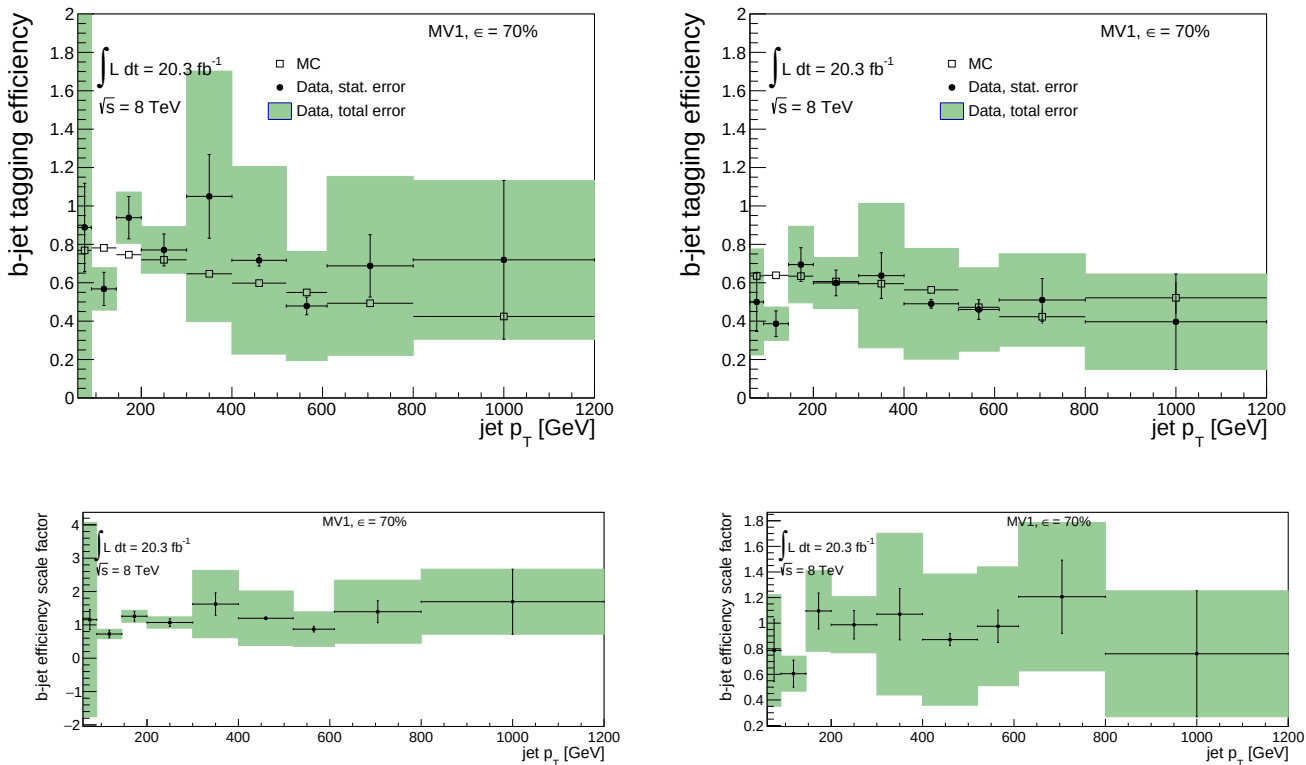


Figure A.29: The b -tagging efficiency and the data-to-simulation scale factors as functions of calo-jet p_T obtained from template fits to the S_{d0}^{t1} distribution of the tracks associated to calo-jets (left) and to track-jets (right) passing the muon-in-jet selection.

E Systematic uncertainties

Source \ p_T [GeV]	60-90	90-145	145-200	200-300	300-400	400-520	520-610	610-800	800-1200
JES up	22.97	3.58	3.86	-2.77	-0.98	-5.81	22.03	9.27	-21.09
JES down	16.2	-2.33	2.19	7.34	-13.22	7.1	-0.3	7.06	-26.55
K_s , Λ	0.78	2	2.92	3.54	6.9	3.98	4.14	7.56	16.11
fake tracks	-0.17	-0.4	-2.37	-2.04	-8.29	-5.02	0.71	-13.46	-32.21
gluon splitting	1.92	0.01	0.34	1.55	0.56	0.88	10.76	1.7	-16.57
trk mult. rew.	8.28	1.24	-0.28	-1.89	-14.39	-12.17	-19.66	-12.87	-27.52
Herwig	248.85	11.04	-5.46	6.87	-54.18	-65.96	-49.19	-59.09	-77.17
Total syst. unc.	250.57	12.08	7.99	11.47	58.61	68	58.53	63.52	97.13

Table A.1: Relative systematic uncertainties (in %) on the b -tagging efficiency for calo-jets passing the muon-in-jet selection.

Source \ p_T [GeV]	60-90	90-145	145-200	200-300	300-400	400-520	520-610	610-800	800-1200
K_s , Λ	-55.64	-14.71	-56.01	-39.53	-58.71	-53.52	-27.66	-32.09	-28.5
fake tracks	-6.24	-0.54	-10.48	-15.8	-24.17	-21.05	-29.15	-31.9	-51.56
gluon splitting	-2.81	-0.3	0.35	-3.82	-1.08	9.88	4.19	8.05	-3.46
trk multip. rew.	-2.91	0.81	0.42	-4.32	-2.25	9.42	5.47	6.58	-3.49
Herwig	-43.9	-12.74	-23.22	-2.43	-49.2	-45.19	-30.35	7.45	63.99
Trk reconst. eff.	0.13	2.09	-0.09	-3.91	-4.86	10.24	6.28	8.44	-3.88
Trk eff. high p_T	3.99	3.38	1.32	-3.27	-3.52	9.65	5.67	7.57	-10.59
Trk. smearing down	-4.54	2.75	0.07	-3.44	-3.97	8.33	4.42	7.35	-11.86
Trk. smearing up	-2.35	1.88	1.14	-4.07	-5.81	8.59	5.97	9.29	-13
Trk. scale down	4.1	0.28	0.5	-3.16	-3.67	9.84	4.39	8.13	-11.15
Trk. scale up	7.88	2.92	-0.49	-3.42	-3.53	9.31	6.32	7.6	-10.03
Total syst. unc.	72.11	20.38	61.56	43.9	81.05	77.85	52.62	51.03	90.84

Table A.2: Relative systematic uncertainties (in %) on the b -tagging efficiency for track-jets passing the muon-in-jet selection.

F Other discriminating variables

F.1 Correlation between the discriminating variables

As can be seen from Fig. 6.5, the MV1 weight correlates only slightly with $S_{d_0}^{t1}$. Figure A.30 shows that $S_{d_0}^{t1}$ is also relatively uncorrelated to the JetProb weight. This allows using also the JetProb weight to calibrate the MV1 tagging algorithm. The correlation between the variables $S_{d_0}^{ti}$, $i = 1, 2, 3$, and between each of them and the JetProb weight is found to be low, as shown in Figs. A.30 and A.31. Consequently, the calibration performance can likely be further improved by making a 2D fit over a pair of these variables. Two additional studies are done using the JetProb weight and $S_{d_0}^{ti}$ ($i = 2, 3$) as discriminating variables. These studies are described in Appendices F.3 and F.4.

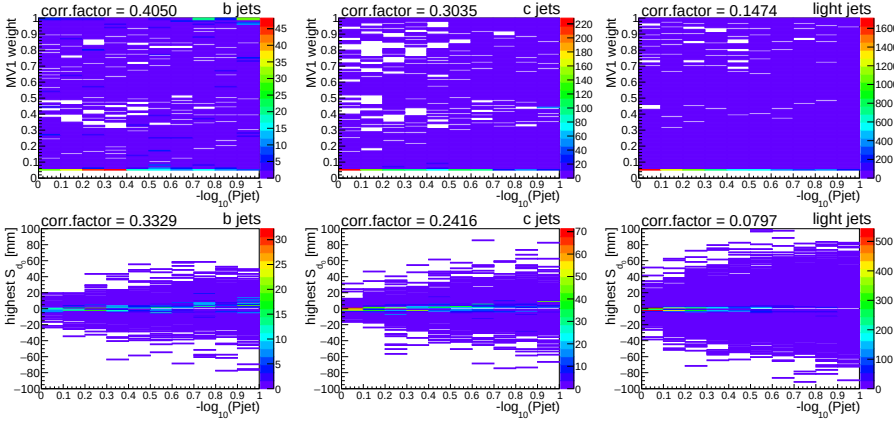


Figure A.30: Correlations between the MV1 weight and $-\log_{10}(\mathcal{P}_{\text{jet}})$ (top), and between $S_{d_0}^{t1}$ and $-\log_{10}(\mathcal{P}_{\text{jet}})$, for b jets (left), c jets (middle) and light jets (right).

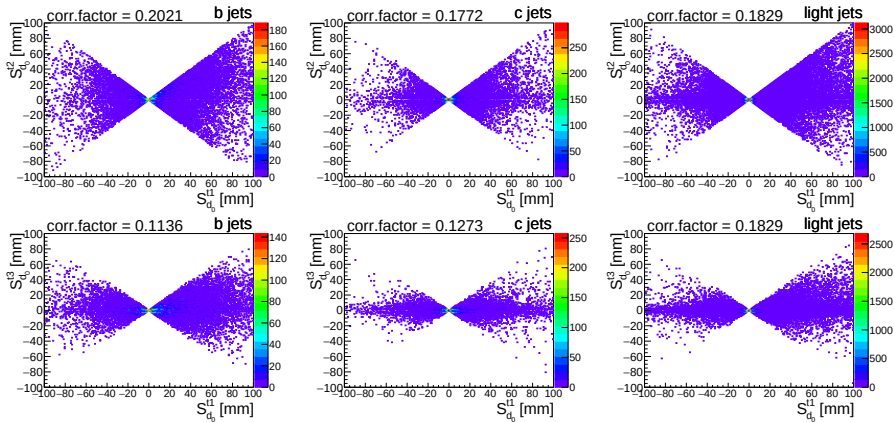


Figure A.31: Correlations between $S_{d_0}^{t2}$ and $S_{d_0}^{t1}$ (top), and between $S_{d_0}^{t3}$ and $S_{d_0}^{t1}$ (bottom), for b jets (left), c jets (middle) and light jets (right).

F.2 JetProb templates

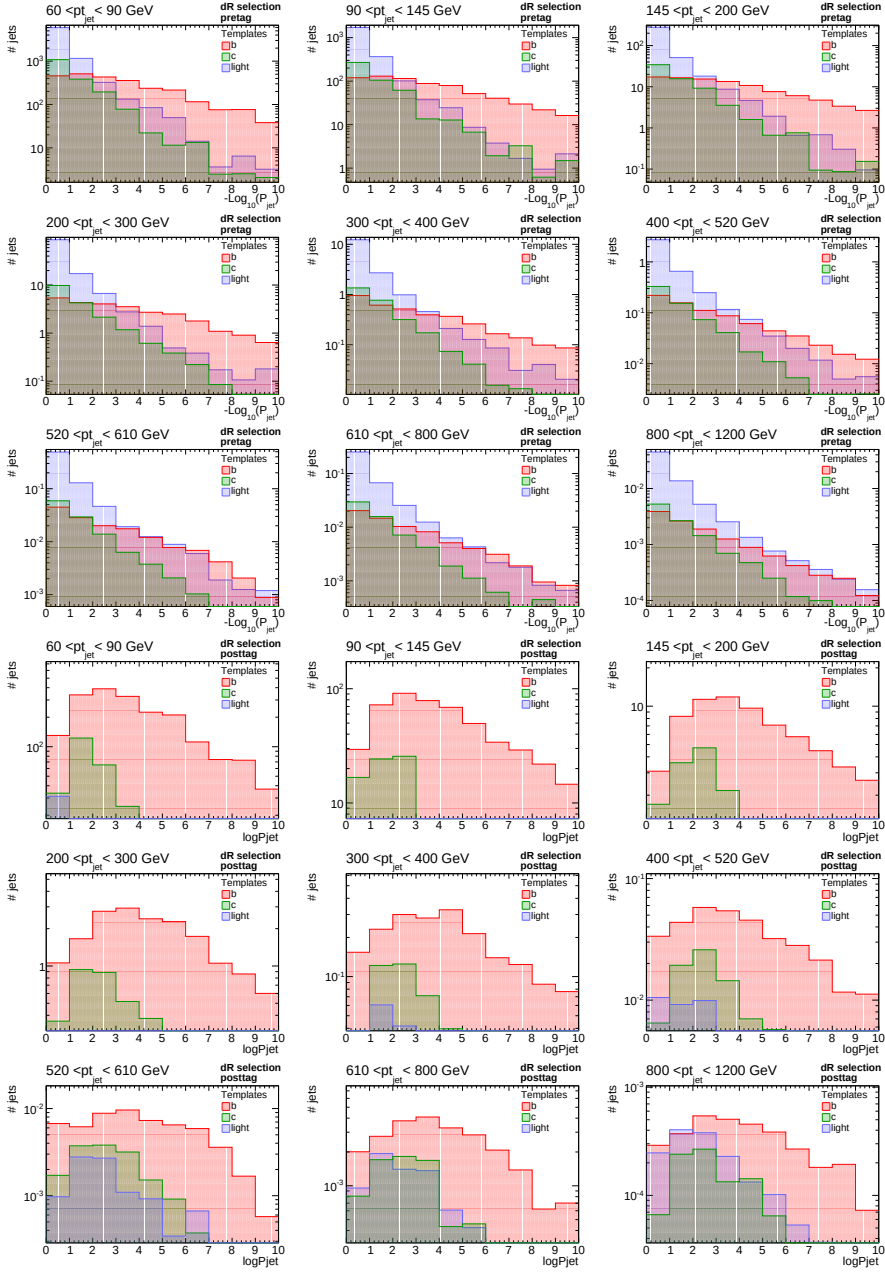


Figure A.32: Pretag (first six) and posttag (last six) b -, c - and light-jet $-\log_{10}(\mathcal{P}_{\text{jet}})$ templates for the dR selection in different jet p_T bins.

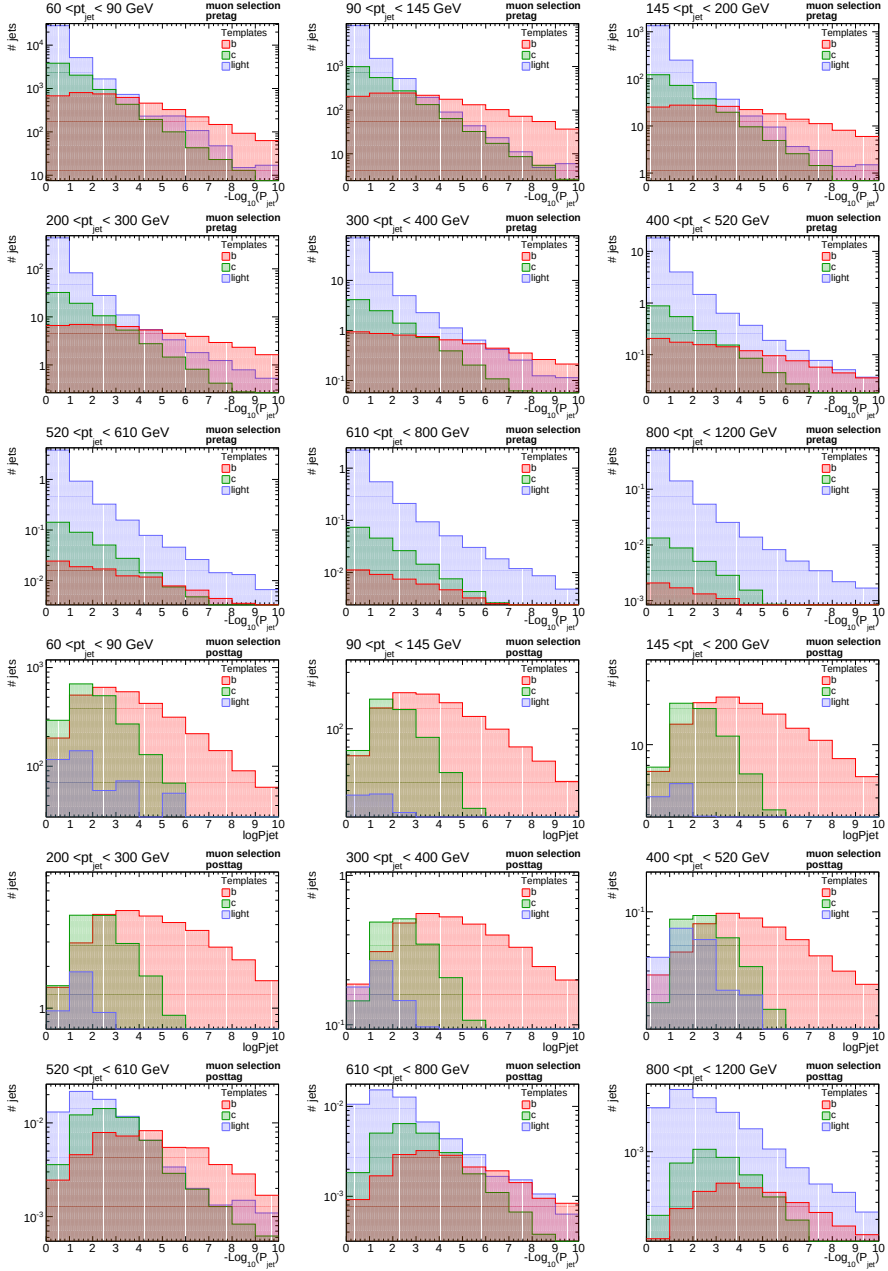


Figure A.33: Pretag (first six) and posttag b -, c - and light-jet $-\text{Log}_{10}(\mathcal{P}_{\text{jet}})$ templates for the muon-in-jet selection in different jet p_T bins.

F.3 Fits to the JetProb weight

The JetProb weight (Section 5.2.2) is investigated as an alternative to the $S_{d_0}^{t1}$ discriminating variable to calibrate the b -tagging efficiency. Templates are built from the distribution of $-\log_{10}(\mathcal{P}_{\text{jet}})$ and used to fit the corresponding distribution in data. The $-\log_{10}(\mathcal{P}_{\text{jet}})$ templates for all the jet p_T bins are shown in Fig. A.32 for the dR selection, and in Fig. A.33 for the muon-in-jet selection. Figures A.35 and A.36 show the pretag and posttag template fits for the dR selection, and Figs. A.37 and A.38 for the muon-in-jet selection. The efficiency of the MV1 b -tagging algorithm as a function of jet p_T , and the data-to-simulation scale factors obtained with template fits to the $-\log_{10}(\mathcal{P}_{\text{jet}})$ distributions are presented in Fig. A.34.

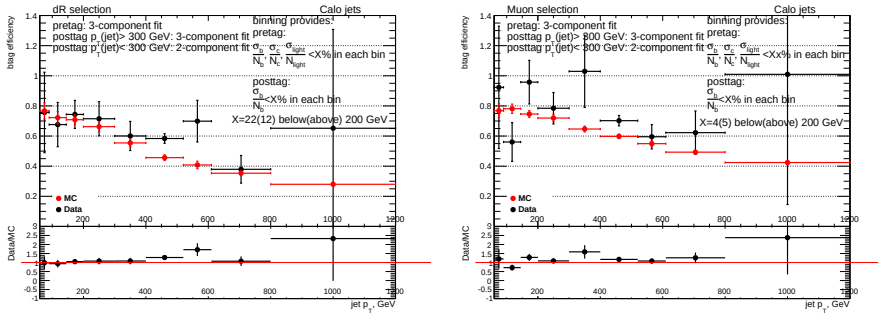


Figure A.34: The b -tagging efficiency and the data-to-simulation scale factors vs calo-jet p_T obtained from template fits to the $-\log_{10}(\mathcal{P}_{\text{jet}})$ distribution of calo-jets for the dR selection (left) and the muon-in-jet selection (right).

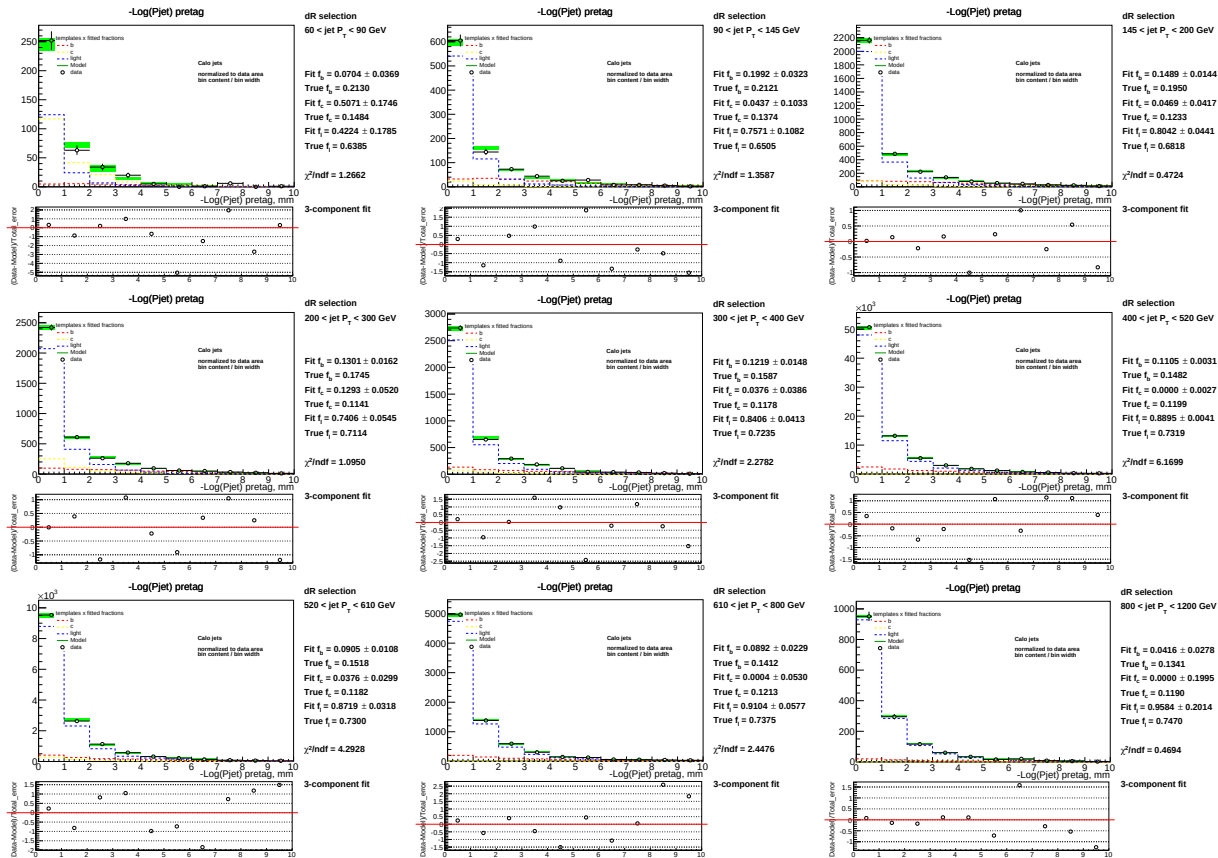


Figure A.35: Template fits to the pretag $-\log_{10}(\mathcal{P}_{\text{jet}})$ distributions of calo-jets for the dR selection in bins of jet p_T .

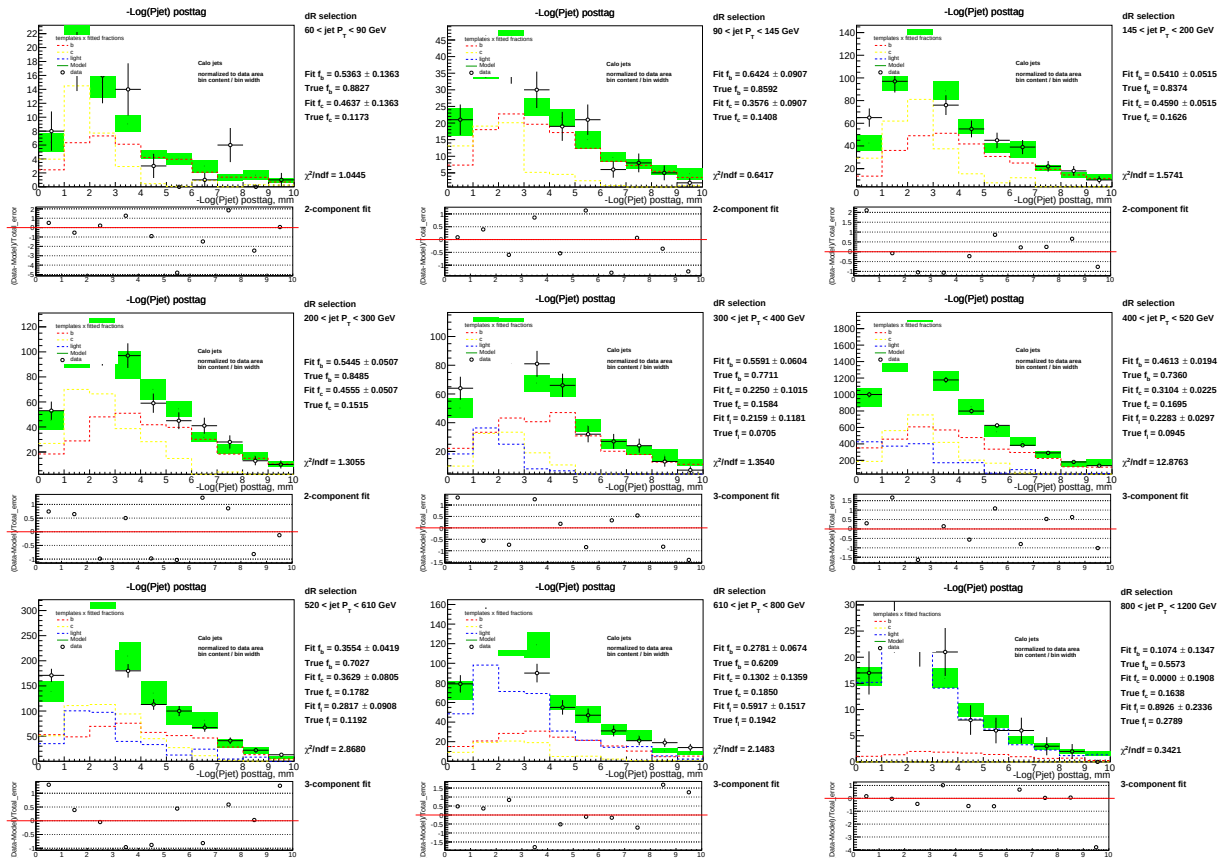


Figure A.36: Template fits to the postag $-\log_{10}(\mathcal{P}_{\text{jet}})$ distributions of calo-jets for the dR selection in bins of jet p_T .

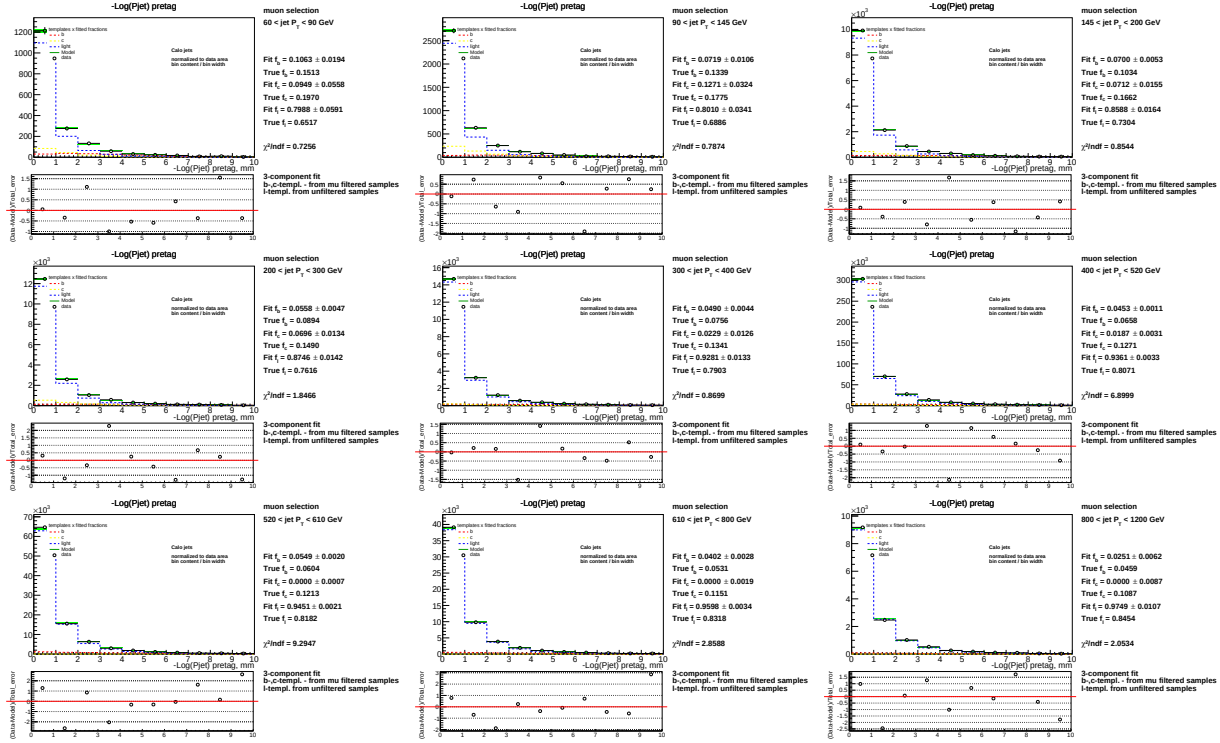


Figure A.37: Template fits to the pretag $-\log_{10}(\mathcal{P}_{\text{jet}})$ distributions of calo-jets for the muon-in-jet selection in bins of jet p_T .

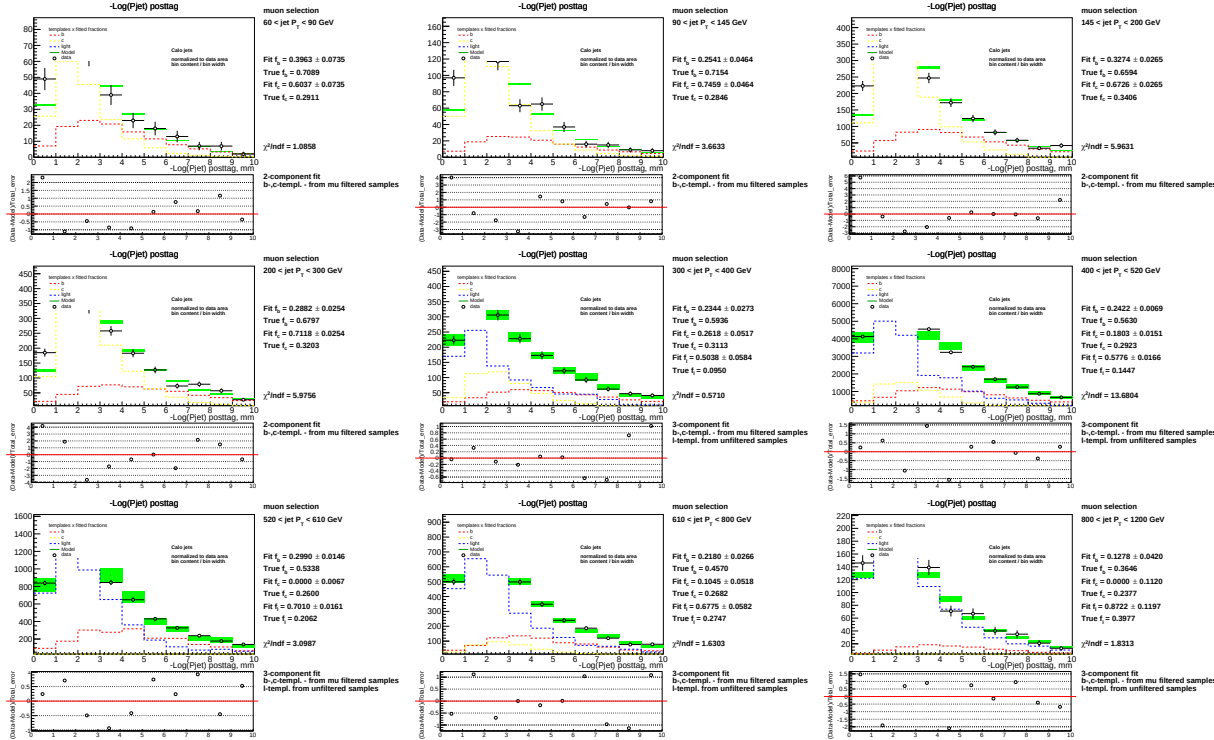


Figure A.38: Template fits to the postag $-\log_{10}(\mathcal{P}_{\text{jet}})$ distributions of calo-jets for the muon-in-jet selection in bins of jet p_T .

F.4 Fits to $S_{d_0}^{t2}$ and $S_{d_0}^{t3}$

The $S_{d_0}^{t2}$ and $S_{d_0}^{t3}$ templates are build the same way as described in Section 6.4.3 and the rebinning procedure is applied to them. The b -tagging efficiency in jet p_T bins, and the data-to-simulation scale factor obtained from fits with these templates are presented in Fig. A.39 for the dR and the muon-in-jet selections.

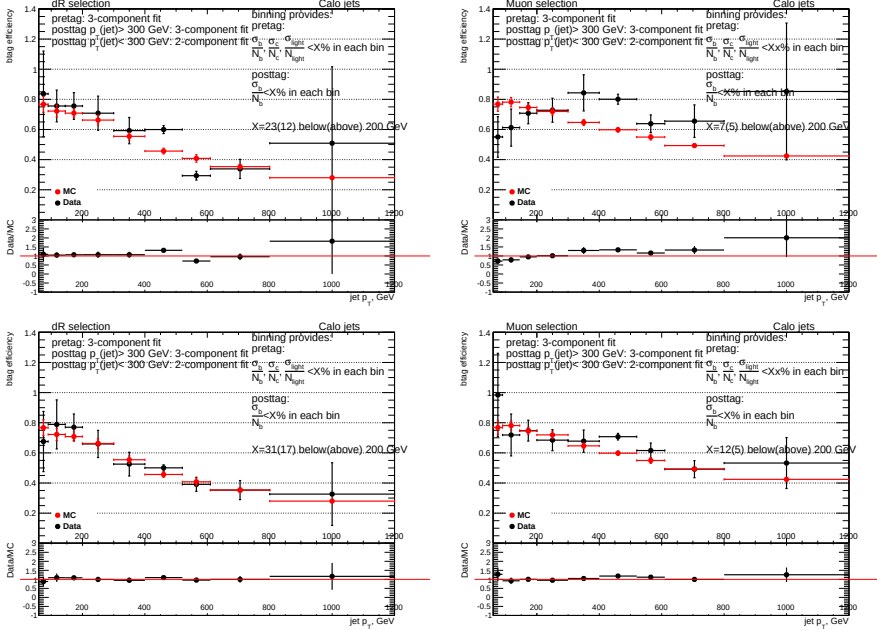


Figure A.39: The b -tagging efficiency and the data-to-simulation scale factor vs calo-jet p_T obtained from template fits to the $S_{d_0}^{t2}$ (top) and $S_{d_0}^{t3}$ (bottom) distribution of calo-jets for the dR selection (left) and the muon-in-jet selection (right).

G Cross sections for $DM+t\bar{t}$ production

Table A.3: Cross sections for signal samples with a scalar (top) and pseudoscalar (bottom) mediator.

m_ϕ [GeV]	m_χ [GeV]	σ_{LO} [pb]	K_F	Filter Eff.	Rel. Unc.
10	1	19.606	1.25574	0.598639	0.0894905
20	1	10.427	1.25444	0.643428	0.089495
50	1	2.94432	1.23831	0.753218	0.087517
100	1	0.673193	1.22298	0.859095	0.0877049
200	1	0.093419	1.2096	1	0.0954139
300	1	0.029441	1.26388	1	0.110934
350	1	0.01967	1.28622	1	0.115217
400	1	0.01191	1.31654	1	0.118999
450	1	0.0075956	1.34815	1	0.121868
500	1	0.0051355	1.38059	1	0.126022
1000	1	0.00036855	1.52055	1	0.148088
5000	1	6.168e-08	1.54523	1	0.166119
10	10	0.0944693	1.24591	0.738134	0.0895105
10	50	0.0019155	1.23414	1	0.0987951
10	100	0.00026658	1.32155	1	0.119911
10	150	8.614e-05	1.3896	1	0.13058
10	500	7.373e-07	1.61671	1	0.183424
10	1000	6.613e-09	1.97943	1	0.291006

m_a [GeV]	m_χ [GeV]	σ_{LO} [pb]	K_F	Filter Eff.	Rel. Unc.
10	1	0.439124	1.30077	0.857522	0.106175
20	1	0.401348	1.31332	0.872838	0.106167
50	1	0.301812	1.3071	1	0.107357
100	1	0.190175	1.29986	1	0.109989
200	1	0.084141	1.27999	1	0.113173
300	1	0.040118	1.33182	1	0.120643
350	1	0.022189	1.34301	1	0.121537
400	1	0.011606	1.35447	1	0.123163
450	1	0.00764289	1.39084	1	0.126995
500	1	0.005342	1.4021	1	0.129902
1000	1	0.00039445	1.52998	1	0.148087
5000	1	7.045e-08	1.56139	1	0.165133
10	10	0.014931	1.30668	1	0.108757
10	50	0.00243225	1.31195	1	0.115309
10	100	0.00065253	1.36852	1	0.124371
10	150	0.0002358	1.39992	1	0.130474
10	500	2.274e-06	1.58663	1	0.173075
10	1000	2.591e-08	1.91355	1	0.265467

H Breakdown of the systematic uncertainties

Uncertainty of channel	DM_low
Total background expectation	13.78
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 3.71
Total background systematic	± 3.60 [26.14%]
mu_ttZ	± 2.42 [17.5%]
alpha_amcnlo_ttV_Modeling	± 2.02 [14.6%]
gamma_stat_DM_low_cuts_bin_0	± 1.19 [8.6%]
alpha_JES_GroupedNP1	± 1.15 [8.3%]
alpha_cTag	± 0.74 [5.4%]
alpha_sherpa22_Wjets_Modeling	± 0.60 [4.4%]
mu_wjets	± 0.54 [3.9%]
alpha_JER	± 0.43 [3.1%]
alpha_powheg_ttbar2L_HardScatter	± 0.34 [2.5%]
alpha_powheg_ttbar2L_Fragmentation	± 0.25 [1.8%]
alpha_lTag	± 0.24 [1.8%]
mu_ttbar2L	± 0.24 [1.7%]
alpha_MET_Reso_para	± 0.23 [1.7%]
mu_wt	± 0.22 [1.6%]
alpha_xsec_sherpa221_diboson	± 0.20 [1.5%]
alpha_powheg_ttbar2L_Radiation	± 0.20 [1.4%]
alpha_sherpa221_diboson_Modeling	± 0.19 [1.3%]
alpha_prw	± 0.16 [1.2%]
alpha_bTag	± 0.15 [1.1%]
alpha_powheg_singletop_Interference	± 0.10 [0.76%]
alpha_MET_Reso_perp	± 0.10 [0.75%]
alpha_powheg_singletop_Fragmentation	± 0.10 [0.72%]
alpha_MET_Scale	± 0.09 [0.65%]
alpha_powheg_singletop_Radiation	± 0.06 [0.43%]
alpha_bextra	± 0.05 [0.37%]

Table A.4: Breakdown of the dominant systematic uncertainties on the background estimates in the signal, control, and validation regions for the DM_low analysis. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

Uncertainty of channel	DM_high
Total background expectation	7.43
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 2.73
Total background systematic	± 2.14 [28.87%]
mu_ttZ	± 1.54 [20.7%]
alpha_amcnlo_ttV_Modeling	± 1.31 [17.7%]
gamma_stat_DM_high_cuts_bin_0	± 0.42 [5.7%]
alpha_prw	± 0.41 [5.5%]
alpha_sherpa22_Wjets_Modeling	± 0.37 [4.9%]
alpha_JES_GroupedNP1	± 0.34 [4.6%]
mu_wjets	± 0.32 [4.3%]
alpha_cTag	± 0.21 [2.8%]
alpha_powheg_ttbar2L_HardScatter	± 0.18 [2.5%]
alpha_lTag	± 0.15 [2.0%]
alpha_xsec_sherpa221_diboson	± 0.14 [1.9%]
alpha_JER	± 0.13 [1.8%]
mu_wt	± 0.13 [1.7%]
alpha_sherpa221_diboson_Modeling	± 0.12 [1.6%]
alpha_powheg_ttbar2L_Radiation	± 0.11 [1.5%]
alpha_powheg_ttbar2L_Fragmentation	± 0.11 [1.4%]
mu_ttbar2L	± 0.09 [1.2%]
alpha_bTag	± 0.08 [1.1%]
alpha_powheg_singletop_Fragmentation	± 0.04 [0.57%]
alpha_MET_Reso_para	± 0.04 [0.50%]
alpha_JES_GroupedNP3	± 0.04 [0.48%]
alpha_powheg_singletop_Radiation	± 0.03 [0.47%]
alpha_powheg_singletop_Interference	± 0.03 [0.46%]
alpha_JET_EtaIntercalibration_NonClosure	± 0.03 [0.45%]
alpha_JES_GroupedNP2	± 0.02 [0.28%]

Table A.5: Breakdown of the dominant systematic uncertainties on the background estimates in the signal, control, and validation regions for the DM_high analysis. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

Uncertainty of channel	DM_low_loose
Total background expectation	48.28
Total statistical ($\sqrt{N_{\text{exp}}}$)	± 6.95
Total background systematic	± 8.23 [17.05%]
alpha_amcnlo_ttV_Modeling	± 4.30 [8.9%]
mu_ttZ	± 4.22 [8.7%]
mu_ttbar	± 2.98 [6.2%]
alpha_JER	± 2.71 [5.6%]
gamma_stat_DM_low_loose_cuts_bin_0	± 2.69 [5.6%]
alpha_powheg_ttbar_HardScatter	± 2.38 [4.9%]
alpha_prw	± 2.18 [4.5%]
alpha_powheg_ttbar_Radiation	± 2.06 [4.3%]
alpha_cTag	± 1.67 [3.5%]
alpha_sherpa22_Wjets_Modeling	± 1.29 [2.7%]
alpha_powheg_ttbar_Fragmentation	± 1.27 [2.6%]
mu_wjets	± 1.12 [2.3%]
alpha_lTag	± 1.01 [2.1%]
alpha_powheg_singletop_Interference	± 0.90 [1.9%]
mu_wt	± 0.74 [1.5%]
alpha_xsec_sherpa221_diboson	± 0.74 [1.5%]
alpha_sherpa221_diboson_Modeling	± 0.69 [1.4%]
alpha_bTag	± 0.58 [1.2%]
alpha_JET_EtaIntercalibration_NonClosure	± 0.49 [1.0%]
alpha_powheg_singletop_Radiation	± 0.30 [0.62%]
alpha_MET_Scale	± 0.29 [0.59%]
alpha_JES_GroupedNP1	± 0.26 [0.53%]
alpha_powheg_singletop_Fragmentation	± 0.20 [0.41%]
alpha_JES_GroupedNP2	± 0.14 [0.30%]
alpha_MET_Reso_perp	± 0.14 [0.30%]
alpha_JES_GroupedNP3	± 0.11 [0.24%]

Table A.6: Breakdown of the dominant systematic uncertainties on the background estimates in the signal, control, and validation regions for the DM_low_loose analysis. Note that the individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty. The percentages show the size of the uncertainty relative to the total expected background.

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Calibration of b -tagging efficiency and search for Dark Matter production in association with heavy flavour quarks with the ATLAS experiment.

Place	Typo/mistake	Correction
Section 3.1.1, 2 nd paragraph, p.25	at 5.5 TeV per ion pair	at a center-of-mass energy of 5.5 TeV per colliding nucleon pair
Section 4.2.5, p.43	transverse momentum of particle i is denoted as k_{Ti}	transverse momentum of entity i is denoted as k_{Ti}
Section 5.2.2, eq.5.2, p.60	missing minus in the upper limit of the integral	$\mathcal{P}_{\text{trk}_i} = \int_{-\infty}^{- S_{d_0}^i } \mathcal{R}(x) dx$
Table 8.4, p.107	missing units	$E_T^{\text{miss}} > 100 \text{ GeV}$ Leading b jet $p_T > 100 \text{ GeV}$ $E_T^{\text{miss}} > 300 \text{ GeV}$
Tables 8.5-8.8, p.p.110-113	missing units for masses	$m_\chi [\text{GeV}]$ $m_\phi [\text{GeV}]$
Section 9.7.2, under eq.9.5, p.139	summation is done over the dominant background processes: the semileptonic and dileptonic $t\bar{t}$ backgrounds for DM_low and DM_high or the $t\bar{t}$ background for DM_low_loose, the single top background, the W +jets and the $t\bar{t}Z$ backgrounds.	, as well as the diboson background.
Section 9.10, p.152	simplifies	simplified

The distributions in Figs. 5.5-5.8 are obtained using the data and the unfiltered multi-jet MC simulated samples described in Section 6.2. The pre-selection and the dR selection described in Section 6.3.5 are applied to them.

The apparent mismodelling of the jet p_T spectrum shown in Fig. 6.2 at low p_T values is not caused by any discrepancy between data and MC simulations, but is rather an effect of the unfortunate choice of binning. The triggers used in the first calo-jet p_T bins are prescaled, which is not modelled in the simulations, therefore the number of simulated events should be scaled to the number of data events in the calo-jet p_T bins. The scaling is done correctly and the shape displayed in Fig. 6.2 does not affect the final result. The same distributions but with finer binning are shown on the figure below.

