

**Novel Trigger-Capable Modules for the
Future CMS Tracking Detector
and
Inclusive Top Quark Pair Production
Cross Section at $\sqrt{s} = 13$ TeV**

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Abstract

This work covers two important aspects in the field of high-energy physics; detector development and physics data analysis. The first part of this thesis is devoted to the detector development activities for the Phase-II upgrade of the Compact Muon Solenoid (CMS) experiment's outer tracking detector. To cope with the increased luminosity during the high-luminosity era of the Large Hadron Collider (LHC), it is foreseen to replace the existing tracking system of CMS with an entirely new system. Owing to a novel module concept called the p_T -module, the upgraded tracking system will be able to provide first level trigger information by means of an on-board momentum discrimination logic. This will be achieved using a new readout chip, the so-called CMS Binary Chip (CBC). The very first test beam measurement using p_T -module prototypes, equipped with the CBC chip is presented and discussed. The obtained results serve as a proof-of-concept for such modules and shows that the CBC performs as expected. In the second part of this thesis, the measurement of the top quark pair production cross section is addressed. The measurement is performed using 2.2 fb^{-1} of data collected by the CMS detector at a center-of-mass energy of 13 TeV. Results are shown in the $e\mu$ di-lepton channel, and for the first time at such energy, in the ee and $\mu\mu$ channels. With an improved treatment of systematic uncertainties, the results in all three channels are found to be in agreement with the theoretical predictions.

Zusammenfassung

In dieser Arbeit werden zwei wichtige Aspekte aus der Hochenergiephysik behandelt: die Detektorentwicklung und die Datenanalyse. Der erste Teil beschäftigt sich mit der Detektorentwicklung für das Phase-II Upgrade des äußeren Spurdetektors des CMS-Experimentes. Um die erhöhte Luminosität in der Hochluminositätsphase des Large Hadron Colliders zu bewältigen, wird der gegenwärtige Spurdetektor des CMS-Experimentes durch ein vollständig neues System ersetzt. Ein neuartiges Modulkonzept verwendet sogenannte pT-Module, um dem zukünftigen Spurdetektor zu ermöglichen, Informationen an die erste Stufe des Triggers zu senden. Hierzu wird auf den Modulen eine p_T -Unterscheidung vorgenommen, wofür ein neuer Auslesechip, der CMS Binary Chip (CBC) benötigt wird. Im ersten Teil dieser Arbeit werden die allerersten Teststrahlungsmessungen mit diesem Chip auf p_T -Modul Prototypen vorgestellt. Diese Messungen veranschaulichen das Funktionsprinzip dieser Module und die Ergebnisse zeigen, dass der Chip wie vorgesehen funktioniert. Der zweite Teil dieser Arbeit widmet sich der Messung des Wirkungsquerschnittes der Produktion des Topquarks. Diese Messung verwendet 2.2 fb^{-1} an Daten, welche vom CMS-Experiment bei einer Schwerpunktsenergie von 13 TeV aufgenommen wurden. Die hier vorgestellten Ergebnisse verwenden den $e\mu$ Di-Lepton Kanal und, erstmalig für diese Energie, die ee und $\mu\mu$ Kanäle. Mit einer verbesserten Behandlung von systematischen Unsicherheiten stimmen Ergebnisse aus allen drei Kanälen mit den theoretischen Vorhersagen überein.

Contents

List of Figures	ix
List of Tables	xiv
1 Introduction	1
2 Theoretical Overview	5
2.1 The Standard Model of Particle Physics	5
2.1.1 Particles and interactions	6
2.1.2 The electroweak symmetry breaking	9
2.1.3 Beyond the Standard Model	11
3 The CMS Experiment at the LHC	13
3.1 The Large Hadron Collider	13
3.2 The CMS Detector	14
3.2.1 Coordinate system and variables	15
3.2.2 The superconducting solenoid	16
3.2.3 Tracking system	17
3.2.4 Calorimetry	18
3.2.5 The muon system	20
3.2.6 The trigger system	22
3.3 CMS Upgrades	23
3.3.1 Phase-I upgrade	24
3.3.2 Phase-II upgrade	25
4 Basic Principles of Semiconductor Detectors	27
4.1 Interaction of Particles with Matter	27
4.1.1 Energy loss of heavy charged particles	28
4.1.2 Energy loss of electrons and positrons	29
4.2 Basic Properties of Silicon Semiconductors	30

4.2.1	Energy band	30
4.2.2	Intrinsic and extrinsic silicon	31
4.2.3	The pn-junction	32
4.2.4	Electrical properties	34
4.3	Silicon Strip Detectors	35
4.3.1	Basic design	36
4.3.2	Charge collection	38
4.3.3	Read-out	40
5	The Phase-II Upgrade of the CMS Outer Tracking Detector	41
5.1	Motivation and Requirements	41
5.2	The Future Outer Tracking Detector	43
5.2.1	The p_T -module concept	44
5.2.2	The 2S module design	47
5.2.3	The PS module design	50
5.3	Track Finding at L1	50
5.3.1	Track finding approaches	51
5.3.2	Performance estimates	53
5.4	The CMS Binary Chip	54
5.4.1	The Chip Design	54
5.4.2	The Logic Block	56
6	CBC2 Performance in Test Beam	61
6.1	Experimental Setup	61
6.1.1	Tested modules	61
6.1.2	Test beam setup	62
6.1.3	Data acquisition setup	64
6.1.4	Recorded datasets	65
6.2	Event Reconstruction	66
6.2.1	Noise suppression	66
6.2.2	Clustering	67
6.2.3	Alignment of the DUT	69
6.3	Beam Parameters	71
6.4	Results	72
6.4.1	Cluster width	72
6.4.2	Cluster efficiency	74
6.4.3	Stub efficiency	78

6.5	Summary and Outlook	80
7	Introduction to Top Quark Physics	83
7.1	Top Quark Production	84
7.2	Top Quark Decay	85
7.3	Top Quark in the SM and Beyond	86
8	Simulation of Collision Events	89
8.1	Event Generation	90
8.1.1	Matrix element generation	90
8.1.2	Parton shower generation	91
8.1.3	Hadronization models	92
8.1.4	Matching matrix elements and parton showers	93
8.1.5	Underlying event	93
8.2	Detector Simulation	94
8.3	Simulated Samples	94
9	Object Reconstruction and Event Selection	97
9.1	Trigger Selection	98
9.2	Primary Vertex Reconstruction	98
9.3	Lepton Reconstruction and Selection	99
9.3.1	Lepton identification	99
9.3.2	Lepton isolation	102
9.3.3	Lepton identification and isolation efficiencies	102
9.3.4	Lepton pair selection	103
9.4	Missing Transverse Energy	103
9.5	Jets Reconstruction, Calibration, and Selection	104
9.6	Identification of b Quark Jets	106
9.7	Selection Summary and Control Distributions	109
10	Inclusive $t\bar{t}$ Cross Section Measurement at $\sqrt{s} = 13$ TeV	119
10.1	Definition of the Cross Section	120
10.2	Background Determination	121
10.3	Systematic Uncertainties	123
10.3.1	Experimental uncertainties	123
10.3.2	Signal modeling uncertainties	125
10.3.3	b-jets reweighting	127

10.3.4 Summary of systematic uncertainties	130
10.4 $t\bar{t}$ Cross Section Using the Baseline Selection	132
10.5 Comparison with Different Selection Scenarios	134
10.6 Comparison to Other Results	142
11 Summary and Outlook	145
Appendix A Scale Factors Used in the $t\bar{t}$ Cross section Measurement	147
A.1 Di-lepton Trigger Scale Factors	147
A.2 Leptons Scale Factors	149
Appendix B Impact of b-jets reweighting	151
Appendix C Electron Efficiencies	159
C.1 Electron Efficiency Calculation Using Tag&Probe	159
C.1.1 Electron identification and isolation efficiencies for $t\bar{t}$ early analysis	160
C.1.2 Electron isolation efficiency for $t\bar{t}H$ analysis	161
Appendix D Tables	167
Bibliography	173

List of Figures

2.1	The Standard Model table of elementary particles.	6
2.2	Summary of measurements of α_s as a function of the energy scale Q . .	8
3.1	The LHC complex.	15
3.2	Schematic representation of the CMS detector and its components. . .	16
3.3	The CMS tracking detector.	17
3.4	The CMS muon system.	21
3.5	Schematic view of a DT chamber with the three super-layers.	22
3.6	The outline of the LHC schedule until 2023.	24
4.1	The stopping power for positive muons in copper as a function of their momentum.	29
4.2	Stopping power of electrons in silicon.	30
4.3	Energy band configuration of conductor, semiconductor, and insulator materials.	31
4.4	Extrinsic n-type (a) and p-type (b) silicon.	33
4.5	A schematic view of the band structure and energy levels in p -doped (left) and n -doped (center) silicon and the pn junction with space-charge region (right).	34
4.6	A schematic view of a p-in-n silicon strip sensor with a traversing ionizing particle.	37
4.7	Basic components of the front-end electronics in a read-out channel. .	40
5.1	The Phase-II tracking detector of CMS.	42
5.2	The coverage and the material budget of the Phase-II outer tracking detector.	43
5.3	Illustration of the p_T -module concept.	44
5.4	The Phase-II outer tracking detector of CMS with the assumed coincidence window sizes.	45
5.5	The Phase-II outer tracking detector of CMS with the proposed spacings between the sensors.	46
5.6	The two independent read-out paths provided by the p_T -modules. . . .	46

5.7	Simulation of the p_T spectrum for all minimum bias particles that leave hits in a sensitive layer at a radius of 25 cm at an average pileup of 400 proton-proton interaction per event.	47
5.8	Simulation of the stub finding performance for muons, electrons, and pions in the inner most layer of the outer tracking detector (left), and only for muons at all detecting layers (right).	48
5.9	Exploded view of the 2S module components (left), 3D view of the assembled module (upper right), and a sketch of the FE Hybrid folded around its support (lower right).	49
5.10	A block diagram of the 2S module electronic system.	49
5.11	Exploded view of the PS module components (left), 3D view of the assembled module(upper right), sketch of the FE Hybrid folded around its support (lower right).	51
5.12	The expected efficiency of the L1 track reconstruction as function of η (a-left) and p_T (a-right) for single muons, electrons, and pions. The expected z_0 resolution (b-left) and relative p_T resolution (b-right) of the L1 track reconstruction as function of $ \eta $ for single muons.	54
5.13	CBC2 analog front-end schematic.	56
5.14	Block diagram of the CBC2.	57
5.15	Operation modes of the hit detection Logic.	58
6.1	The mini-2S module.	63
6.2	Schematic view of the DESY-II test beam facility.	63
6.3	Schematic drawing of the test beam setup.	64
6.4	Schematic drawing of the DAQ setup.	65
6.5	Number of hits per strip for the two DUT sensors S0 and S1 (a) and for sensor S3 of the REF before and after masking (b).	67
6.6	Two dimensional correlation plots as function of strip numbers.	68
6.7	The cluster multiplicity for S0 given in percent (a), and the cluster multiplicity distribution of all sensors (b) shown in logarithmic scale.	70
6.8	Distribution of the stub direction of the DUT in clean events for two different angles of the rotation stage (a) and mean stub direction as a function of the angle of the rotation stage including fit (b).	71
6.9	The beam divergence given as the distribution of the difference of stub positions of both modules.	72
6.10	Cluster width distributions for different incident angles (a) and Mean cluster width (b).	73
6.11	Fraction of clusters with different strip multiplicities shown as a function of incident angle.	74
6.12	Cluster width distribution and mean cluster width as function of the cluster position.	75

6.13	TDC phase distribution and chip cluster efficiency at $V_{CTH} = 120$ and $V_{CTH} = 85$ as function of the TDC phase.	76
6.14	Cluster efficiency as function of V_{CTH}	77
6.15	Cluster efficiency as function of V_{CTH} and median charge.	78
6.16	Trigger stub efficiency of the DUT as a function of beam incident angle and as a function of p_T	79
7.1	Leading order Feynman diagrams of the $t\bar{t}$ production.	85
7.2	The leading order Feynman diagrams of the single top quark production.	86
7.3	Feynman diagrams of Higgs boson production.	87
8.1	Sketch showing the simulation chain.	90
9.1	Distributions of the reconstructed vertices before (a) and after (b) the vertex reweighing.	100
9.2	Distributions of the di-lepton mass m^l in the $e^\pm\mu^\mp$ (a) and $\mu^\pm\mu^\mp$ (b) channels.	104
9.3	Two dimensional distributions of the b-tagging efficiency.	108
9.4	Distributions of the lepton p_T after the full event selection.	111
9.5	Distributions of the di-lepton p_T after the full event selection.	112
9.6	Distributions of the di-lepton mass after the full event selection.	113
9.7	Distributions of E_T^{miss} after the full event selection.	114
9.8	Distributions of the jet multiplicity after the full event selection.	115
9.9	Distributions of the jet p_T after the full event selection.	116
9.10	Distributions of the b-jet multiplicity after the full event selection.	117
10.1	Summary of LHC and Tevatron measurements of the $t\bar{t}$ production cross section as a function of $\sqrt{s}$	120
10.2	Two dimensional distribution of the b-tagging efficiency obtained at a medium b-tagging working.	129
10.3	Two dimensional distribution of the b-tagging efficiency obtained at a tight b-tagging working point.	129
10.4	The inclusive $t\bar{t}$ cross section results obtained in the $e^\pm e^\mp$, $e^\pm\mu^\mp$, and $\mu^\pm\mu^\mp$ channels together with the di-lepton combination.	133
10.5	The obtained uncertainties (a) and cross sections (b) at different selection scenarios.	136
10.6	The breakdown of the systematic and experimental uncertainties obtained for different selection scenarios in the $e^\pm e^\mp$ channel.	137
10.7	The obtained uncertainties (a) and cross sections (b) at different selection scenarios.	138
10.8	The breakdown of the systematic and experimental uncertainties obtained for different selection scenarios in the $e^\pm\mu^\mp$ channel.	139

10.9	The obtained uncertainties (a) and cross sections (b) at different selection scenarios.	140
10.10	The breakdown of the systematic and experimental uncertainties obtained for different selection scenarios in the $\mu^\pm\mu^\mp$ channel.	141
10.11	Comparison of the inclusive $t\bar{t}$ cross section results in the $e^\pm\mu^\mp$ channel of the presented analysis with all published measurements.	143
A.1	Two dimensional distribution of the data-to-simulation trigger efficiency ratio ($SF_{trigger}$), for the $e\mu$ HLT trigger paths.	147
A.3	Two dimensional distribution of the data-to-simulation trigger efficiency ratio ($SF_{trigger}$), for the ee HLT trigger paths.	148
A.2	Two dimensional distribution of the data-to-simulation trigger efficiency ratio ($SF_{trigger}$), for the $\mu\mu$ HLT trigger paths.	148
A.4	Two dimensional distribution of the data-to-simulation lepton Identification and isolation efficiency ratio ($SF_{lep.}$) for electrons.	149
A.5	Two dimensional distribution of the data-to-simulation lepton Identification and isolation efficiency ratio ($SF_{lep.}$) for muons.	149
B.1	Distributions of the b-jet multiplicity in the $e^\pm\mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the Q^2 scale down variation.	152
B.2	Distributions of the b-jet multiplicity in the $e^\pm\mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the Q^2 scale up variation.	152
B.3	Distributions of the b-jet multiplicity in the $e^\pm\mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the parton showering and hadronization variation.	153
B.4	Distributions of the b-jet multiplicity in the $e^\pm\mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the matrix element generator variation.	153
B.5	Distributions of the b-jet multiplicity in the $e^\pm e^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the Q^2 scale down variation.	154
B.6	Distributions of the b-jet multiplicity in the $e^\pm e^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the Q^2 scale up variation.	154
B.7	Distributions of the b-jet multiplicity in the $e^\pm e^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the parton showering and hadronization variation.	155

B.8	Distributions of the b-jet multiplicity in the $e^\pm e^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the matrix element generator variation.	155
B.9	Distributions of the b-jet multiplicity in the $\mu^\pm \mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the Q^2 scale down variation.	156
B.10	Distributions of the b-jet multiplicity in the $\mu^\pm \mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the Q^2 scale up variation.	156
B.11	Distributions of the b-jet multiplicity in the $\mu^\pm \mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the parton showering and hadronization variation.	157
B.12	Distributions of the b-jet multiplicity in the $\mu^\pm \mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the matrix element generator variation.	157
B.13	Signal modeling uncertainties values if no b-jets reweighting is applied.	158
C.1	An example fit of the tag and probe pair mass for the passing, failing, and all probes.	160
C.2	Passing and failing probes fits performed on data and simulated events in different kinematic regions.	162
C.3	Passing and failing probes fits performed on data and simulated events in different kinematic regions.	163
C.4	Distribution of the electron identification and isolation efficiencies as a function of p_T (a) and $ \eta $ (b) of the electron.	164
C.5	Two dimensional distribution of the electron identification and isolation efficiencies as a function of $ \eta $ and p_T of the electron.	164
C.6	Distribution of the electron isolation scale factors and uncertainties. .	165

List of Tables

6.1	Parameters of 2S prototype modules available during the test beam.	62
6.2	Efficiency of S0 and S1 per chip at a threshold of $V_{CTH} = 120$ ($6440 e^-$).	76
8.1	Summary of the simulated background samples and their corresponding matrix element and parton shower generators.	95
9.1	Summary of the jet energy resolution correction factors and its uncertainties in different η ranges of reconstructed jets.	106
9.2	The CSV b-tagging discriminator values.	107
10.1	Summary of the measured number of events in data and simulation per channel after the full event selection.	122
10.2	Summary of the different $t\bar{t}$ simulated samples used for the estimation of the signal modeling uncertainties.	126
10.3	Summary of the experimental and theoretical uncertainties in the three channels obtained using the baseline event selection.	131
D.1	Summary of simulated signal and background samples. The theory cross section used for the normalization of each sample is also given.	168
D.2	Data samples used in the measurement of the $t\bar{t}$ production cross section.	168
D.3	Summary of the di-lepton HLT paths used in data for the three dilepton channels ($ee, e\mu, \mu\mu$).	169
D.4	Summary of the variables used to define the identification and isolation criteria of electrons.	169
D.5	Number of expected signal and background events, compared to the event yields in the data, after each selection step.	170

Chapter 1

Introduction

The Standard Model (SM) of particle physics, upon writing, is the most precise and advanced theoretical interpretation of the fundamental elements of matter and their interactions. The theory which was developed throughout the 1970s incorporated all that was known about subatomic particles at that time and predicted the existence of additional particles as well. It has been probed and investigated by a variety of experiments, and since has proven its robustness. A significant and most recent evidence of the its success is the discovery of the Higgs Boson in 2012 at the Large Hadron Collider (LHC), which was the final missing piece to complete the SM. The discovery which was accomplished by two major LHC experiments, ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid), using high-energy proton-proton collisions has lead to the Nobel Prize in Physics award of 2013.

The CMS experiment is a multi-purpose particle detection apparatus designed to probe the physics processes of the SM and to look for new physics phenomena. With a cylindrical shape of about 22 m long and a diameter of about 15 m, it is built of different subdetectors for particle tracking and calorimetry. For optimal performance these sub-detectors undergo constant repairs and upgrades. One of the planned upgrades is the replacement of its tracking system which will be discussed in this thesis. An example of the SM physics research conducted by CMS, and relevant to the work in this thesis, are the measurements of the the top quark properties. These measurements are based on the identification and reconstruction of the particles produced in the collisions using the data collected by the different subdetectors of CMS.

After a general introductory part, the structure of this thesis is divided into two parts, the first related to the upgrade of the CMS tracking system and the second to the top quark pair ($t\bar{t}$) production cross section measurement. The introductory part consists

of a theoretical overview, given in Chapter 2, where the SM will be briefly discussed. The experimental setups of the LHC and CMS will be described in Chapter 3.

The LHC accelerator is foreseen to undergo an upgrade which will lead to a phase of increased collision luminosity starting around the year of 2025. Operated under the foreseen conditions, the current CMS tracking system would suffer from inefficiencies and data loss due to radiation damage and incompatibility of the read-out electronics. Therefore, for the High Luminosity LHC (HL-LHC) era, a major upgrade is planned for the CMS experiment. The current tracking system of CMS will be replaced with an entirely new system. The upgraded tracking detector will, for the first time, contribute to the trigger decision by providing trigger information to the first level trigger system of CMS. This will be achieved using the so-called p_T -modules, a novel module design with trigger capabilities and on-board momentum discrimination. Owing to a new front-end readout chip, the CMS Binary Chip (CBC), the modules will be able to reject tracks corresponding to particles traversing with low-momentum, while only delivering the information of high-momentum tracks. In this thesis, the performance of the CBC read-out chip with p_T -module prototypes is evaluated in a test beam which took place at DESY (Deutsche Elektronen-Synchrotron) in 2013. A positron beam was used to emulate operating conditions similar to the ones foreseen in the CMS experiment after the upgrade.

The first part of this thesis begins with an introduction to the basic principles of semiconductor tracking detectors given in Chapter 4. In Chapter 5, the upgrade of the CMS tracking system is discussed with an introduction to the planned tracking detector layout, the discussion of the p_T -modules concept and design, and the CMS Binary Chip read-out electronics. Chapter 6 is devoted to the discussion of the test beam performed using the p_T -module prototypes, describing the test beam setup, the analysis strategy, and the results of the CBC performance.

The second part of this thesis is dedicated to the measurement of the top quark pair ($t\bar{t}$) production cross section. The top quark is the heaviest known fundamental particle which is primarily produced in quark-antiquark pairs at the LHC. The top quark properties are important ingredients of the SM, and therefore the precise measurement of the total $t\bar{t}$ cross section is essential to test the theory. The top quark decays almost exclusively to a bottom quark and a W boson. The final-state topology of the $t\bar{t}$ processes is governed by the W boson decay mode. In this thesis, the measurement of the $t\bar{t}$ production cross section in the di-lepton channel (ee , $e\mu$, or $\mu\mu$) is performed using the data of 2.2 fb^{-1} integrated luminosity collected by CMS at a center-of-mass energy $\sqrt{s} = 13\text{ TeV}$.

The $t\bar{t}$ cross section measurement part of this thesis starts with an introduction to top quark physics, in Chapter 7. In this chapter the production and decay modes of the top

quark, as described by the SM, are discussed, along with a brief discussion of the role of the top quark in theories beyond the SM. The simulation of events of the top quark pair signal and background are described in Chapter 8. In this chapter, the different event generators and theoretical models utilized to simulate these events are briefly described. The event reconstruction and selection are discussed in Chapter 9. The results of the cross section measurement are given in Chapter 10 including systematic uncertainties. For the evaluation of the used event selection, the results are compared using different selection scenarios which are also discussed.

Finally, the thesis closes with a summary and outlook chapter, Chapter 11, briefly summarizing the results and providing an outlook for potential future improvements and measurements.

Chapter 2

Theoretical Overview

Theories and ideas suggesting that all matter is composed of elementary particles dates back to, at least, the 6th century BC. These ideas kept developing with no profound evidence until the breakthrough by John Dalton, who in the 19th century concluded that each element of nature is composed of a unique type of particles. These particles are referred to as atoms, after the Greek word *atomos* meaning *indivisible*. Soon after, physicists found that atoms are not the fundamental particles of nature, but are composite of even smaller particles, such as the electron [1]. Later on, a variety of particles were discovered in scattering experiments throughout the 1950s and 1960s. In the 1970s these particles were explained by the *Standard Model* (SM) based on more fundamental particles.

2.1 The Standard Model of Particle Physics

The Standard Model of particle physics, upon writing, is the most modern and precise theoretical explanation of the fundamental building blocks of matter. Developed throughout the 20th century, based on various preceding concepts and experimental results, it summarizes the current knowledge of elementary particles and their interactions.

The SM describes matter through fundamental spin- $\frac{1}{2}$ particles, the so-called *fermions* which are categorized according to their interactions. Three forces are described by the SM, the *electromagnetic* force, the *weak* force, and the *strong* force. These forces govern the interactions between the fermions and are mediated via spin-1 particles known as *bosons*. Mathematically, the SM is formulated based on the Quantum Field Theory (QFT) and the local $SU(3) \times SU(2) \times U(1)$ gauge symmetry.

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$	0	0
spin →	$1/2$	$1/2$	$1/2$	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS	$\approx 4.8 \text{ MeV}/c^2$ $-1/3$ $1/2$	$\approx 95 \text{ MeV}/c^2$ $-1/3$ $1/2$	$\approx 4.18 \text{ GeV}/c^2$ $-1/3$ $1/2$	0 0 1	
	d down	s strange	b bottom	γ photon	
	$0.511 \text{ MeV}/c^2$ -1 $1/2$	$105.7 \text{ MeV}/c^2$ -1 $1/2$	$1.777 \text{ GeV}/c^2$ -1 $1/2$	0 1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	$< 2.2 \text{ eV}/c^2$ 0 $1/2$	$< 0.17 \text{ MeV}/c^2$ 0 $1/2$	$< 15.5 \text{ MeV}/c^2$ 0 $1/2$	$91.2 \text{ GeV}/c^2$ ± 1 1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
				GAUGE BOSONS	

Figure 2.1 The Standard Model table of elementary particles. Shown are the three generations of matter particles, the fermions, and the force carrier particles, the gauge bosons, in addition to the Higgs boson. Electric charge, spin, and the mass of each particle are also noted.

2.1.1 Particles and interactions

In the SM, twelve known fermions are grouped into two classes, *quarks* and *leptons*, according to the interactions they undergo. Quarks participate in all the three types of the aforementioned interactions, while leptons do not experience the strong force. Positively and negatively charged quarks are divided into up-type and down-type groups respectively. Leptons are also separated into two groups. One with the electrically charged leptons which interact via electromagnetic and weak forces, and the other with the neutral particles (neutrinos) which only interact weakly. In addition, both quarks and leptons are classified into three generations according to their mass. The classification of the elementary particles is illustrated in Figure 2.1.

According to Dirac's relativistic wave equation [2], which describes the behavior of fermions, all quarks and leptons have a corresponding anti-particle. This prediction implies the presence of anti-matter and has been experimentally confirmed by observing the positron (the anti-particle of the electron) [3]. Anti-particles share the same properties with their corresponding partner particle but with opposite charge.

When fermions interact, five gauge bosons corresponding to the different types of interactions are exchanged. A massless boson, the photon γ , is exchanged when an electromagnetic interaction takes place. When a strong interaction between quarks

occurs, a massless boson known as the *gluon* is exchanged. Three gauge bosons can carry the weak force, the charged $W^\pm$ and the neutral Z^0 . An additional boson, the *Higgs* boson H , predicted by the SM was observed in July 2012 at the LHC completing the picture of the SM and will be discussed in Section 2.1.2. In the following, the three fundamental forces are briefly explained.

The electromagnetic force

The electromagnetic force is described by the relativistic quantum field theory of electrodynamics (QED), an abelian gauge theory with the symmetry group $U(1)$. It describes the phenomenon of photon exchange upon interaction of charged fermions. Photons can only couple to charged particles, with the coupling strength given as the constant

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \approx \frac{1}{137} \ll 1, \quad (2.1)$$

where e is the elementary charge, ϵ_0 is the vacuum permittivity, $\hbar$ is the reduced Planck constant, and c is the speed of light¹. Even though it is referred to as a constant, the coupling strength increases with the increase of the energy scale Q . For example, at an energy scale corresponding to the Z boson mass around 90 GeV $\alpha(M_Z^2) \approx 1/127$, but still $\ll 1$. Such a small coupling strength can be used as an expansion parameter in perturbation theory.

The strong force

The strong force is the force responsible of holding ordinary matter together. It is described by the non-abelian gauge theory of quantum chromodynamics (QCD) which is based on the $SU(3)$ symmetry group. The strong interaction between quarks is carried by eight gluons as defined by QCD. In order to preserve the Pauli exclusion principle, QCD requires an additional charge, known as the color charge, with three eigenstates (red, green, and blue) for the quarks and the gluons. Since gluons carry a color charge, they can interact with each other.

The coupling strength of the strong interaction, known as the strong coupling constant α_s , varies depending on the momentum transfer of the interaction, hence it is referred to as the running constant. The variation of α_s with the energy scale Q is shown in Figure 2.2.

When quarks interact at long-distances, where Q^2 is low, they undergo the phenomenon known as *confinement* which leads to the creation of *hadrons*. This effect is referred to as *hadronization* and will be further discussed in Chapter 8. Hadrons are quark bound

¹Throughout this thesis, the natural units are used and c , $\hbar$ are set to unity. Energy, momentum and mass are therefore given in units of electron Volts (eV).

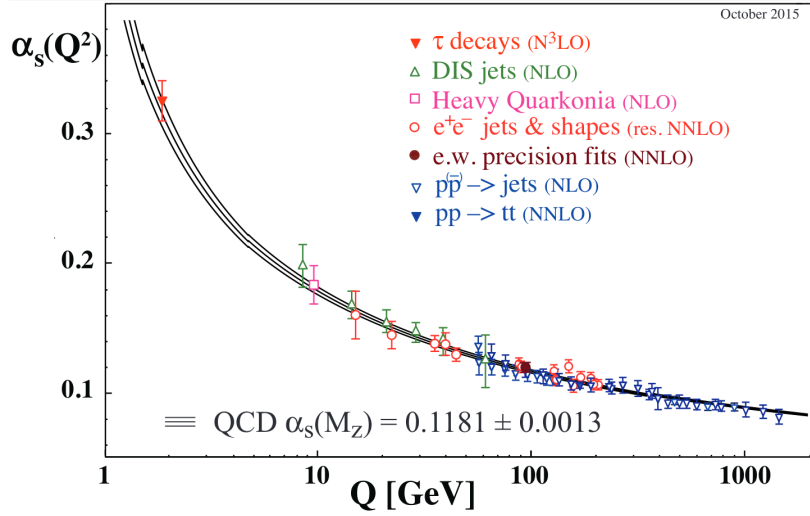


Figure 2.2 Summary of measurements of α_s as a function of the energy scale Q . The respective degree of QCD perturbation theory used in the extraction of α_s is indicated in brackets (NLO: next-to-leading order; NNLO: next-to-next-to leading order; res. NNLO: NNLO matched with re-summed next-to-leading logs (NLL); N³LO: next-to-NNLO). From [4]

states with singlet color charge. They can be *mesons*, with a quark-antiquark pair, or *baryons*, with a quark or antiquark triplet. A very relevant example of a baryon is the proton which consists of two u and one d quarks. Recently experimental results consistent with a hadron state of four quarks and one antiquark known as *pentaquark* have been reported [5].

On the other hand, when quarks interact at short-distances, i.e. at very high energy, another effect, known as asymptotic freedom of quarks takes place [6, 7]. At such scales α_s tends to drastically decrease. This allows perturbative calculations of interactions at high energies.

The weak force

The weak force is the force responsible for radioactive decays, described by the theory of quantum flavourdynamics (QFD), under the $U(1)$ symmetry group. The weak force is mediated by two charged ($W^\pm$) and one neutral (Z^0) gauge bosons. Due to their large mass of $m_{W^\pm} = 80.4 \text{ GeV}$ and $m_{Z^0} = 90.2 \text{ GeV}$, these force carrier particles have a short lifetime of under 10^{-24} s , which restricts the range of the weak interactions.

The weak interaction has a coupling strength about 10^6 weaker than the strong coupling, while at very short-distances, where the energy scale is comparable to the carrier bosons masses, the weak and the electromagnetic forces become unified. They are described as one force called the electroweak force addressed in Section 2.1.2.

The charged gauge bosons are capable of transforming a quark from one flavor to another through so-called charged current reactions, while that is not observed for neutral current reactions via the Z^0 . In the SM, the probability of a quark changing flavor is governed by the Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$\begin{pmatrix} u \\ c \\ t \end{pmatrix} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \times \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (2.2)$$

The CKM matrix is assumed to be unitary. The diagonal components of the matrix reflect a higher probability for a quark transformation within its generation. A quark transformation into a different generation is possible but less probable. For instance, the $|V_{tb}|$ element is close to unity (experimentally obtained to be 0.998 ± 0.041 [8]) while $|V_{ts}|$ is two orders of magnitude smaller, which implies that the top quark decays almost exclusively into a W boson and a b quark. An example of the flavor change via the charged weak reaction is the β decay, where a neutron emits an electron and an anti-neutrino and transforms into a proton. In this case, one of the d quarks of the neutron is transformed into an u quark.

2.1.2 The electroweak symmetry breaking

The electroweak interaction is a unified approach of the electromagnetic and the weak interactions. Although both interactions are different at low energies, they can be merged into one gauge theory at high energy regimes, beyond ~ 100 GeV. Mathematically the unification occurs under the $SU(2) \otimes U(1)$ symmetry group. This unification sometimes referred to as the GSW model, after Sheldon Glashow, Abdus Salam, and Steven Weinberg, has lead to the Nobel prize in physics in 1979 [9].

The four corresponding gauge bosons, W_1, W_2, W_3 , and B of this unified model are massless. However, measurements have shown that the mediators of the weak force are massive, and thus these masses must be acquired in a certain way which was not known until the *Higgs mechanism* was proposed in 1964 by Robert Brout, François Englert, and Peter Higgs.

The Higgs mechanism is mathematically based on *Goldstone's theorem*, which allows the symmetry of the gauge theory to be broken without disrupting the gauge invariance. This spontaneous symmetry breaking (SSB) is induced by the so-called Higgs field, which –by its potential– breaks the three out of the four degrees of freedom of the $SU(2) \otimes U(1)$. These three degrees of freedom, the *Goldstone bosons*, mix with the three $W^\pm$ and Z^0 bosons, and become only observable as components of these weak

bosons, which now become massive. The remaining degree of freedom amounts for a massive scalar particle, the Higgs boson H .

The Higgs field can be expressed in terms of a scalar field which describes the physical Higgs boson $h(x)$, and the vacuum expectation value v as

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \quad (2.3)$$

and its scalar potential is expressed as

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad (2.4)$$

where μ is a mass parameter and λ is a positive dimensionless coupling parameter. The choice of $\lambda > 0$ is consistent with the vacuum stability. $\mu^2 > 0$ leads to a parabolic potential with vanishing vacuum state at $\phi = 0$, which is a representation of non-symmetry broken QED theory. However, $\mu^2 < 0$ leads to a non-vanishing vacuum state where the vacuum expectation value can be written as

$$v = \sqrt{-\frac{\mu^2}{2\lambda}} = 246 \text{ GeV}. \quad (2.5)$$

Introducing the Higgs field gives mass to three of the vector bosons ($W^\pm$ and Z^0) while the forth, the photon γ , remains massless. The obtained masses can be expressed in terms of the weak coupling constant g and the vacuum expectation value as

$$m_W = \frac{1}{2}gv \quad \text{and} \quad m_Z = \frac{m_W}{\cos \theta_W}, \quad (2.6)$$

where θ_W is known as the electroweak mixing angle. The mixing angle and the vacuum expectation value are both obtained from the precise experimental measurements of m_W and m_Z .

Fermions on the other hand, acquire their masses through the coupling between the fermion field and the Higgs field. This coupling is known as the Yukawa coupling, which after symmetry breaking results in the original mass terms proportional to the vacuum expectation value of the Higgs field.

The mass of the Higgs boson is not predicted by the SM, and thus it has to be determined experimentally. This mass has been measured, using data samples collected with the ATLAS and CMS experiments in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ decay channels [10], and is obtained to be

$$m_H = 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.) GeV}. \quad (2.7)$$

2.1.3 Beyond the Standard Model

Despite its success in answering many questions, the SM is an incomplete theory. There are fundamental physical phenomena in nature where the SM fails to give an explanation. In addition, there are many theoretical problems, which have no solution in the SM. Some of these open topics and unsolved problems are:

- The SM does not explain one of the four known forces in nature, the gravity. The approach of simply adding a gravity force mediator, the so-called *graviton*, to the SM does not agree with experimental observations without more modifications to the theory.
- Dark energy and dark matter, which combined contribute to around $\sim 95\%$ of the mass of the universe, are not addressed by the SM.
- Neutrino oscillation experiments have shown that neutrinos do in fact have mass, however, in the SM they are treated as massless particles. It is also unclear if the neutrino masses arise in the same way as for other fundamental particles.
- Observations have shown an asymmetry between matter and anti-matter, while in the SM a similar amount of matter and anti-matter is predicted.

Different theories are being developed and experimentally investigated trying to provide explanations which might complete the SM. One example of such theories is Super-symmetry (SUSY). By adding the terms of space-time symmetry to the SM, SUSY implies the existence of a new class of particles known as the super-partners where each fermion (boson) in the SM is associated with a partner boson (fermion) with a half-integer spin difference.

In an unbroken SUSY, the masses of the SM particles and their super-partners would be the same, and thus would be easily observed in current experiments. However, since no such observations have been made, this means that the super-partners masses differ from the SM partners. This is allowed in a spontaneously broken SUSY. Such approach is realized in the so-called Minimal Super-symmetric Standard Model (MSSM) [11]. In addition to the super-partners, the MSSM suggests the existence of two Higgs doublets, with the fermionic super-partners of the Higgs boson, Higgsinos. The two doublets are needed in the MSSM in order to have the Higgs couplings separated between down-type and up-type quarks. This results in five physical Higgs bosons, three neutral and two charged. Even though the MSSM has its own complications, e.g. introducing a large number of parameters, yet if proven to exist, it can hold the answers to most of the SM problems listed above. This makes the MSSM (and MSSM-based) theory one of the most investigated theories beyond the SM. Such investigations focus on finding evidences for the existence of the super-partner particles, additional Higgs bosons, or dark matter candidates.

Chapter 3

The CMS Experiment at the LHC

Particle colliders are utilized as probing tools at the subatomic scale to allow scientists to gain knowledge about elementary particles and their interactions. Colliders, typically, are designed to accelerate either two beams of particles to collide head-on, as in ring and linear accelerators, or as a single beam to collide against a fixed target. At high energies, these collisions lead to the transformation of the initially colliding particles under different physics processes into other particles. The detection of the resulting particles gives insight into these processes and the physics behind them.

In this chapter, the Large Hadron Collider will be introduced together with the CMS detection experiment.

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [12] is currently the largest particle accelerator and collider in operation. It is installed 100 m underground in the 27 km ring tunnel formerly used to house the Large Electron-Positron Collider (LEP) [13] at CERN, the European Organization for Nuclear Research, near Geneva. The LHC is designed to accelerate and collide two counter rotating beams of protons or heavy ions using superconducting magnets. The beams are kept on their circular path using 1232 dipole magnets, with field strength of about 8 T, and are focused using 392 quadrupole magnets. In addition, eight sets of so-called inner-triplet magnets are installed to further focus the particle beams at the collision points. The magnets temperature is maintained at 1.9 K via a super-fluid Helium cooling system.

Before being injected into the LHC ring, protons are pre-accelerated by successive systems that gradually increase their energy. First a linear particle accelerator LINAC-2 accelerates 50 MeV protons and injects them to the Proton Synchrotron Booster (PSB). There the protons are accelerated to 1.4 GeV and transferred into the Proton Synchrotron (PS), where they are accelerated to 26 GeV. Finally the Super Proton Synchrotron (SPS) is used to further increase the energy of the protons up to 450 GeV before they are injected into the LHC ring. The proton beams consist of 2808 bunches, separated by 25 ns, with 1.15×10^{11} protons per bunch.

For ions a different linear particle accelerator is used, LINAC-3, which accelerates lead ions and passes them to the Low Energy Ion Ring (LEIR). The ions are then fed to the PS and SPS before being injected to the LHC ring. Heavy ion collisions at the LHC usually take place during a one month run, where lead-lead beams or hybrid proton-lead beams collide. The main LHC ring together with the injectors are shown in Figure 3.1.

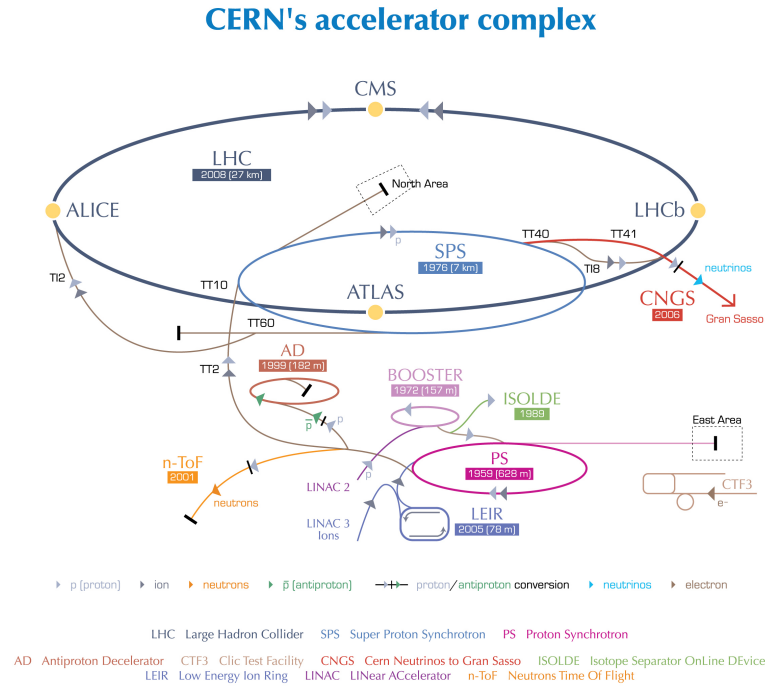
During the second run of the LHC proton beams are accelerated to 6.5 TeV resulting in collision center-of-mass energies of $\sqrt{s} = 13$ TeV. The beams collide at four interaction points where four of the major experimental apparatuses are located. The largest two are the multi-purpose experiments ATLAS [14] and CMS [15]. The two other experiments, ALICE [16] and LHCb [17], are dedicated to more specific physics programs. ALICE is designed to study the quark-gluon plasma using heavy ion collisions, while LHCb is focused on studying B-mesons¹ physics as a way for understanding the matter-antimatter asymmetry in the universe.

The CMS experiment is introduced in the following section together with the sub-detectors relevant to the work presented in this thesis.

3.2 The CMS Detector

The CMS detector, shown in Figure 3.2, is about 22 m long, has a diameter of about 15 m and an overall weight of 14000 tons. It is located in an underground cavern close to the town Cessy in France, just across the border from Geneva. It is built around the beam pipe in a cylindrical form and symmetric with respect to the interaction point. The subcomponents of the experiment are arranged in barrel shaped layers in the central region and in form of disks or end-caps in the forward regions. The CMS detector comprises, from the inner to the outer parts, a silicon pixel system, a tracking silicon strip system, followed by an electromagnetic calorimeter and a hadronic calorimeter, all housed in a superconducting solenoid. Surrounding the solenoid, a

¹B-mesons are composed of a bottom antiquark and either an up, down, strange, or charm quark.



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Figure 3.1 The LHC (dark gray) with the four major experiments (yellow) are shown together with the LINACs and Synchrotrons. From [18].

muon system with three types of muon detectors alternating with layers of magnet iron return yoke is installed.

3.2.1 Coordinate system and variables

The origin of the right-handed Cartesian coordinate system used by CMS is at the interaction point of the two colliding beams in the center of the detector. The x -axis points to the center of the LHC ring and the y -axis points vertically upwards. The z -axis points in the direction of the anti-clockwise rotating beam. The azimuthal angle ϕ is measured from the x -axis in the xy -plane, where r is the radial coordinate in the same plane. The polar angle θ is measured from the positive z -axis in the rz -plane.

For the reconstruction of physics objects (electrons, muons, photons, jets², etc.) in the detector, it is more practical to use the pseudorapidity η and the rapidity y . These variables use the coordinates components, and can be expressed in terms of the momentum p of a particle and its projection along the z -axis, the longitudinal

²A jet is a narrow cone of hadrons and other particles produced by the hadronization of a quarks or a gluon arising from hard scattering processes. The hadronization process and the reconstruction of jets will be further discussed throughout this thesis.

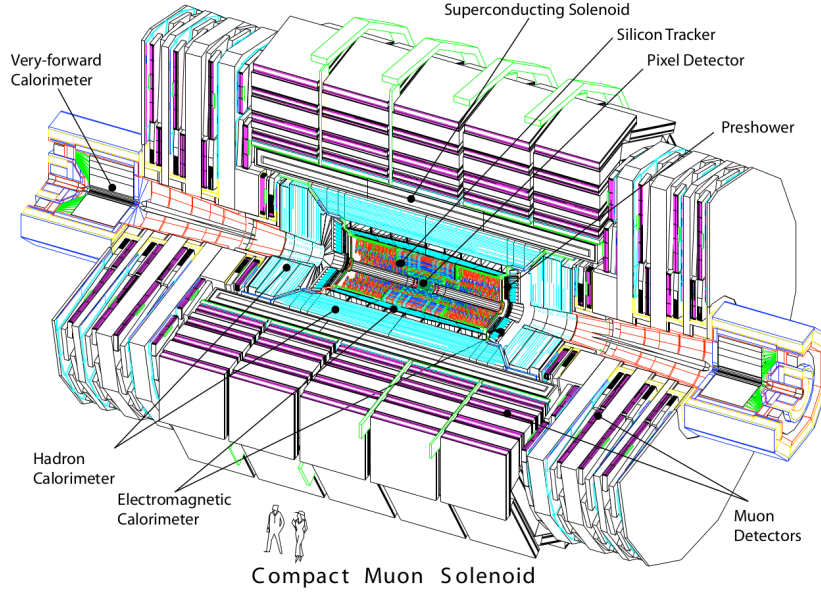


Figure 3.2 A schematic representation of the CMS detector and its components. Several layers of the detector are built around the beam pipe, resulting in a symmetric cylindrical form, and are accompanied by disk shaped end-caps from both sides. From [19].

component p_L . The pseudorapidity is given as

$$\eta = -\ln \tan \frac{\theta}{2} = \frac{1}{2} \ln \frac{|p|+p_L}{|p|-p_L}. \quad (3.1)$$

The rapidity is used for massive particles, like the top quark, where p is replaced by the energy E . For massless or light particles $y = \eta$. These variables are invariant under Lorentz boosts in the z direction.

The momentum component transverse to the beam direction, denoted by p_T , is derived from the x and y components of the momentum as

$$p_T = \sqrt{p_x^2 + p_y^2}. \quad (3.2)$$

3.2.2 The superconducting solenoid

CMS is equipped with a 13 m long and 6 m diameter superconducting solenoid with 3.8 T field strength. Providing a homogeneous magnetic field over the whole volume of the tracking detector, the solenoid field bends the trajectories of charged particles emerging from the collisions. This property, combined with the high-precision position measurement of the tracking detectors, allows accurate measurement of the momentum of charged particles.

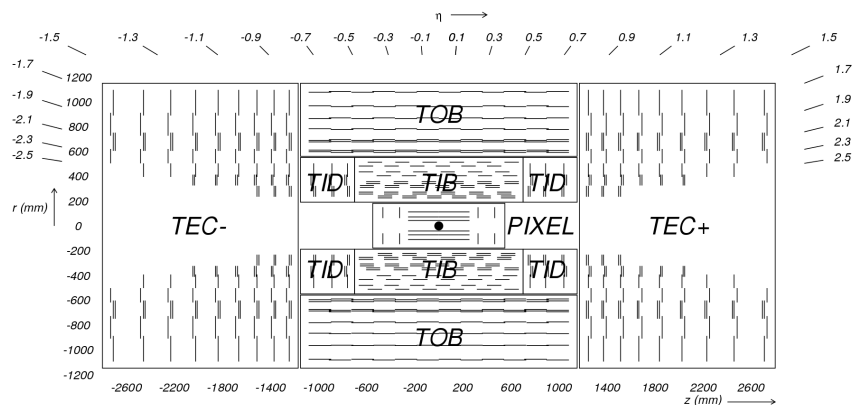


Figure 3.3 The CMS tracking detector. In the center is the pixel detector surrounded by the inner and outer layers of the strip detector. From [15].

An iron return yoke surrounds the solenoid for containment of the magnetic field and embeds the different stations of the muon system. The yoke consists of five barrel rings around the coil and three end-cap disks on each side providing a flux of ~ 2 T. It also acts as a filter, only allowing muons and weakly interacting particles to pass through. CMS benefits from this configuration in the charge determination of high energy muons, and in improving the isolation efficiency and energy resolution.

3.2.3 Tracking system

The tracking system of CMS has the form of barrel layers and end-cap disks as shown in Figure 3.3. In its center it features a silicon pixel detector, sometimes referred to as the inner detector, located around the beam pipe and near the interaction point, where the particle flux is at its highest. The pixel detector is contained in a silicon strip tracking detector, referred to as the outer tracking detector.

The CMS tracking detector resolves the trajectories of the traversing charged particles with an efficient and precise measurement of their charge and momentum. In addition to the track information, and owing to the pixel detector, the primary and secondary vertices³ can be reconstructed as well as the impact parameter. These parameters, as will be shown later in this thesis, are of special importance to the top quark pair cross section measurement.

The silicon pixel detector

The CMS silicon pixel detector [20] consists of 1440 segmented silicon sensor modules providing two dimensional position information of traversing particles with a total

³The primary vertex is the point where a proton-proton interaction occur. The secondary vertex, is the point where a byproduct particle of the proton-proton interaction decays.

of 66 million read-out channels and a pixel size of $150\,\mu\text{m} \times 100\,\mu\text{m}$. These modules are spread over three barrel layers at radii 4.4 cm, 7.3 cm, and 10 cm, and four end-cap disks at ± 34.5 cm and ± 46.5 cm in the z direction. The pixel detector covers a pseudorapidity of $|\eta| \leq 2.5$ and has a hit efficiency of above 99.5%.

In addition to the sensor design, the detector geometry also plays a role in achieving high resolution. The barrel modules are mounted with the sensor surface parallel to the magnetic field of the solenoid, while the modules in the end-cap disks are tilted by 20° around their central radial axis. This tilt enhances the Lorentz drift (see 4.3.2) of the charge in the pixel sensors increasing the charge sharing effect, important for high resolution in the $r\phi$ plane. With such a configuration, the detector can achieve a hit position resolution of $15\,\mu\text{m}$ in the $r\phi$ direction and $\sim 20\,\mu\text{m}$ in the z direction [15, 21].

The silicon strip detector

Surrounding the pixel detector is the CMS silicon strip tracking detector, which has a length of 5.8 m and a diameter of 2.4 m covering up to $|\eta| = 2.5$. The all-silicon detector has an active area of about $200\,\text{m}^2$. The silicon strip detector is composed of four inner barrel layers (TIB), three inner end-cap disks (TID) on each side, six outer barrel layers (TOB), and nine outer end-cap disks (TEC) on each side.

The four subsystems of the silicon tracking detector contain 15148 single-sided detector modules with a total of 9.3 million read-out channels. The modules are equipped with silicon sensors segmented in one dimension which provide the measurement of one local coordinate. Only at large radii of the tracking system, double-sided modules, consisting of two single-sided modules mounted back-to-back with a stereo angle of $100\,\text{mrad}$, are used to allow for the measurement of the second local coordinate. The silicon strip detector has more than 20 different module geometries, with strip pitches ranging from $80\,\mu\text{m}$ to $205\,\mu\text{m}$.

3.2.4 Calorimetry

Calorimeters are usually built of homogeneous⁴ or sampling⁵ high-density materials, and measure the deposited energy of particle showers initiated by a traversing particle. If segmented perpendicular to the particle trajectory, calorimeters can also provide information about the direction of the particle. Combining the information from the calorimeters with the tracks reconstructed from the tracking system is fundamental for physics objects identification.

⁴A homogeneous calorimeter is built using the same material in which the entire volume is sensitive and contributes a signal.

⁵In a sampling calorimeter, the material that produces the particle shower is distinct from the material that measures the deposited energy.

At CMS, calorimetry is performed depending on the nature of the particle by either an electromagnetic or a hadronic calorimeter. Since both calorimeters are placed within the solenoid, the energy loss due to secondary interactions is minimized. In order to maintain the hermeticity required for accurate calculation of missing transverse energy (E_T^{miss}) –due to undetected particles such as neutrinos– the calorimetry system provides full geometric coverage up to $|\eta| = 5$.

The electromagnetic calorimeter

The electromagnetic calorimeter (ECAL) [22] measures the energy of electrons and photons. The CMS ECAL is a homogeneous and hermetic crystal calorimeter built of 76000 lead tungstate (PbWO_4) crystals which serve as absorbers and scintillators. It is divided into three parts. The barrel calorimeter (EB) with a pseudo-rapidity coverage of $|\eta| \leq 1.5$, and the two end-cap calorimeters (EE) with a coverage up to $|\eta| = 3$.

The design of the ECAL has been optimized for achieving an excellent energy resolution required for the Higgs boson searches in the $H \rightarrow \gamma\gamma$ decay mode, necessitating a highly granular system. The fine granularity is achieved by using crystals with a face cross section of $22 \times 22 \text{ mm}^2$ in the barrel and $28.6 \times 28.6 \text{ mm}^2$ in the end-cap disks.

The energy deposited in the crystals by photons and electrons produces scintillating light with a response time of less than 25 ns. This light is collected by photodiodes glued to the end of each crystal. The energy resolution of the ECAL has been measured to be around 0.5% for electrons with an energy of 120 GeV [23].

In front of the EE occupying the region $1.65 \geq |\eta| \geq 2.60$ pre-shower detectors (ES) are installed. These detectors are sampling calorimeters made of lead absorbers and equipped with silicon strip sensors. The main purpose of the ES is to identify neutral pions and to improve the position measurement of electromagnetic showers from electrons and photons.

The hadronic calorimeter

The hadronic calorimeter (HCAL) [24, 25] of CMS is a sampling calorimeter that measures the energy of strongly interacting particles. The design of the HCAL was driven by the primary requirement to provide a precise measurement of the energy of hadronic jets, and a good containment and hermeticity for the E_T^{miss} calculation. It consists of the barrel (HB), the outer barrel (HO), the end-cap disks (HE), and the forward calorimeters (HF).

The HB and HE are contained within the solenoid and use alternating layers of brass absorbers and plastic scintillators. The induced light of the scintillators due to

hadronic showers is carried to the read-out system by wavelength-shifting fibers. The photodetection read-out is based on multi-channel hybrid photodiodes (HPDs). The HB covers a pseudorapidity of $|\eta| \leq 1.4$ while the HE covers the region $1.3 < |\eta| < 3$.

The HO is the only calorimetry system not contained by the solenoid and is covering the region $|\eta| \leq 1.26$. It serves as a *tail-catcher* designed to identify late starting showers and to measure the energy deposited after the HB. The 10 mm thick scintillators of the HO surrounding the solenoid and immediately before the muon system complete the measurement using the coil itself as an absorber material. Grouped in 30° -sectors they match the segmentation in the muon system described in Section 3.2.5, and improve the energy resolution of the calorimeter.

The two HF fulfill the requirement of hermeticity by sampling showers up to $|\eta| = 5$ using 5 mm thick steel absorber plates with embedded quartz fibers as active medium. Located at ± 11.2 m from the interaction point, the HF detects Cherenkov light⁶ emitted by charged particles in the shower and thus is mainly sensitive to the electromagnetic component of the hadronic shower. In its very forward location, the HF experiences particle fluxes with energies up to 760 GeV compared to 100 GeV in the rest of the HCal.

3.2.5 The muon system

Muons propagate through the solenoid magnet while the hadronic background is mostly contained within the calorimeter. Therefore, muons can be used as a clear indication of a signal event over background. As a consequence, muons are heavily exploited for triggering purposes. In addition, events with one or two muons in the final state are of significant importance for many Higgs (e.g. $H \rightarrow ZZ \rightarrow 4l$) and top (e.g. $gg \rightarrow t\bar{t} \rightarrow \mu\mu/e\mu$) physics analyses. The latter process will be discussed in the $t\bar{t}$ cross section measurement chapters of this thesis.

The muon system, shown in Figure 3.4, is the outermost part of the CMS detector. It comprises three different subsystems based on gaseous ionization detectors. Alternating with the iron yoke, these systems are integrated in different positions depending on the performance requirements.

In the central region ($|\eta| < 1.2$), where the muon rate is low and the neutron induced background is relatively small, drift tube (DT) chambers are employed for precise position measurement. In this region the magnetic field is uniform with strength below 0.4 T. The basic element of the DT system is the drift cell. It is a 4 cm wide gas

⁶Named after the Soviet scientist Pavel Alekseyevich Cherenkov, the 1958 Nobel Prize winner. It is an electromagnetic radiation emitted when a charged particle (such as an electron) moves through a dielectric medium faster than the phase velocity of light in that medium.

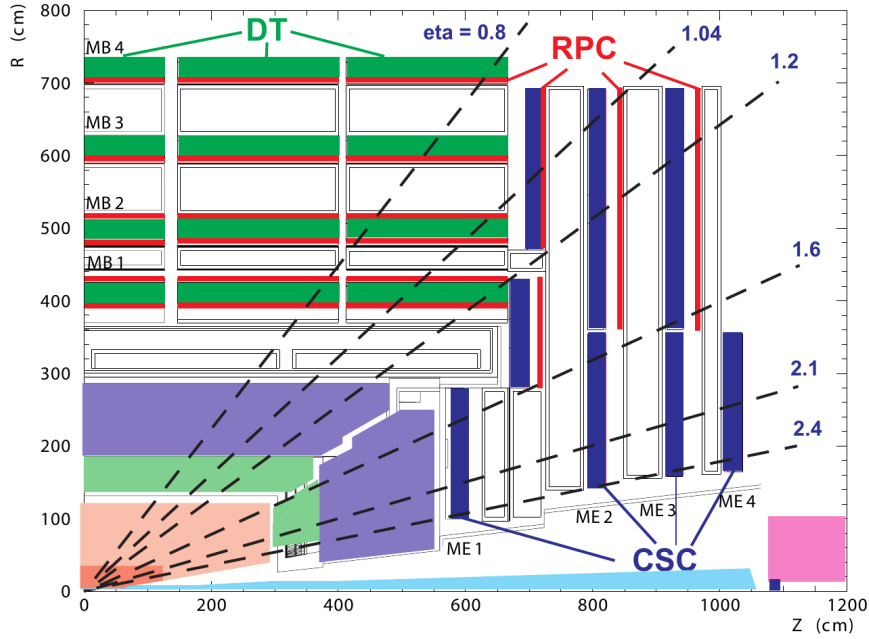


Figure 3.4 The CMS muon system. The drift tube (DT) chambers are installed in the barrel region alternating with the iron yoke. The cathode strip chambers (CSCs) are installed in the end-cap regions. For position measurements resistive plate chambers (RPCs) are installed in the barrel and the end-cap regions. From [19].

tube with a stretched gold-plated stainless-steel anode wire in its center operating under a very high voltage (~ 3600 V). The DT chambers are arranged in 5 wheels along the z -direction with 12 ϕ -segments per wheel. In such configuration they form 4 stations at different radii interspersed between the plates of the return yoke. In each chamber there are 12 layers of contiguous drift tube cells grouped in three so-called super-layers (SL) with four staggered layers each as shown in Figure 3.5. The innermost and outermost SLs, are dedicated to coordinate measurement in the $r\phi$ plane, while in the central SL the hits are measured along the beam axis. The outermost stations, located outside the steel return yokes, have only two SLs (i.e. 8 layers of drift tube cells) measuring the hit position in the $r\phi$ plane. The spatial resolution provided by the DT system ranges from $80\text{ }\mu\text{m}$ to $120\text{ }\mu\text{m}$.

In the end-cap region ($0.9 < |\eta| < 2.4$) where the magnetic field strength and the muon rate are higher, cathode strip chambers (CSCs) are installed. On each of the end-cap disks four CSCs are mounted perpendicular to the beam direction. Each of the CSCs consist of 6 layers with arrays of positively-charged anode wires perpendicularly crossed by negatively-charged copper cathode strips within a gas volume. The strips run radially outward and provide a precision measurement in the $r\phi$ plane, while the wires provide a coarse measurement in the radial direction. The CSCs have a trapezoidal shape with various sizes, ranging in length from 1.7 m to 3.4 m in the radial

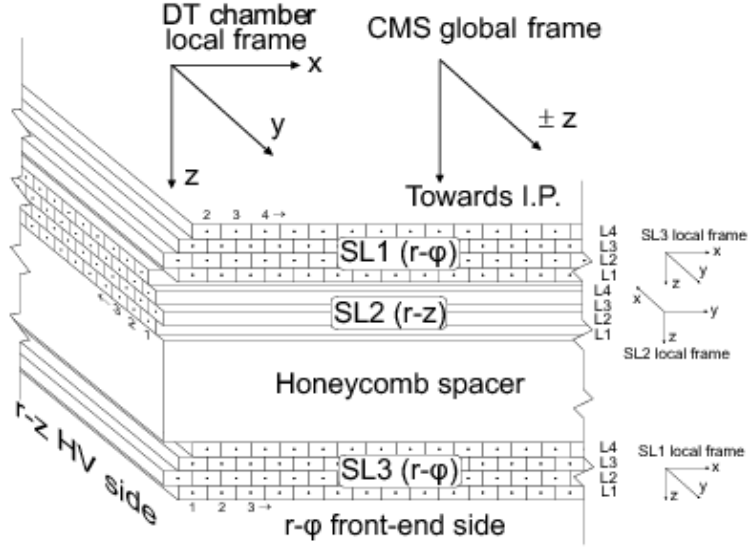


Figure 3.5 Schematic view of a DT chamber with the three super-layers. From [26].

dimension. Depending on the position of each chamber, each CSC covers a ϕ angle of about 10° to 20° . Each layer of the CSCs comprises 80 cathode strips projecting to the beam line. The wires range in diameter from $30\text{ }\mu\text{m}$ to $50\text{ }\mu\text{m}$ and from 16 mm to 51 mm in width. With such a configuration the CSCs provide a two-dimensional position measurement with a point resolution of 100 - 200 μm [19].

The third technology used in the CMS muon system is resembled by the resistive plate chambers (RPCs), which are present throughout the barrel and the end-cap regions. They provide a position measurement with a spatial resolution of 0.8 - 1.2 cm and a precise timing resolution of the order of 1 ns essential for triggering. The RPCs are double-gap chambers, operated in avalanche mode. They consist of two 2 mm thick high-resistivity Bakelite plates separated by a 2 mm gas-filled volume where a high electric field is applied. The read-out strips are aligned in η inbetween the gas gaps.

3.2.6 The trigger system

At the LHC, the total proton-proton cross section expected at the nominal collision energy of $\sqrt{s} = 14\text{ TeV}$ is expected to be roughly 100 mb [27]. This corresponds to about 20 simultaneous proton-proton collisions in the 25 ns bunch crossing interval at the design luminosity of $10^{34}\text{ cm}^{-2}\text{ s}^{-1}$. With such a collision rate, CMS observes approximately 10^9 inelastic events per second. Reading out and recording all these events to computer storage media is technically impossible, where most of these events would be less likely to correspond to any interesting physics processes. Thus, the trigger system of CMS has to reduce this huge rate by at least six orders of magnitude, keeping only potentially interesting events for further processing.

The trigger system performs the data reduction in two stages using a first level (Level-1 or L1) and a high-level (HLT) trigger systems. While the first stage is based on programmable custom-designed electronics, the latter is a software based system implemented in a farm of processors.

The L1 performs a primary coarse event selection using the input of the calorimetry and the muon systems. This selection is fully implemented in hardware with flexible logic using FPGAs⁷ and ASICs⁸ with programmable Look-Up Tables for speed. The decision of the L1 to keep or discard an event is based on the presence of so-called primitive trigger objects, such as photons, electrons, muons, and jets which are reconstructed using low-granularity and low-resolution data. This decision has to be taken within 3.2 μ s. During this latency the full event data is stored in pipelines in the detectors front-end electronics for a possible read out in case the event is accepted by the L1 trigger. The L1 reduces the event rate to 10-100 kHz. The data of events accepted by the L1 are sent to the CMS Data Acquisition (DAQ) system for buffering, and passed to the HLT for processing.

The HLT uses the L1-accepted events as an input to perform further event selection. This selection is based on HLT trigger menus composed of sets of trigger paths. A trigger path defines the characteristics, including kinematics (p_T and η), of physics objects required to accept an event. The pure software implementation allows for configuring the HLT selection at runtime. The HLT reduces the event rate to few hundred Hz. Accepted events at this stage are forwarded for storage at the CERN Tier-0 computing center and for data quality monitoring.

3.3 CMS Upgrades

In the coming years, the LHC will gradually increase the instantaneous luminosity reaching up to $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This will be followed by the High-luminosity LHC (HL-LHC) era where the instantaneous luminosity will be even higher.

In order to allow for the luminosity upgrade three long shutdowns are planned. The first long shutdown LS1 took place in 2013/2014 and is followed by an intermediate technical stop, the extended year end technical stop EYETS, in 2016/2017. A second shutdown LS2 is planned for (2018/2019). The HL-LHC era will begin after LS3, which is foreseen in 2023/2024. The planned shutdowns together with the expected peak and integrated luminosities are shown in Figure 3.6.

It is foreseen that the CMS detector will use the shutdowns and technical stop periods to undergo several repairs and upgrades in order to meet the upcoming challenges.

⁷Field Programmable Gate Arrays

⁸Application Specific Integrated Circuits

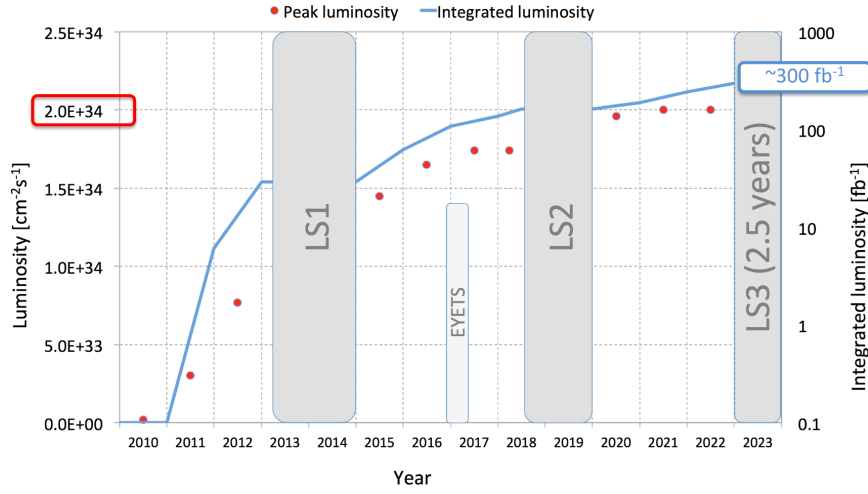


Figure 3.6 The outline of the LHC schedule until 2023, where the different shut-downs are shown. Also, the targeted peak luminosity (the red dots) and the estimated integrated luminosity (the blue line) for CMS are shown. From [28].

The main challenges, which will be addressed by the upgrades are the increase in the instantaneous luminosity and the integrated luminosity. While the former leads to an increase in pileup due to more interactions per bunch crossing, the latter causes performance degradation induced by the ionizing radiation damage. These challenges will mostly affect the efficiency of the inner detection systems and the trigger system. Therefore, upgrades of the different subsystems of CMS are planned and will take place in two phases.

3.3.1 Phase-I upgrade

The Phase-I upgrade of CMS extends over LS1, EYETS, and LS2. The first part of the phase-I upgrade during LS1 was successfully concluded. For the muon system, additional CSCs and RPCs were installed into the fourth end-cap disk which improve the redundancy in the $|\eta|$ region between 1.2 and 1.8, and preserve a low p_T threshold for the L1 muon trigger at high instantaneous luminosity. In addition, optical links that allowed the relocation of some DT electronics from the collision hall were installed. Moreover, electronics in the innermost set of CSC chambers were improved using FPGA-based boards.

The expected integrated luminosity delivered to CMS during the phase-I operation will be around 300 fb^{-1} where the radiation fluency experienced by the pixel detector is expected to exceed $1.2 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$. The present pixel system would not be able to cope with such a fluency and in addition, it would suffer severe data losses due to limitations in the in the read-out chip. This would require the replacement of the entire pixel detector, which will take place during the EYETS. A new pixel detector

comprising 4 barrel layers and 6 end-cap disks will be installed. Featuring new read-out electronics and less material budget the new pixel detector will tolerate the extreme operating conditions. The addition of the fourth layer will avoid the deterioration in the tracking efficiency in case the first silicon strip layer degrades due to radiation damage. The innermost layer of the new pixel system will be installed at a smaller radius thanks to a narrower beam pipe.

The HCAL as well will undergo several improvements during the phase-I upgrade. The key feature of the upgrade of the HB, HE, and the HO is the replacement of the HPDs by silicon photomultipliers (SiPMs). This replacement has already been in place for the HO during LS1, while for the HB and HE it will be implemented during the LS2. The choice of SiPMs is driven by its higher gain, better radiation tolerance and immunity to magnetic field compared to the HPDs. Furthermore, new read-out front-end electronics will be introduced featuring time to digital converters (TDCs) and analog-to-digital-converters (ADCs) which will improve the the bunch crossing identification accuracy and background rejection.

3.3.2 Phase-II upgrade

During the HL-LHC operation CMS is expected to experience even more extreme challenges compared to the Phase-I era. It is foreseen that the overall integrated luminosity will reach 3000 fb^{-1} by 2035. The LHC will be delivering collisions at center-of-mass energy of $\sqrt{s} = 14 \text{ TeV}$ with an instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and mean pileup of around 140 interactions per bunch crossing.

The inner and the outer tracking detectors of CMS are going to experience unprecedented radiation damages caused by the high fluxes of traversing particles at the HL-LHC. It is expected to reach a fluency of up to $10^{16} \text{ n}_{eq}/\text{cm}^2$ in some of the inner regions. Under such conditions, the demand for a new tracking detector with radiation tolerant sensors and read-out electronics is evident. Therefore, a plan to install an entirely new tracking system is scheduled for the third long shutdown (LS3). In addition to the radiation hardness, the new tracking system will counteract the high pileup with higher granularity. Furthermore, the outer part of the tracking detector will be able to contribute to the L1 trigger decision, owing to a track-trigger concept based on novel detector modules. The upgrade of the outer tracking system together with the track-trigger concept will be discussed in more details in Chapter 5.

The ECAL and HCAL end-cap disks will also suffer significant radiation damage by LS3, and thus will be replaced. The end-caps will be replaced by a High Granularity Calorimeter (HGC) which will provide three dimensional images of showers, based on

the concepts for 3D measurement of shower topologies. The fine granularity will allow precise timing measurements, which will help mitigating the pileup effects.

In order to maintain good L1 muon trigger acceptance in the $1.5 < |\eta| < 2.4$ region it is planned to enhance the four existing muon stations with additional chambers based on new detector technologies with higher rate capability. Two stations based on Gas Electron Multiplier (GEM) chambers will be installed in front of the first and second muon stations. Two other stations will use low-resistivity Resistive Plate Chambers (RPC), and will be installed behind the third and forth stations. In addition, the implementation of a GEM station in the space that becomes free behind the new end-cap calorimeters is proposed in order to increase the coverage for muon detection to $|\eta| < 3$.

For the phase-II operation the trigger system will also undergo various major upgrades. In addition to the incorporation of the outer tracking detector in the L1 trigger decision, it is planned to upgrade the L1 and HLT trigger systems. The L1 trigger latency will be increased from $3.2\,\mu\text{s}$ to $12.5\,\mu\text{s}$ to allow sufficient time needed to make use of the track-trigger information. This will yield in up to 1 MHz L1 read-out and up to 7.5 kHz permanent event storage rate. For this to be achieved, the front-end electronics of the subsystems contributing to the L1 trigger will be upgraded. In addition, to allow for an increasing number of parallel L1 trigger algorithms, the upgrade foresees the use of multiple high speed FPGA boards.

Chapter 4

Basic Principles of Semiconductor Detectors

The phenomena associated with electromagnetic radiation and charged particles interacting with matter include a wide variety of physical effects. The characteristics of such interactions are defined by the type of the interacting particles as well as their energy. A variety of materials can be used for the detection of these interactions including gases, liquids, and solid-state materials such as semiconductors.

In high energy physics experiments, the need for detectors capable of measuring particle trajectories with very high spatial resolution ($\sim 10\text{ }\mu\text{m}$), drove the fast development of position-sensitive semiconductor detectors since the 1980s. Beside the spatial precision demand, many additional challenges such as fast timing and radiation resistance are to be addressed in high-luminosity colliders.

This chapter will introduce the principles of particle interactions with matter, before going into an overview on the basic properties of semiconductor particle detectors. Silicon strip detectors will be discussed at the end of this chapter.

4.1 Interaction of Particles with Matter

In matter, radiation and charged particles lose energy by ionizing atoms along their trajectory and around their interaction point. The energy loss and the ionization depend on the nature of the interacting particle and on its kinetic energy. Therefore, studying the physical properties of these interactions is an important aspect of developing the right detection techniques for specific applications.

4.1.1 Energy loss of heavy charged particles

Charged particles of any type (α -particle, p, K, π , e, μ , etc.) lose energy when moving through matter. The energy losses for heavy particles with rest mass much larger than the electron rest mass m_e arise mainly from the excitation and ionization of atoms of the medium close to their passage. This process is known as *collision loss* or *electronic energy loss*. The energy E and velocity v of the traversing charged particle of mass M are related by relativistic kinematics given as

$$E = \gamma Mc^2 = \frac{Mc^2}{\sqrt{1 - \beta^2}}, \quad \text{with} \quad \gamma = \frac{1}{\sqrt{1 - \beta^2}} \quad \text{and} \quad \beta = \frac{v}{c}. \quad (4.1)$$

The maximum transferable energy from the incident particle to atomic electrons of the traversed medium is described by

$$T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}, \quad (4.2)$$

which for $M \gg 2\gamma m_e$ reduces to $T_{max} = 2m_e c^2 \beta^2 \gamma$. On the other hand, for $2\gamma m_e \gg M$, T_{max} is equivalent to $Mc^2 \beta^2 \gamma$ [4].

The mean rate of energy loss by collision per unit path length is given by the *energy loss formula* known as the *Bethe-equation*:

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left\{ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right\}, \quad (4.3)$$

where K is a constant¹, z is the charge of the incident particle, Z and A are the atomic number and the atomic mass of the medium atoms, respectively, I is the mean excitation energy of these atoms, and $\delta(\beta\gamma)$ is a correction for density-effect [29]. The negative sign for dE/dx indicates that the energy is lost by the particle. The stopping power for muons in copper is shown in Figure 4.1 in $\text{MeV g}^{-1}\text{cm}^{-2}$.

The loss rate of a massive particle at low β values (non-relativistic energies) is inversely proportional to its velocity squared (i.e. to its energy). Owing to the $1/\beta^2$ term in the Bethe-equation, the energy loss rate decreases rapidly as the velocity increases. At relativistic energies, when the particle velocity approaches the speed of light ($\beta \approx 1$), a minimum of energy loss is reached, followed by a relativistic rise owing to the logarithmic term. Particles at the energy loss minimum are called *minimum ionizing particles* (MIPs).

¹ $\frac{K}{A} = 0.307075 \text{ MeV g}^{-1} \text{ cm}^2$ for $A = 1 \text{ g mol}^{-1}$

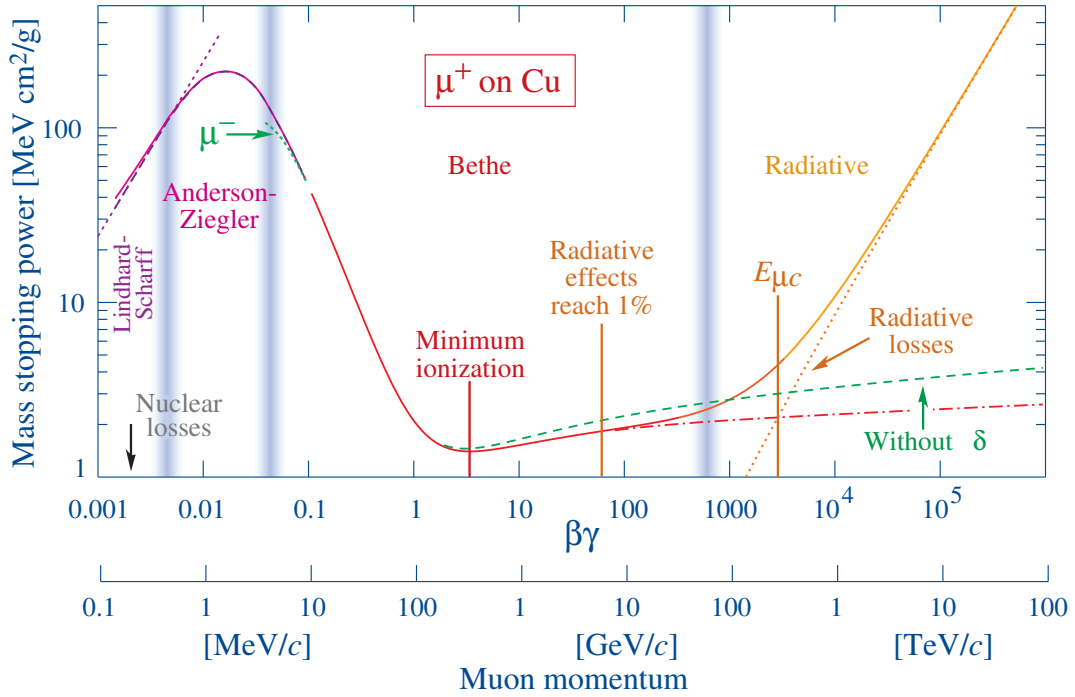


Figure 4.1 The stopping power for positive muons in copper as a function of their momentum. The solid curve indicates the total stopping power and the vertical bands represent boundaries between theoretical approximations or dominant physical processes. The short dotted line labeled as μ^- corresponds to the negative muon stopping power. From [29].

4.1.2 Energy loss of electrons and positrons

Just like heavy particles, electrons and positrons lose energy by collisions while traversing matter. Their interaction with the atomic electrons leads to excitation and ionization of the absorber atoms. The electrons freed by ionization, may possess sufficient kinetic energy to cause secondary ionization, such energetic electrons are referred to as *delta-ray*. In addition to ionizing energy loss, and due to their mass, electrons (positrons) undergo a significant energy loss by radiation emission, known as *bremstrahlung*, which also depends on their kinetic energy. This radiative loss occurs due to the deceleration of electrons (acceleration of positrons) in the Coulomb field of the nuclei.

The collision energy loss of incident electrons (positrons) due to the interaction with the atomic electrons is described by the Bethe-equation. In the case of electrons, the maximum transferable energy is half their kinetic energy $T_{max} = m_e c^2 (\gamma - 1)/2$ [4], while for positrons $T_{max} = m_e c^2 (\gamma - 1)$.

The collision energy loss rate changes logarithmically with the electron energy, and it dominates at energies lower than a critical energy (≈ 37.6 MeV in silicon) [4]. Ionization

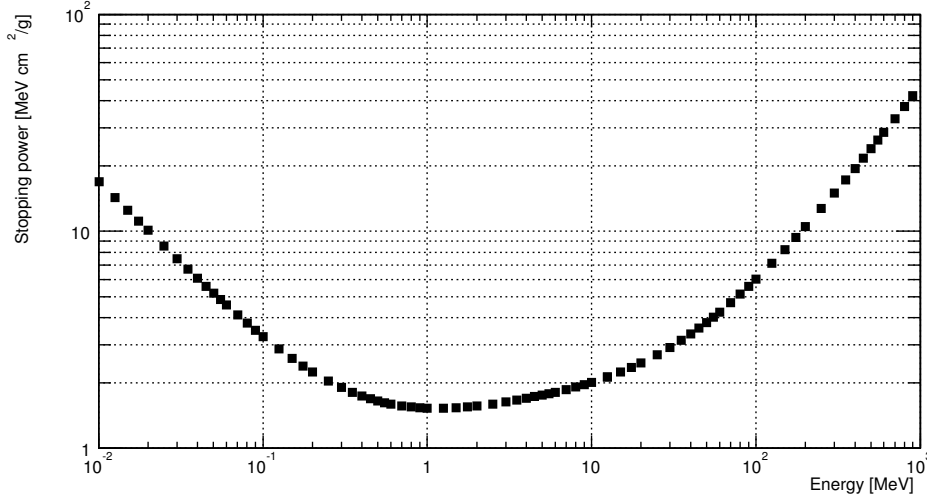


Figure 4.2 Stopping power of electrons in silicon. Graph produced with data from [32].

is the largest contribution of the collision energy loss, although other processes like Møller-scattering (electron-electron scattering), Bhabha-scattering (electron-positron scattering), and electron-positron annihilation contribute to the total energy loss. At higher collision energies the energy loss rate is dominated by bremsstrahlung emission which scales nearly proportional to the incoming electron energy as shown in Figure 4.2.

The quantity describing the amount of matter traversed by a high-energy electron (positron) is known as the radiation length X_0 and is measured in g/cm^2 . It is the mean distance over which the electron (positron) loses all but $1/e$ of its energy due to bremsstrahlung emission. According to calculations [30]

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1) \ln\left(\frac{287}{\sqrt{Z}}\right)} \quad [\text{g}/\text{cm}^2], \quad (4.4)$$

with the atomic number $Z > 4$. For silicon with a density of $2.33 \text{ g}/\text{cm}^3$ the radiation length obtained from Equation 4.4 is $X_0 \approx 21.82 \text{ g}/\text{cm}^2$ [30, 31].

4.2 Basic Properties of Silicon Semiconductors

4.2.1 Energy band

Semiconductor materials have a small energy gap between their electronic conduction and valance bands. These bands are the closest to the *Fermi level* which determines the electrical conductivity of a material. The valence band is the highest range of electron energies in which electrons are normally found at 0 K, while the conduction band is the lowest range of free electron states. The value of the energy gap E_g between

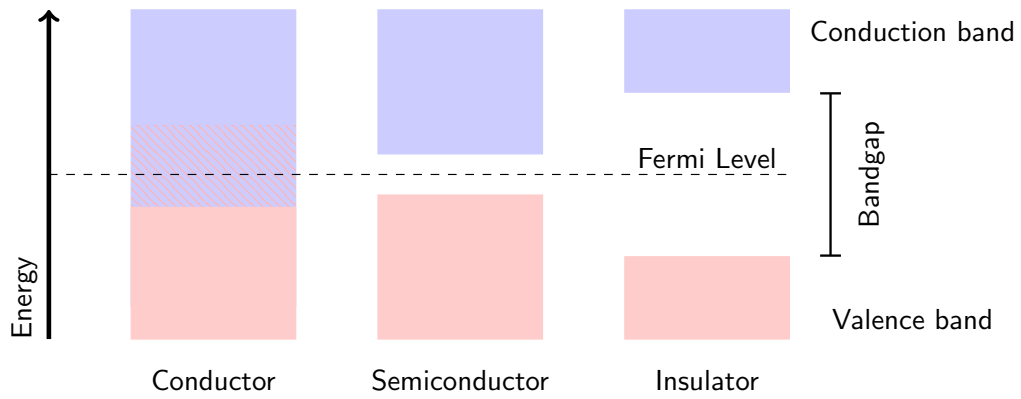


Figure 4.3 Energy band configuration of conductor, semiconductor, and insulator materials. In conductors, the valence and the conduction bands overlap, while it is not the case for both semiconductors and insulators. Semiconductors have a small energy band between the valence and the conduction bands, while insulators have a larger band gap.

the two bands characterizes the conductivity of each material, and it represents the required energy to excite an electron from the valence band to the conduction band. In conductors the bands are in contact and can even overlap. Insulators have their bands separated by a large energy gap compared to semiconductors. The energy bands of conductor, semiconductor, and insulator materials are illustrated in Figure 4.3. For semiconductors such as silicon and germanium E_g amounts to 1.11 eV and 0.67 eV at room temperature [33], respectively, while for insulators it is usually larger than 5 eV. In this chapter, the focus will be on silicon as a semiconductor material.

4.2.2 Intrinsic and extrinsic silicon

In a semiconductor, under thermal excitation, electrons move from the valence band to the conduction band leaving vacancies behind, called *holes*. Therefore, a current of holes in the valence band is created as a counterpart of the electric current in the conduction band. The generated electrons and holes due to thermal excitation are known as *charge carriers*.

In an ideal silicon crystal with no impurities, the amount of thermally excited charge carriers is of the order of 9.65×10^9 electrons/cm³ at room temperature [34]. This may be compared to the number density of free electrons in a typical metal, which is of the order of 10^{22} electrons/cm³.

Silicon is a group-IV element of the periodic table with four valence electrons per atom. In pure silicon the valence band is completely filled at 0 K. At finite temperatures the only free charge carriers are the ones arising from thermal excitation. These free

charge carriers are called *intrinsic charge carriers*. Pure silicon is an example of an *intrinsic semiconductor* with equal numbers of electrons and holes.

Intrinsic semiconductors have a high electrical resistivity and relatively low conductivity. In order to increase the conductivity, artificial impurities can be introduced to the silicon lattice. This process, known as *doping*, replaces some silicon atoms with foreign impurity atoms, where a very small controlled addition of such atoms ($10^{18}/\text{cm}^3$) is sufficient to increase the conductivity of silicon.

If a very small number of atoms of a group-V element, such as phosphorus (P), is added to the silicon as substitution atoms in the lattice, additional valence electrons are introduced into the material due to the five valence electrons in the phosphorus atoms, as can be seen in Figure 4.4a. These additional electrons are bound only weakly to their parent impurity atoms, and even at very low temperatures these electrons can be promoted into the conduction band of the semiconductor. This kind of doping manifests itself as an addition of a donor level just below the conduction band. Semiconductors which have been doped in this way will have a surplus of electrons (donors), and are called *n-type* semiconductors where electrons are the majority free charge carriers.

On the other hand, if a group-III element, such as boron (B), is used to replace some of the atoms in the silicon lattice, there will be a deficit in the number of valence electrons in the material, as shown in Figure 4.4b. This introduces electron acceptor levels just above the valence band, and causes more holes to be introduced into the valence band. Hence, the majority of free charge carriers are positive holes in this case, known as acceptors. Semiconductors doped in this way are termed *p-type* semiconductors.

Semiconductors with either n-type or p-type doping are known as extrinsic semiconductors.

4.2.3 The pn-junction

The formation of a *pn-junction* in a silicon crystal occurs when a p-type region is brought into contact with a n-type region. This junction, shown in Figure 4.5, is created by the diffusion of electrons from the n-type region into the p-type region and vice versa for the holes. The diffusion arises from the charge carriers concentration gradient caused by the difference in doping types and concentrations. Due to the non-mobility of donors and acceptors on both sides of the junction an electric field builds up. This field acts against the diffusion process until an equilibrium state is reached. A depletion zone also known as space-charge region (SCR), depleted from free charge carriers, forms at the interface between the two regions. A potential difference U_{bi} in the order of millivolts builds up between the boundaries of the depletion zone with a thickness d and is called the *built-in voltage*. It is expressed using the following

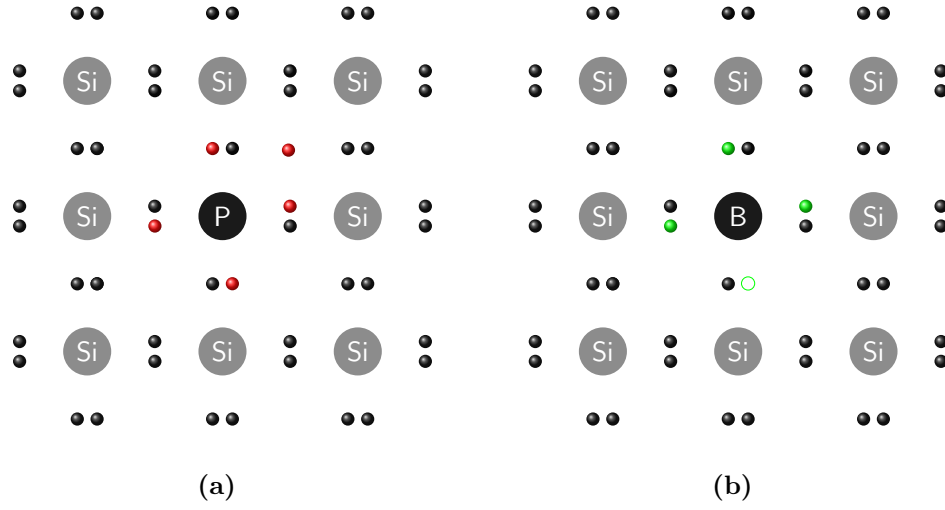


Figure 4.4 Extrinsic n-type (a) and p-type (b) silicon. In n-type silicon a phosphorous atom replaces a silicon atom bringing an extra electron to the lattice, referred to as donor. In the p-type silicon a boron atom replaces a silicon atom creating a hole, referred to as acceptor.

relation

$$U_{bi} = \frac{1}{2\epsilon_0\epsilon_{Si}} \cdot |N_{eff}| \cdot d^2, \quad (4.5)$$

where $\epsilon_0\epsilon_{Si}$ are the relative permittivities of vacuum and silicon, and N_{eff} , the effective doping concentration, is the difference between the individual doping concentrations of the acceptors N_A and donors N_D , expressed as

$$N_{eff} = N_A - N_D, \quad (4.6)$$

The depletion thickness is of the order of a few micrometers. This thickness can be increased by applying an external reverse bias voltage U_{bias} , and can be determined using

$$d(U_{bias}) = \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{|N_{eff}|} \cdot (U_{bias} + U_{bi})}. \quad (4.7)$$

The depleted zone in a silicon semiconductor can serve as a sensor for particle detection. An ionizing particle passing through this zone generates charge carriers in excess to the equilibrium which can be collected and measured. An ionizing energy of $E_{ion} = 3.62$ eV is enough to produce an electron-hole pair in silicon. This will be discussed in more details in Section 4.3.2.

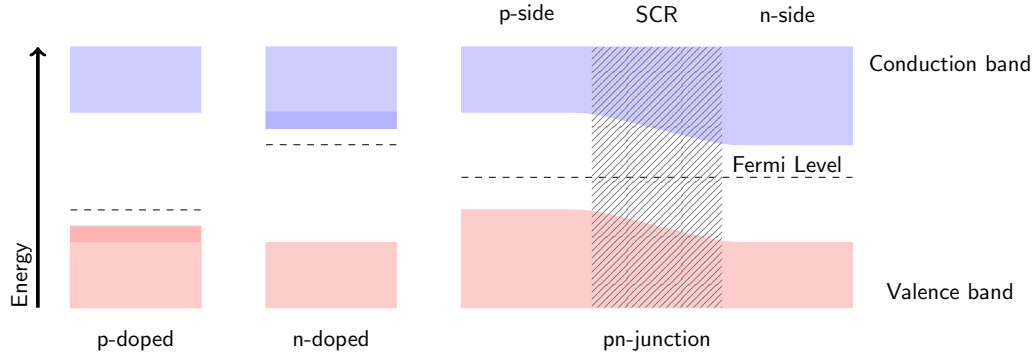


Figure 4.5 A schematic view of the band structure and energy levels in *p*-doped (left) and *n*-doped (center) silicon and the *pn* junction with space-charge region (right).

4.2.4 Electrical properties

The performance of a silicon sensor for a certain application can be evaluated by its electrical characteristics. These characteristics, in addition to the depletion zone thickness, include the depletion voltage, capacitance, and leakage current.

Depletion voltage

In order to have the whole sensor bulk of thickness D depleted of free charge carriers, a reverse bias must be applied. The minimum voltage at which the full depletion is achieved is called the depletion voltage U_{dep} and can be derived from Equation 4.7 as follows

$$U_{dep} = \frac{|N_{eff}| \cdot D^2}{2\epsilon_0\epsilon_{Si}}, \quad (4.8)$$

assuming that the built-in voltage U_{bi} is small compared to U_{dep} . Silicon detectors are usually operated in an *over-depletion* mode, where U_{bias} is set slightly higher than the full depletion voltage. This is important in applications where fast electronics are used for read out, since higher electric fields result in a faster charge collection time, and thus the signal formation is sped up.

Capacitance

The depleted region acts as a parallel plate capacitor with the capacitance C , which can be obtained using the following equation

$$C = A \sqrt{\frac{q_0 \epsilon_0 \epsilon_{Si} \cdot |N_{eff}|}{2 U_{bias}}} = \epsilon_0 \epsilon_{Si} \frac{A}{U_{bias}} \quad \text{for } U_{bias} \leq U_{dep}, \quad (4.9)$$

where q_0 is the elementary charge, and A is the effective area of the silicon sensor.

Once the bias voltage exceeds the depletion voltage, C reaches a saturated constant value, inversely proportional to the depletion thickness D , and is then expressed as

$$C_{sat.} = \epsilon_0 \epsilon_{Si} \frac{A}{D} \quad \text{for } U_{bias} > U_{dep}. \quad (4.10)$$

This value is known as *geometrical* capacitance, since it only depends on the sensor geometry and not on the bias voltage. It can be used to obtain the full depletion voltage by plotting the applied voltage versus $1/C^2$. Thus, the full depletion voltage can be determined from the intersection point of the straight line with linear voltage dependence, below depletion, and the saturated constant line, above depletion.

Leakage current

The leakage current in silicon sensors, also known as the *dark current*, is generated from two main sources: the diffusion of charge carriers from the non-depleted region into the depleted region, and dominantly from the thermally excited charge carriers. It also increases with the reverse bias. The leakage current is an important characteristic of the detection device, since it has a direct influence on its noise level and power consumption.

Since it is dominantly caused by thermally excited electron-hole pairs, the leakage current is highly dependent on temperature. The scaling can be performed using the following expression

$$I(T_2) = I(T_1) \cdot \left(\frac{T_2}{T_1}\right)^2 \exp\left(-\frac{E_{eff}}{2k_B} \left[\frac{1}{T_2} - \frac{1}{T_1}\right]\right), \quad (4.11)$$

where $E_{eff} = 1.21$ eV [35], k_B is Boltzmann's constant, $I(T_1)$ is the current measured at temperature T_1 , and T_2 is the temperature for which the current is determined.

The leakage current increases due to radiation induced effects. In order to keep the leakage current as low as possible, and thus reducing the noise and the power consumption, detectors are cooled when operated. At the LHC for example, the present silicon detectors are cooled to around -10°C during operation and it is foreseen to operate below -20°C during the HL-LHC era where the high radiation dose will significantly increase the leakage current.

4.3 Silicon Strip Detectors

The first silicon strip detectors to operate in a high energy physics experiment were designed for the NA11 experiment [36] at CERN, which was constructed to measure

the lifetime of Charm mesons. Its basic form, structured as a row of segmented diodes on a single silicon wafer, is still in use nowadays. Nevertheless, many improvements to the design and the production techniques have been made. These developments went hand in hand with the rapid evolution of integrated circuits, which broadened the application range of silicon as detecting material. Silicon strip detectors are by far the most widely used semiconductor devices for particle tracking.

4.3.1 Basic design

Implant segmentation

One of the commonly used designs in the production of silicon strip detectors is known as the planar layout. It is based on the segmentation of one or both sides of the silicon wafer with narrow implants, called *strips*. Strips are usually implanted with the opposite doping type and higher concentrations² compared to the sensor bulk, each of them forming a separate pn-junction. For particle tracking purposes the bulk thickness typically varies from 50 μm to 500 μm while the distance between the center of the strips, known as the *pitch*, ranges from 25 μm to few hundreds of microns.

The segmentation into parallel strips provides a one dimensional position sensitive silicon detector. In the case of double sided implantation, the sensor is capable of providing two dimensional position information, given a certain angle between the implants of both sides. In the following, the focus will be on single-sided strip detectors only.

An aluminum layer is deposited on top of each strip and on the backplane implantation of the sensor. This metalization provides the connection of each strip to the read-out electronics and the biasing of the sensor from the backside via wire-bonds. The contact between the strip implant and the metalization can be established via AC or DC coupling. In the case of DC coupling the aluminum layer is placed directly on the implant, while in the case of AC coupling the strips are capacitively connected to the aluminum layer by a silicon dioxide layer. The latter case is more expensive –due to the additional steps required in the manufacturing process– however AC coupling prevents leakage current from directly flowing through the read-out electronics.

In silicon strip detectors the charge carriers created by a traversing MIP drift due to the electric field created by the application of external voltage. The drift direction toward the strips or the backplane depends on the direction of the electric field. For instance, in a sensor with n-type bulk material and p⁺-type strips, the holes move

²Typically, the doping concentration of the segmented implants is higher than the bulk by at least four orders of magnitude.

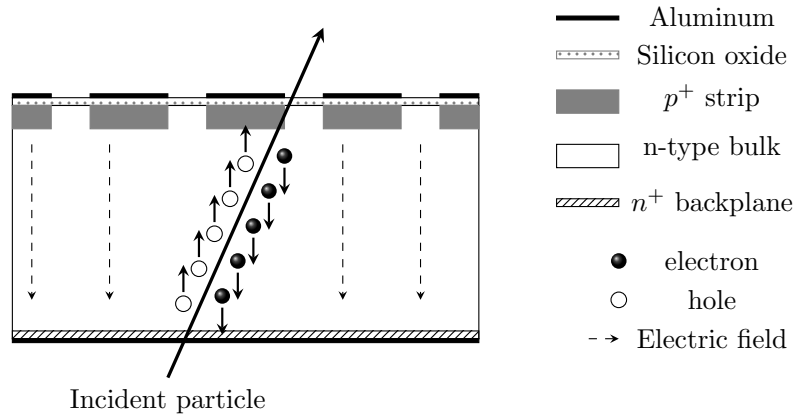


Figure 4.6 A schematic view of a p-in-n silicon strip sensor with a traversing ionizing particle. The electron-hole pairs created by the ionization in the n-type bulk travel towards the sensor electrodes. Electrons drift towards the backplane, while holes are collected by the p^+ strip implants.

toward the strips and the electrons move, in the direction of the electric field, toward the n^+ -type backplane as illustrated in Figure 4.6.

P-stop and p-spray

One of the disadvantages of using a p-bulk sensor is that it allows the accumulation of electrons around the implants, due to the positive charge of the silicon dioxide layer, which can lead to a short between neighboring strips. The solution for this problem is by isolating the n^+ implants using p-type implantations. Two common options of isolation are available nowadays: p-stops, where separate p-implantations are implanted between the n^+ implants, and p-spray, where a thin p^+ layer is implanted on the whole sensor surface, except from over the n^+ implants. Both options prevent a conductive connection between the strips from building up. However, the latter has the advantage of not introducing yet another structure.

Biasing and guard rings

Biasing of the strip detectors is normally applied through the backplane metalization as mentioned earlier. The voltage is applied via a bias structure, usually a ring around the active area, and internally distributed to the individual strips via bias resistors. There are three different approaches of bus systems that can be implemented to perform the bias distribution: polysilicon bias resistors, punch-through bias, and FOXFET³.

³FOXFET: Field OXide Field Effect Transistor

implantation bias. The choice of the biasing scheme depends on the application, namely on the radiation dose that the detector is expected to receive.

In addition to the bias structure, silicon strip sensors also feature ring structures on their edges, known as guard rings, which control the potential drop from the active area of the sensor to the physical edge. Using multiple guard rings guarantees a smooth transition from the high field beneath the last strip to ground potential at the edge of the device. Potential drops over short distances may lead to local breakdown at voltages much lower than the required bias voltage. The absence of the guard rings can also lead to the increase of the leakage current, generated from edge processing defects if the depletion zone extends to the edges of the sensor.

4.3.2 Charge collection

The amount of charge carriers created in a silicon sensor is proportional to the energy deposited by the traversing ionizing particle. The mean amount of these carriers $N_{e,h}$ is given by the following relation

$$N_{e,h} = \frac{E_d}{E_{ion}}, \quad (4.12)$$

where E_d is the deposited energy in the silicon depleted zone. Electrons with minimum ionizing energy lose about 390 eV/ μm in silicon, i.e. $N_{e,h} \sim 110$ pairs/ μm . But due to the Landau nature of the deposited energy distribution⁴, this is reduced to about 70 pairs.

The externally applied electric field causes the generated electron-hole pairs to drift to the sides of the depleted zone as explained earlier. The drift velocity $v_d(x, t)$ depends on the strength of the electric field and can be expressed in terms of the mobility μ in silicon. In a low field region $v_d(x, t) = \mu_0 E(x)$, where $\mu_0 \sim 1400$ (450) $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ for electrons (holes) at 300 K [37]. In high electric field regions the drift velocity saturates. Charge carriers arriving at the electrode and moving in its vicinity induce a measurable signal. The signal measured on the implant electrode is not directly caused by the collection of the free charge carriers themselves, but owing to the variation of the electric field flux in the electrode. This variation results from the drift of the charges toward the implants causing a displacement current and generating the detectable signal. This current can be calculated using the *Shockley–Ramo theorem* [38, 39].

In addition to the electric field and the mobility, the charge carrier trapping life time τ_t is another factor which has an influence on the charge collection. Charge carrier trapping is a phenomenon that exists in the silicon bulk due to processing and radiation

⁴The Landau distribution is a probability distribution describing the energy loss including delta-rays effects. It features a Gaussian core with an extended tail towards large energies.

induced defects. The trapped carriers are shielded from the external electric field and thus require larger energy and take a longer time to be collected. The increase in the number of traps in the sensor bulk due to the accumulation of radiation induced defects increases the probability of thermally excited charge carriers which translates into higher leakage current. This effect can significantly diminish the performance of the detector by reducing its signal-to-noise ratio.

Another effect that has an influence on the charge collection is known as the Hall effect⁵. As mentioned earlier, the charge carriers drift toward the read-out electrodes under the influence of the electric field. Normally, the drift direction is parallel to that of the electric field. However, if the strip detector is operated under a magnetic field the charge carriers will experience what is known as the Lorentz⁶ force which deflects their direction. The Lorentz force F_L acting on a single charge q under a magnetic field B is expressed as

$$\mathbf{F}_L = q(\mathbf{E} + (\mathbf{v} \times \mathbf{B})), \quad (4.13)$$

where E and v are the electric field and the drift velocity respectively, assuming the magnetic field to be perpendicular to the electric field. This force results in an inclination of the charge carriers drift with an angle Φ_L , known as the Lorentz angle

$$\tan(\Phi_L) = \frac{\Delta X}{d}, \quad (4.14)$$

where ΔX is the shift in the center of charge position and d is the sensor thickness. It can also be expressed in terms of the charge carrier mobility μ and the magnetic field as,

$$\tan(\Phi_L) = r_H \mu \cdot B, \quad (4.15)$$

where r_H is the Hall coefficient which describes the influence of the magnetic field on the charge carriers, and it differs for electrons and holes yielding in different Lorentz drifts for the two charge carriers. With a CMS-like magnetic field strength of 4 T, Lorentz angles of 31° and 7° have been measured for electrons and holes, respectively, in a 300 μm thick silicon detectors [40].

A consequence of the Lorentz drift in a silicon strip sensor is the charge sharing between neighboring strips, resulting in the formation of *clusters*. For particle physics applications charge sharing is a desired phenomena, since it allows the determination of the hit position more precisely by measuring the relative charge collected by each strip in the cluster.

⁵Edwin Herbert Hall (1855-1938). American physicist who discovered the effect known by his name in 1879.

⁶Hendrik Antoon Lorentz (1853 – 1928). The Dutch physicist made the derivation of the force which is the combination of electric and magnetic force on a point charge due to electromagnetic fields.

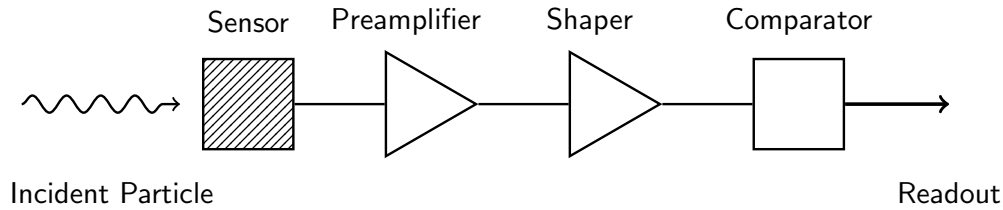


Figure 4.7 Basic components of the front-end electronics in a read-out channel. Signals induced by an incident particle in the sensor are processed by the preamplifier and the shaper. Then the comparator discriminates the signals using a preset threshold.

4.3.3 Read-out

As mentioned previously, each strip is connected to its corresponding read-out channel via a wire-bond in order to extract the signal from the detector. Typically, the front-end of each channel constitutes analog and digital blocks. The analog block, as shown in Figure 4.7, commonly features a preamplifier, which amplifies the signal collected at the strip; a pulse shaper that tailors the signal in a suitable shape for being digitized; and a comparator with configurable threshold for rejecting low signals and noise.

In a 300 μm thick silicon detector the induced signal due to a MIP is of the order of several thousands electron-hole pairs. This signal is usually, due to charge sharing, collected by more than one strip. This means that each strip encounters a fraction of the induced signal. Therefore, it is important that the input stage of the amplification process at each strip contributes very little noise. This can be accomplished by placing the preamplifier as close to the detector bulk as possible, and by optimizing the connections to reduce the pick-up noise.

For applications where fast timing is of concern, the comparator output signal would be enough to transmit for further processing. This signal only holds the address information of the strip of which the comparator threshold was exceeded. This mode, known as *binary* mode, does not transport the pulse-height information to the DAQ system. Usually, the decision to operate in this mode is mainly driven by the limitation of the available bandwidth for data transfer. This kind of operation will be further discussed in Chapter 5. In some cases, where the pulse-height is of concern, the analog information is read out together with the strip address. In this mode, the charge information is transmitted to the DAQ system to be processed off-line. Valuable information can be extracted by analyzing the analog data, such as the charge sharing between neighboring strips, and charge collection efficiency.

Chapter 5

The Phase-II Upgrade of the CMS Outer Tracking Detector

Following the third long shutdown (LS3) of the LHC, between 2023 and 2025, the machine will start operating with higher instantaneous luminosity compared to the Phase-I era [41]. In the proposed scenario the accelerator will reach a luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, which yields around 3000 fb^{-1} integrated luminosity over 10 years of operation. This implies great challenges to the CMS detector in its Phase-I configuration, especially to the pixel and the outer tracking detectors.

5.1 Motivation and Requirements

According to simulations [42], the aging of the pixel detector after the first few years of operation (1000 fb^{-1}) under the HL-LHC luminosity would lead to almost a factor of two in degradation in the longitudinal impact parameter prediction and a data loss of about $\sim 7\%$ in the first pixel detector layer, which is crucial for primary and secondary vertex reconstruction. The outer tracking detector would also suffer from the increase in leakage current due to radiation damage, leading to thermal runaway of a large fraction of its sensors. Even with the minimum achievable cooling temperature of -20°C , a huge fraction of the modules of the outer tracking system would be rendered non-functional. Moreover, the planned CMS trigger upgrade is foreseen to provide higher output rate and an improved discriminating power of the event selection including trigger information from the tracking detector.

Therefore, an upgrade of the tracking system with entirely new components is planned to take place during LS3. The main requirements to be addressed in the new tracking system are described in the following:

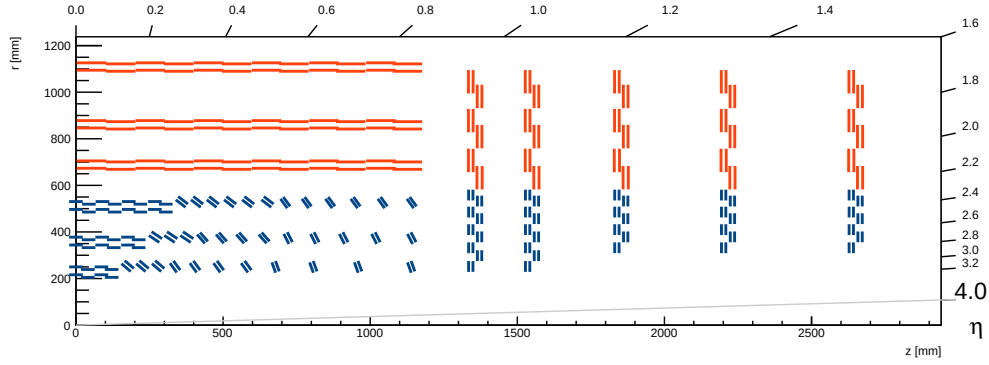


Figure 5.1 The Phase-II tracking detector of CMS featuring the entirely new outer tracking detector with the PS and 2S modules shown in blue and red, respectively. From [42].

Radiation hardness; to maintain functionality up to an integrated luminosity of 3000 fb^{-1} all the components of the tracking detector, especially the sensors, must be sufficiently tolerant against radiation to cope with the expected particle fluency of up to $2 \times 10^{16} \text{ 1 MeV n}_{eq} \text{ cm}^{-2}$ in the pixel detector and a maximum of $1.1 \times 10^{15} \text{ 1 MeV n}_{eq} \text{ cm}^{-2}$ in the outer tracking detector region [43].

High granularity; an average of 140 collisions per bunch crossing are estimated as the number of pileup events after LS3. To cope with such pileup while maintaining an efficient tracking performance, the channel occupancy must be kept close to 1%. This will be achieved by increasing the channel density by shortening the lengths of the silicon sensor strips relative to those in the current detector.

Low material budget; the amount of material in the fiducial volume at high luminosities will significantly limit the tracking performance and the overall event reconstruction in CMS due to multiple scattering and radiation effects. To keep the material budget at its lowest, ultra-light mechanics and a low mass evaporative CO_2 cooling system will be used.

Trigger capability; the increased event rate and the extreme pileup conditions at this high luminosity place stringent requirements on the trigger system. With a new track-trigger concept, the tracking detector will be able to back the calorimeters and the muon system by providing trigger information. Based on novel modules, the so-called p_T -modules, capable of identifying high transverse momentum tracks, data with trigger information will be delivered by the tracking system to the L1 trigger at every bunch crossing. This upgrade element will be discussed further in the following sections.

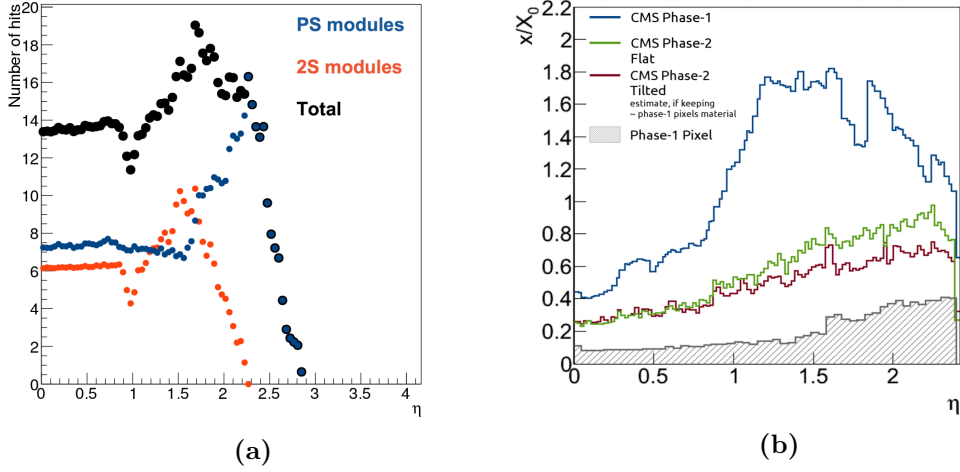


Figure 5.2 The extended coverage of the outer tracking detector is reflected by the hit distribution (a) as function of $|\eta|$. The material budget of the Phase-II tracking detector is reflected by the radiation length distribution (b) as a function of $|\eta|$. The radiation length distribution is shown for the tracking acceptance of the Phase-I tracking detector, and reflects only the material inside the tracking volume; the expected contribution of the Phase-I pixel detector (hashed histogram) is provisionally used also for the Phase-II tracking detector. A comparison between the configuration using tilted PS modules and all flat PS modules is also included. Both plots are obtained using the tkLayout modeling tool [44] and are taken from [45].

5.2 The Future Outer Tracking Detector

The upgraded CMS outer tracking detector will consist of six barrel layers in the central region and two end-caps with five disks on each side. The entirely silicon detector will have a total active surface of 218 m^2 and will extend the tracking acceptance up to a pseudorapidity of $|\eta| \leq 3$, compared to the $|\eta| \leq 2.5$ coverage of the current CMS tracking detector. The outer tracking system layout is shown in Figure 5.1. The extended tracking acceptance is shown in terms of number of hits as function of $|\eta|$ in Figure 5.2a.

The upgraded tracking detector will comprise two different p_T -modules: the PS module, made of a micro-pixel sensor and a strip sensor, and the 2S module, made of two strip sensors. About 5700 PS modules occupy the first 3 barrel layers and the part of the disks closest to the beam pipe, starting at a radius of 200 mm, while around 8400 2S modules form the rest of the layers and complete the disks outside a radius of approximately 600 mm.

In the Phase-II tracking system the inactive material inside the tracking volume will substantially be reduced. This will be achieved by integrating the control electronics with the read-out in a single optical data link. In addition, the cross section of the

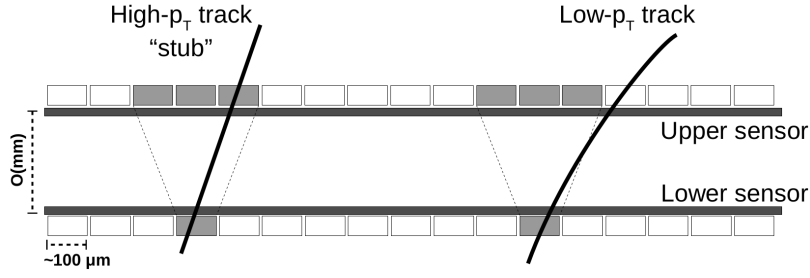


Figure 5.3 Illustration of the p_T -module concept.

conductors for the front-end powering will be reduced owing to the implementation of an on-module powering scheme, which will be discussed further in Section 5.2.2. Furthermore, the optimized configuration of the tilted PS modules lead to a significant reduction in the number of required modules. The inactive material inside the tracking volume is shown in the Figure 5.2b, where the distribution of radiation length as a function of η for the Phase-I tracking system is compared to that expected for the Phase-II.

5.2.1 The p_T -module concept

Besides providing an improved overall tracking performance with lower mass, one of the main features of the outer tracking detector of CMS during the HL-LHC phase will be providing L1 trigger information. This will be achieved owing to the p_T -modules. These modules will enable the outer tracking system to locally discriminate between low- p_T and high- p_T tracks.

The p_T -module concept, proposed in [46–49], is based on modules utilizing novel front-end electronics that correlate hits on the two closely separated silicon sensors of the module. An event with a charged particle traversing the first sensor triggers the functionality of the common front-end logic which searches for a correlated hit on the second sensor within a programmable correlation window defined in units of strips. Owing to the 3.8 T magnetic field of CMS, which will cause different curvatures of high- p_T and low- p_T tracks, the p_T of the bended track associated with clusters on both sensors can be locally measured. An illustration of the stub concept is shown in Figure 5.3.

The local p_T measurement as a function of the charged particles radius of curvature can be derived from the Lorentz force (defined in Equation 4.13) and the centripetal force. Considering the transverse plane and in the absence of external electric field, F_L can be expressed as

$$F_L = qv_TB, \quad (5.1)$$

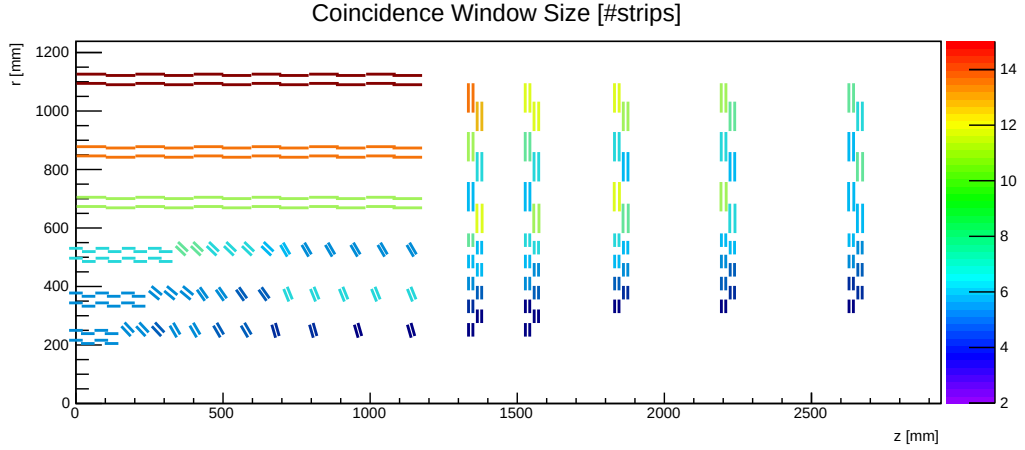


Figure 5.4 The Phase-II outer tracking detector of CMS with the assumed coincidence window sizes in the PS and the 2S modules. The window size is given in number of strips. From [50].

which is equivalent to the centripetal force, and thus can be written as

$$F_L = qv_TB = \frac{mv_T^2}{r}, \quad (5.2)$$

where m and r correspond to the mass and the radius of curvature of the particle, respectively. Using this relation, the transverse momentum can be extracted as a function of r ,

$$p_T = mv_T = qrB, \quad (5.3)$$

and can be written in natural units as

$$p_T[\text{GeV}] = 0.3QB[\text{T}]r[\text{m}], \quad (5.4)$$

where Q is the charge in units of the elementary charge e .

In order to define a uniform p_T threshold over the whole volume of the outer tracking detector, the dependency of p_T on the curvature is compensated with the choice of three parameters: the coincidence window size, the separating distance between the sensors of the same module, and the radius in the tracking detector at which the module will be located. The window size is programmable and can be controlled via the front-ends of the modules. The optimized window sizes for operation are shown in Figure 5.4, and the separation between the sensors of the modules is illustrated in Figure 5.5. The third parameter is defined by the layout of the outer tracking system. With such a configuration, only 5 different modules geometry will be used, compared to the 20 configurations in the current system.

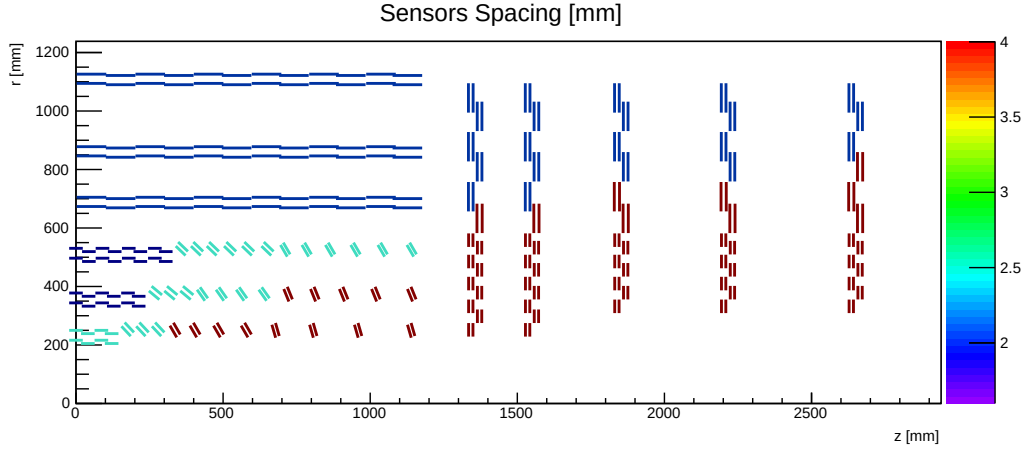


Figure 5.5 The Phase-II outer tracking detector of CMS with the proposed spacings between the sensors of the PS modules and the 2S modules. The spacing is given in mm. From [42].

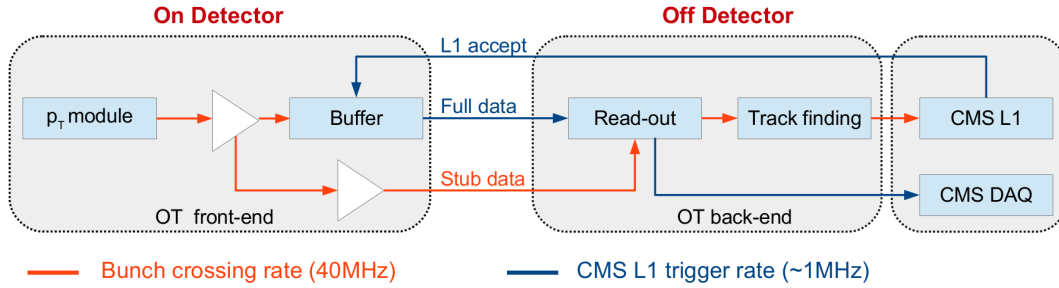


Figure 5.6 The two independent read-out paths provided by the p_T -modules. The whole outer tracking detector sends trigger data (stubs) at each bunch crossing (40 MHz) while event data are buffered and read out only if a L1-accept signal is received. The full data is then transmitted to the CMS DAQ system.

With optimized parameters a threshold of $p_T \approx 2$ GeV can be maintained uniformly over the whole volume of the tracking detector. Hits produced by low- p_T tracks with $p_T \leq 2$ GeV fall outside the correlation window and thus are rejected. Only data of correlated pairs of hits, corresponding to high- p_T tracks will be read out, and are referred to as a *stubs*.

Stubs are then used as input to the L1 track-finding. The stub data are sent out at the bunch crossing frequency of 40 MHz rate, while the event data are buffered in the modules front-end pipelines to be read out and transmitted to the CMS DAQ system, once a L1 trigger-accept signal is received, as illustrated in Figure 5.6. For this purpose, the read-out electronics of the p_T -modules feature two output streams, which will be discussed further in Section 5.4.

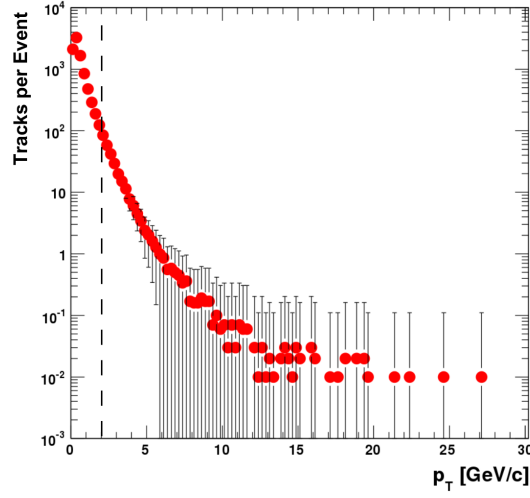


Figure 5.7 Simulation of the p_T spectrum for all minimum bias particles that leave hits in a sensitive layer at a radius of 25 cm at an average pileup of 400 proton-proton interaction per event. Events were simulated within a magnetic field of 4 T and a coverage of $|\eta| < 2.5$ [51]. The dashed line represents the 2 GeV threshold.

Tracks with $p_T < 2$ GeV form more than 95% of all tracks in minimum bias events¹. Such tracks can be ignored since they correspond to soft interactions and are not produced by hard inelastic scattering processes. Therefore, the threshold is chosen not to affect the physics performance, but at the same time to provide a data volume reduction sufficient for the purposes of the L1 data transmission. One order of magnitude reduction, due to this threshold, is expected. Figure 5.7 shows a simulation, performed in [51], of the p_T spectrum of minimum bias events and reflects the estimation of the rejected tracks per event if a 2 GeV threshold is applied.

The performance of the p_T -modules concept was studied by simulating muons, electrons and pions traversing the different layers of the outer tracking detector. Taking into account the different sensor spacings and correlation window sizes, the 2 GeV threshold can be achieved as seen from the efficiency turn-on curves in Figure 5.8a and Figure 5.8b. Further tuning and optimization of the different parameters is still ongoing, especially for the modules near the beam pipe where the stub rate is by far the highest.

5.2.2 The 2S module design

The 2S module, shown in Figure 5.9, consists of two (100 mm $\times$ 100 mm) stacked silicon strip sensors mounted with the strips parallel to each other. Both sensors are glued

¹Minimum bias events belong to interactions that are selected with a loose trigger intended to select inelastic collisions with as little bias as possible.

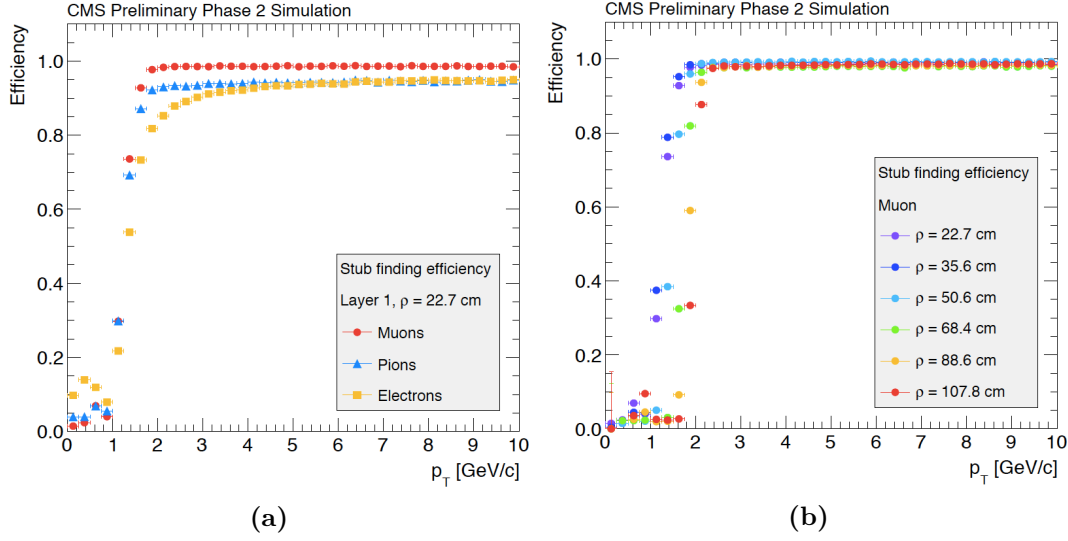


Figure 5.8 Simulation of the stub finding performance for muons, electrons, and pions in the inner most layer of the outer tracking detector (left), and only for muons at all detecting layers (right). From [42].

to Aluminum-Carbon Fiber² (Al-CF) spacers which extend beyond the sensor edges, providing mounting and cooling supports. Each sensor is divided into two independent halves, each half comprising 1016 parallel strips of about 50 mm length and with 90 μ m pitch.

Flexible front-end hybrids (FE-hybrids) [52] located on both sides of the sensors are folded around an Al-CF spacer, each receiving wire bonds from the strips of the stacked sensors. The FE-hybrids provide the HDI³ routings to the read-out ASICs. The flexible structure is driven by the requirement of the simultaneous read out of the upper and the lower sensors, which is essential for the p_T -module concept. The read out of the sensors is handled via a binary ASIC produced in 130 nm technology, known as the CMS binary chip (CBC). The design and functionality of the CBC will be discussed in Section 5.4. Each of the FE-hybrids hosts eight bump-bonded CBCs with 254 channels each to read out and correlate signals from the 127 strips from each of the stacked sensors.

The trigger and read-out data generated by all eight CBCs are transferred at 320 Mb/s to one Concentrator Integrated Circuit (CIC) buffer located on each FE-hybrid. In the CIC, the CBC read-out data are sparsified and funneled out at 320 Mb/s to a service hybrid, while trigger data (stub data) are sent out in block synchronous mode, aggregated over a fixed number of 8 bunch crossings.

²The choice of Al-CF is driven by its coefficient of thermal expansion (CTE), which matches the CTE of Silicon.

³High Density Inter-connector

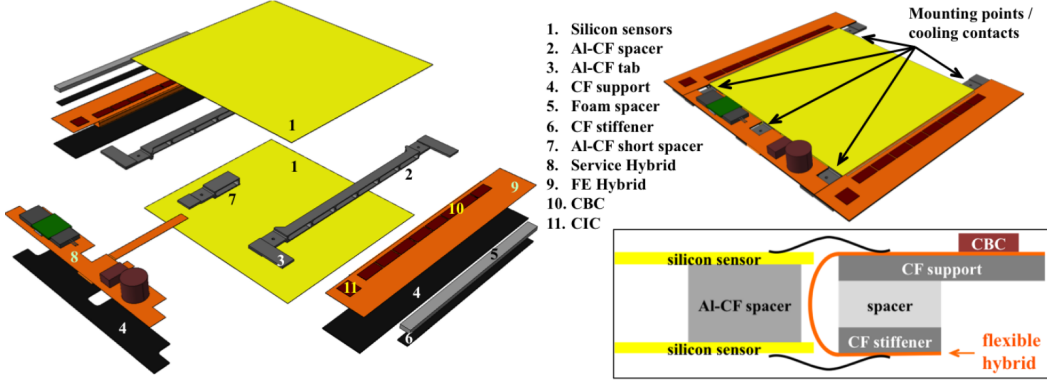


Figure 5.9 Exploded view of the 2S module components (left), 3D view of the assembled module (upper right), and a sketch of the FE Hybrid folded around its support (lower right). The module is mounted on five cooling elements on the mechanical support structure. From [42].

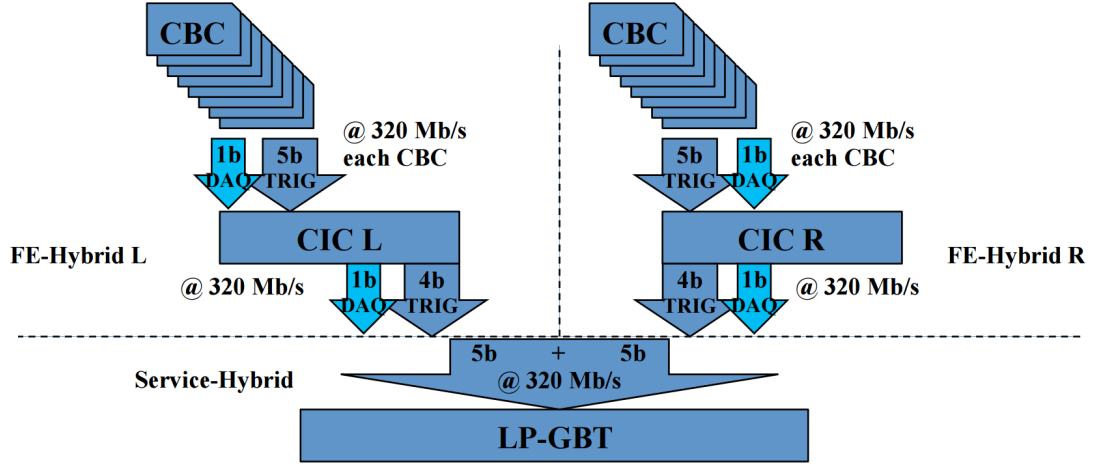


Figure 5.10 A block diagram of the 2S module electronic system. The data rates transfer within and inbetween the FE-hybrids and the service hybrid are shown. From [50].

The service hybrid is placed between the two FE-hybrids. It hosts a Low Power Gigabit Transceiver (LP-GBT) chip [53] which receives the data packets from the CIC and passes them serialized to the back-end electronics where the track-finding logic takes place. It also receives and deserializes data from the back-end to the front-end. In addition to data transmission, the LP-GBT chip supports the control of the front-end ASICs via an I2C bus⁴, receives and distributes clock and trigger signals, and provides local monitoring. An optoelectronic transceiver (VTRx+), located on the service hybrid, converts all upstream and downstream data to optical and electrical signals, respectively. The transfer rate within and between the hybrids is shown in the block diagram in Figure 5.10.

⁴Inter-Integrated Circuit bus

The service hybrid also carries a step-down DC-DC converter⁵ and a miniature high voltage connector for the necessary low voltage supply for the front-end electronics and the sensors biasing, respectively.

5.2.3 The PS module design

The PS module, shown in Figure 5.11, is constructed using closely separated macro-pixel and strip sensors. The two sensors are separated by Al-CF spacers, and the whole module is mounted on a carbon fiber reinforced plate which provides the mechanical support and the interface to the cooling structure.

The PS module sensors are split into two halves. Each half of the strip sensor consists of 960 strips, ~ 25 mm long and with $100\,\mu\text{m}$ pitch. Each half of the macro-pixel sensor contains 960 pixelated strips, where each strip comprises sixteen ~ 1.5 mm long pixels with $100\,\mu\text{m}$ pitch. With this configuration, the macro-pixel sensor provides an additional coordinate information.

For read out, the channels of the strip sensor are wire-bonded to folded flexible FE-hybrid which host eight Short Strip ASICs (SSAs) with 120 channels each. The macro-pixel sensor is bump-bonded to sixteen Macro-Pixel ASICs (MPAs), which in turn are wire-bonded to the FE-hybrid. The SSAs perform strip signal amplification and discrimination, while the MPAs, in addition to the readout of the pixels, are also responsible for the hits correlation between the macro-pixels and strip sensors. The FE-hybrid, as in the 2S module, also comprise CICs which format the raw and trigger data from the MPAs and forward them to the LP-GBT optical block. The LP-GBT is placed on a service hybrid between the two FE-hybrids, and the DC/DC converter is located on the opposite side.

5.3 Track Finding at L1

The stream of the aggregated stub data from the CICs are sent to the back-end where the L1 track finding system is implemented. It is estimated that each bunch crossing produces of the order of 10,000 stubs, where only 5 to 10% of these stubs actually correspond to tracks with $p_T > 2\,\text{GeV}$ [42]. The rest are random combinations of hits, or are due to lower- p_T particles and secondary particles produced by interactions of primary particles with the material in the detector. Finding the combinations of stubs compatible with high- p_T tracks at a latency of $\sim 5\,\mu\text{s}$ is the main challenge to be encountered by the track finding system.

⁵The amount of power required by the outer tracking detector will increase compared to the current one. This will be compensated by supplying higher input voltages. The DC-DC conversion will then provide the low voltage needed for the front-end electronics despite the higher voltage supplied.

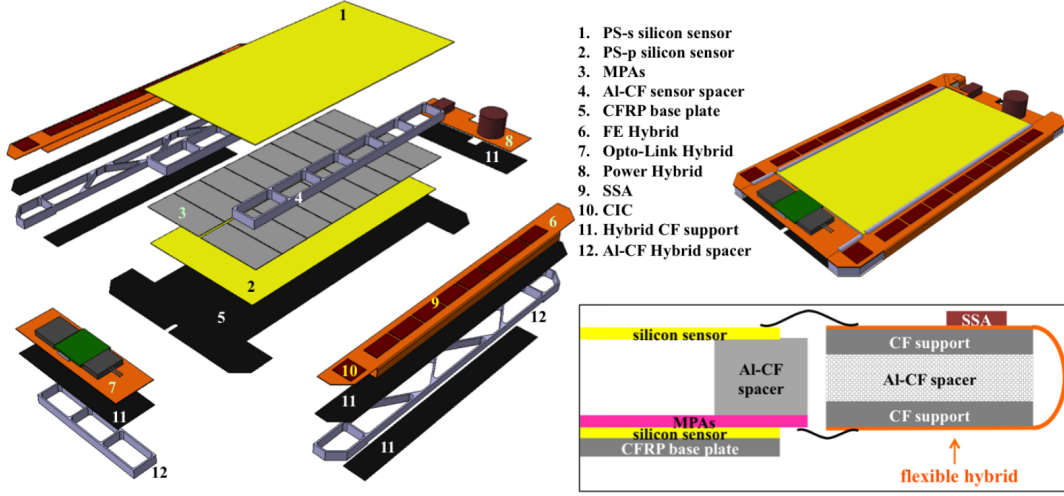


Figure 5.11 Exploded view of the PS module components (left), 3D view of the assembled module (upper right), sketch of the FE Hybrid folded around its support (lower right). The base plate is glued onto a flat surface on the support structure that is kept cold during operation. From [42].

5.3.1 Track finding approaches

Three alternative approaches, based on FPGAs and ASICs, are currently under development to demonstrate the feasibility of the track finding at L1 during the Phase-II operation era. Any of the three approaches must be able to receive the stub information and perform the track finding within the allowed latency. The different approaches with preliminary performance estimation are briefly discussed in the following.

Tracklet approach

The tracklet approach [54, 55] is based on commercial FPGAs. It utilizes traditional road search techniques to perform track recognition at L1. The track finding is performed in multiple steps. First tracklets are seeded from stub pairs in neighboring layers of the outer tracking detector. The seeding is done multiple times in different combinations of barrel layers and end-cap disks to ensure high efficiency. At this stage tracklets must pass certain selection requirements in order to be considered for the next steps. These requirements, implemented in fast look-up tables, include the selection of tracks with transverse momentum of $p_T > 2 \text{ GeV}$ and longitudinal impact parameter of $|z_0| < 15 \text{ cm}$. Then the tracklets are extrapolated to other layers and disks to search for matching stubs. If at least two are found, a linearized χ^2 fit which gives the final track parameters is performed. Duplicates due to multiple seeding of tracklets which belong to the same track are removed in the final step based on the χ^2 fit.

Associative memory and FPGA approach

The associative memory (AM) and FPGA approach [56] is a two-stage L1 tracking procedure. The first stage makes use of a massively parallel system based on AM chips to match a set of stubs with track patterns stored in the memories. This stage begins with a FPGA data organizer receiving stub information at 40 MHz from the tracking detector and passing them in low resolution format to the AM chips. The received information is compared to the precomputed patterns almost simultaneously. Once the pattern recognition is performed, matched patterns with the corresponding high-resolution stub data are retrieved by the data organizer. In a second stage another FPGA system receives the matched data from the data organizer to perform the track fit. This approach has been successfully exploited by the CDF experiment [57, 58] and will be implemented in the Fast Track Trigger (FTK) [59] project for the ATLAS Phase-I upgrade.

In order to ease the task of the FPGAs, the detector is subdivided into 48 trigger sectors, 8 in ϕ and 6 in η . Each sector is expected to receive around 300 stubs, for an average pileup of 140. The number of required patterns in each sector depends on the track resolution and p_T .

Time multiplexed trigger approach

This FPGA based approach [60] relies on time-multiplexing⁶. It uses two processing layers, with a passive switching network between them, the pre-processor (PP) and the main-processor (MP) FPGA boards. The PPs organize the received stubs and distribute them to the MPs. Each MP receives data from many PPs that belong to a single event. Data from the next event flow to a second MP, out of phase by one LHC clock cycle. The system will have a time-multiplexed period of 24 bunch crossings, therefore each MP has 24 bunch crossings to run the algorithm. In this way, combinatorial background from high pileup events can be avoided. The MPs make use of the Hough transformation [61], known as line detection algorithm, in order to build track candidates. In order to cope with the stub data rate, the tracking detector has to be subdivided into five ϕ trigger regions processed in parallel. Therefore data from each event will be processed in 5 MP boards.

Such a method is already implemented in the CMS calorimeter trigger system for the Phase-I upgrade [62]. The same hardware can be also used here. The architecture is based on readily available Micro Telecommunications Computing Architecture mTCA

⁶Time multiplexing is a method of transmitting and receiving independent signals over a common signal path by means of synchronized switches at each end of the transmission line, so that each signal appears on the line only a fraction of the time in an alternating pattern. It is used when the data rate of the transmission medium exceeds that of the signal to be transmitted.

MP7 boards [63]. This board hosts a Xilinx Virtex 7 FPGA [64] with 72 I/O links, each operating at up to 12.5 Gbps.

5.3.2 Performance estimates

Preliminary studies based on simulations have been devoted to the optimization and qualification of the different track trigger approaches in order to estimate their potential performance. The desired performance has to ensure a high L1 tracking efficiency while keeping the event rates under control.

The simulations are carried out on special samples with a uniform η , ϕ , and p_T spectrum, and a Gaussian distributed d_0 and z_0 , consistent with the expected HL-LHC beam envelope. Single muon, pion, and electron samples, overlaid with an average pileup of 140, are generated. The selection criteria used for the performance study requires tracks to have $p_T > 2$ GeV and $|\eta| < 2.5$ with a minimum of four stubs. The efficiency of the tracklet approach, defined with respect to the truth-level tracks, is shown in Figure 5.12a. For muons an overall efficiency of about 99% with a sharp turn-on curve at 2 GeV is obtained, while for electrons and pions the efficiencies are lower, $\sim 87\%$ and 95% respectively, due to the higher interaction rate with the detector material. Similar results are expected with the other two approaches.

The p_T and z_0 resolutions of the L1 tracks are also studied for single muon, shown in Figure 5.12b. Owing to the PS modules, the z_0 resolution is obtained to be around 1 mm in the central region. This allows for the selection of tracks originating from the same vertex, which is important for the HLT trigger algorithms. For p_T , a resolution of 1% is achieved in the central region while a deterioration starts to occur at $|\eta| > 1.5$ due to the lower lever arm of the tracking detector.

Further studies and optimizations to improve the performance of the three approaches are taking place in parallel and are still to be completed. Based on these studies the most viable approach will be adopted for performing the track finding for the L1 trigger during the HL-LHC era.

In order to make use of the track trigger concept, L1 trigger objects information must be combined with the L1 track information. This is performed by matching the L1 trigger information from the muon and calorimeter system to the L1 tracks. The matching results in an improvement of the muon momentum and provides electron identification, track isolation variables, and the determination of the z position of the electrons, muons and taus. In addition L1, tracks can also be used for primary vertex reconstruction and to perform vertex association for jets used in hadronic triggers.

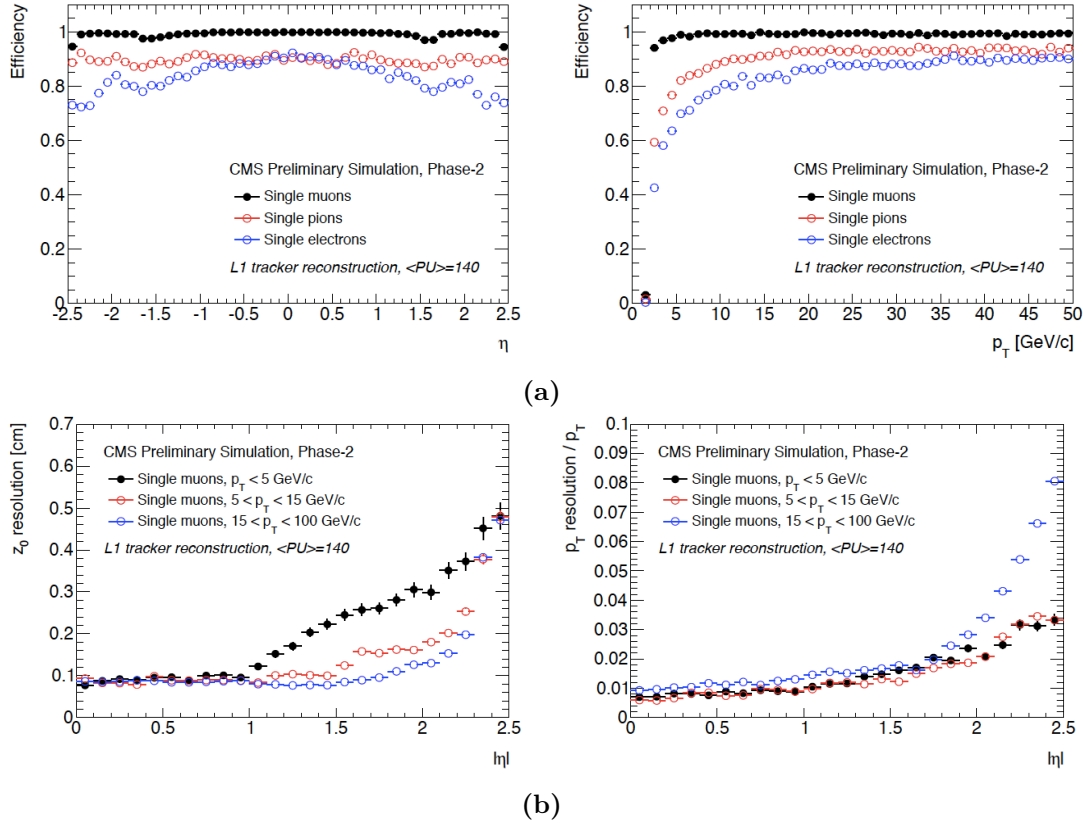


Figure 5.12 The expected efficiency of the L1 track reconstruction as function of η (a-left) and p_T (a-right) for single muons, electrons, and pions. The expected z_0 resolution (b-left) and relative p_T resolution (b-right) of the L1 track reconstruction as function of $|\eta|$ for single muons.

5.4 The CMS Binary Chip

The aforementioned CMS binary chip (CBC) is the foreseen chip for the read-out of the 2S modules of the outer tracking detector during the HL-LHC era. Connected to both sensors of the 2S-module, the CBC will provide L1 trigger information with p_T -discrimination. It is designed to guarantee a p_T -threshold of 2 GeV at tracking detector level. Therefore, the chip binary architecture has been optimized to reduce the amount of data that need to be processed by at least one order of magnitude compared to the current detector configuration.

5.4.1 The Chip Design

The CBC is manufactured in 130 nm CMOS technology. The CBC2 [65–67] is an evolved version of the first CBC [68]. The chip is designed and produced with high lead C4 bumps with a pitch of 250 μm . The C4 bumps allow for the flip-chip interconnection between the ASIC and the front-end hybrid of the 2S-modules, replacing the wire

bond connections in the CBC and reducing the chip size. The CBC2 has a size of $11 \times 4 \text{ mm}^2$ with 254 input channels to read out 127 strips from each of the 2S module sensors. The front-end of each channel consists of a preamplifier, a gain amplifier, and a comparator as shown in Figure 5.13. The analog components of the front-end are discussed further in the following.

Front-end circuitry

The signal resulting from the charge generated by an ionizing particle is initially processed by a preamplifier that includes a 100 fF feedback capacitor and a resistive feedback network. The primary function of the preamplifier is to extract the signal from the detector via the feedback capacitor, without significantly degrading the intrinsic signal-to-noise ratio, and to act as an interface between the detector and the pulse processing electronics that follows. The input circuit of the preamplifier is optimized to match the characteristics of the detector and its low output impedance serves in compensating the gain amplifier.

The CBC2 preamplifier circuit can be coupled to sensors of either polarity owing to its resistive feedback network design. This network optimizes the circuit depending on the sensor polarity; in n-in-p type sensors, the electron mode is selected by a switch network and a single 200 k Ω resistor forms the feedback resistance. For p-in-n type sensors, the hole mode is selected and a T-network of three resistors is used. For both modes, the decay time of the output pulse is about 20 ns. The preamplifier is AC-coupled to the gain amplifier which provides the necessary gain for the following comparator stage. The AC coupling removes any DC contribution arising from the leakage current of the sensor. The input voltage (V_{PLUS}) to the gain amplifier is set globally by a programmable 8 bit digital-to-analog converter (DAC), and its output is adjusted by a local (per channel) 8 bit DAC setting in order to compensate for channel-to-channel variations. The peaking time of the gain amplifier signal is sufficiently small to avert pileup effects.

The comparator

The comparator operates as a discriminator by either suppressing or letting pass incoming signals by comparing their voltages to a predetermined threshold (V_{CTH}). In the case of signals exceeding the V_{CTH} value, the comparator produces and feeds a digital pulse to the next stage. Owing to the global and local 8 bit DACs mentioned earlier, a uniform threshold can be set across the chip. In addition, the comparator features a programmable resistive hysteresis network that prevents any rapid oscillations in the comparator output that may arise from input signal fluctuations.

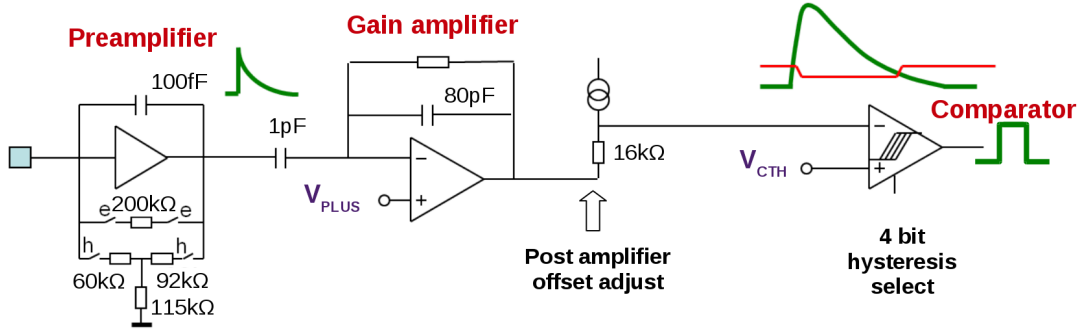


Figure 5.13 CBC2 analog front-end schematic. The signal at each stage is shown in green. Modified from [69].

Typically, the comparator response time is dependent on the rise time of the input signal. The difference in response time for different signals is known as *time walk*. In order to ensure that the incoming signals are associated with the correct bunch crossing the time walk is required to be less than 16 ns for a 1.25 fC to 10 fC signal range when the threshold is 1 fC, following the specification documented in [70]. The CBC is designed to meet such a requirement.

5.4.2 The Logic Block

The CBC2 logic block design, shown in Figure 5.14, is implemented in successive stages such that the binary output of the comparator of each channel is processed by the *Hit detection logic*, and the *Stub-finding logic* described in the following.

Hit detection logic

The hit detection logic is first to receive the comparator binary signals. It is optimized to synchronize those signals with the bunch crossing clock and sample them to a 256 bit deep pipeline memory for read-out. It can function in two different selectable modes, shown in Figure 5.15. It can either pass a synchronized version of the signals with the same length of the comparator signal to the pipeline memory, or it can detect the rising edge of the comparator signal and produce a pulse of one clock cycle length, regardless of the length of the comparator signal. In the pipeline memory data are stashed awaiting the L1 trigger decision for a maximum latency of 6.4 μ s. Once the L1 accept signal is received, the pipeline control logic transfers the relevant data to a 32 bit deep buffer memory pending for read-out. Data from the second path are processed through blocks of combinatorial logic responsible for the identification of stub candidates. The hit detection logic also allows the flexibility of masking noisy channels individually.

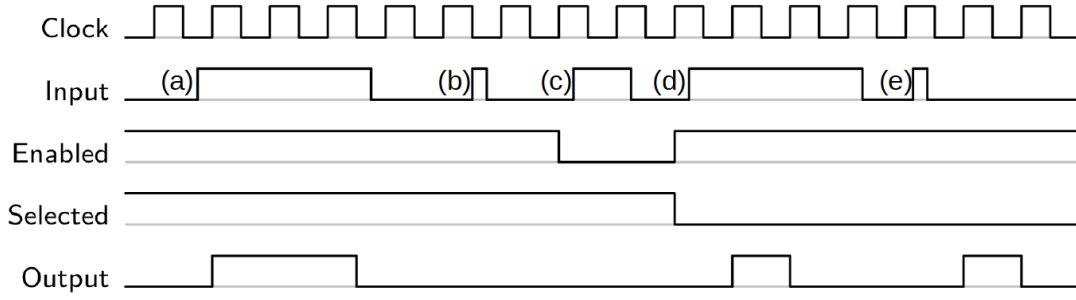


Figure 5.15 Operation modes of the hit detection Logic. For case (a) and (b) the circuit is enabled (Enabled = 1) and Selected = 1 which means a synchronized version of the input should pass through to the output. This is true of (a), however (b) was not high for enough time to be synchronized to the clock. In case (c) the circuit is disabled (Enabled = 0) and nothing passes to the output. In cases (d) and (e), the circuit is enabled and Selected = 0. This means that all comparator pulses are increased or decreased in length to be one clock cycle in length. Modified from [69].

Due to the limited output bandwidth available at the CWD stage, and in order to accommodate more stub data, only the position of the central strip of a cluster is transmitted further. In case of two strip clusters, the center is assigned to the strip with the lower address.

Correlation logic and offset correction: Following the CWD, the CBC2 chip features a logic block that correlates valid clusters from the lower and the upper sensors. For every central strip of a valid cluster on the lower sensor, the correlation logic probes for a valid cluster within the coincidence window in the upper sensor. In order to maintain a uniform p_T -threshold throughout the whole tracking detector volume the correlation logic block allows the adjustment of the window size for each chip. The size can be configured in the range of ± 8 strips symmetrically around the central strip.

At this stage, the window position can be adjusted to account for geometrical effects across the same module. This offset correction can be programmed up to 3 strips in four programmable groups within each chip. This correction is necessary since a straight trajectory does not cross the same channel number in the upper and lower sensors. The maximum expected offset Δ at a module edge can be derived as

$$\Delta = \frac{W}{R \cdot S} \quad (5.5)$$

where W is the half-width of the module, R is the radius where the module is located from the beam pipe, and S is the spacing between the sensors of the p_T -module. From

Equation 5.5 one can obtain that the maximum Δ for a 2S module in the barrel region or the end-cap region is 1.5 strips.

Inter-chip communication:

Each half of the 2S-module will be read out by eight CBCs. In order to avoid trigger efficiency loss in the case of particles crossing adjacent chip regions in the silicon sensors, an inter-chip communication is implemented in the CBCs boundaries. For the boundary connection between two adjacent chips, the CWD logic requires the input of four adjacent channels per sensor, and the offset correction and the coincidence window logic requires eleven. Therefore, 15 input and 15 output links on both edges of each CBC2 are implemented.

Read-out

As mentioned earlier, the CBC2 has two data output streams for stub and read-out data. Stub data are latched into a 131 cell deep parallel-input/serial-output shift register (127 cells for channels, 3 for data header, and 1 for trailer). Data are loaded in parallel format to the shift register where they are converted to serial format to be read out. Read-out data from the hit detection logic are continuously loaded into a 254 bit wide pipeline memory, matching the number of channels, with 256 bit depth. The sequence of writing and reading data to and from the pipeline memory is handled by a pipeline control logic. Only data of triggered events are read for each bunch crossing from the pipeline memory and are written to a 32 bit deep buffer memory. The buffer memory is 262 bit wide, including 8 bits to contain the pipeline address of which the data came from, and can store up to 32 triggered data events. Those events are then serialized through a shift register before being output from the chip. A detailed overview of the control components of the CBC2 can be found in [69].

Chapter 6

CBC2 Performance in Test Beam

In order to test the performance of the CBC2 chip described in Chapter 5, two prototype modules equipped with the chip are measured in a test beam. Different scans relevant for testing the CBC2 front-end features and logic are performed. The aim of this test is to provide the proof of concept, showing that the CBC2 is capable of performing the p_T discrimination and of delivering trigger information simultaneously.

The analysis results presented in this chapter are based on an off-line data analysis framework developed as a part of this work [71]. The software implementation of the framework is based on the CMS software (CMSSW) [19], and the *ROOT* data analysis software [72]. The successful test beam commissioning and data taking is owed to the collaborative effort of the different groups [73].

In this chapter, a description of the experimental setup is given followed by an explanation of the event reconstruction and beam parameter extraction. Finally, the results of the test beam are discussed.

6.1 Experimental Setup

Two prototype modules, each equipped with two CBC2 chips, were installed and operated in the DESY-II test beam facility [74, 75]. In the following, the tested prototypes, the test beam setup, and the data acquisition (DAQ) setup are presented and a summary of the collected datasets is given.

6.1.1 Tested modules

The two prototypes exploited in the test beam are constructed using two different sensor types from different manufacturers, CNM [76] and Infineon [77]. Each module

Manufacturer	bulk	pitch	thickness	strip length	number of strips
Infineon	n-type	80 μm	300 μm	50 mm	256
CNM	p-type	90 μm	270 μm	54 mm	254

Table 6.1 Parameters of 2S prototype modules available during the test beam.

is composed of two parallel strip sensors separated by about $d = 2.75$ mm. The sensors of the CNM module have 254 strips, while the sensors of the Infineon module have 256 strips. The strip size varies slightly between the two modules. While the CNM sensors have about 50 mm long strips with 90 μm pitch, the Infineon sensors have 54 mm long strips with 80 μm pitch.

The sensors are wire-bonded to a prototype readout rigid hybrid [78] on which two CBC2 chips are bump-bonded. Due to the smaller sensors and less numbers of chips of these modules compared to the 2S module design, the prototypes are referred to as mini-2S modules. The main features of the two mini-2S modules are summarized in Table 6.1.

Each of the modules is mounted in an aluminum case, which is prepared to provide the mechanical integration and support of all components. The cases are equipped with electrical interfaces for control, bias and low voltage supply. The hybrids were kept at 20°C throughout the test using a Peltier¹ element mounted to each module. Also mounted to each module is an interface board which provides the electrical interface to the hybrid by supplying power and adapting the signals to LVDS² standard levels for transmission to and from the DAQ system. Figure 6.1 shows a picture of one of the mini-2S modules before and after being assembled with the other components in the aluminum case.

The module with CNM sensors was used as the device under test, hereafter referred to as DUT, and the module with the Infineon sensors as a reference, hereafter referred to as REF.

6.1.2 Test beam setup

DESY operates a test beam facility with three separate beam lines delivering electrons or positrons to the three test areas TB21, TB22, and TB24 [74]. The primary electron beam is first converted into bremsstrahlung photons by directing it onto a 10 μm thick carbon-fiber target. These photons are then converted via a thick copper or aluminum target into electron-positron pairs. The resulting beam is then spread out into a

¹Named after Jean Charles Athanase Peltier (1785-1845). In 1834 the French physicist discovered the presence of heating or cooling at an electrified junction of two different conductors.

²Low Voltage Differential Signaling

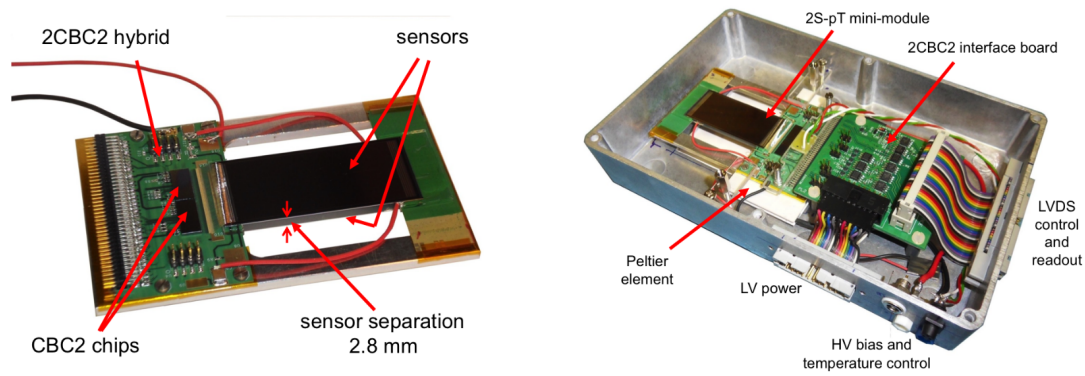


Figure 6.1 The mini-2S module before and after mounting into the aluminum case, shown in the left and right pictures, respectively.

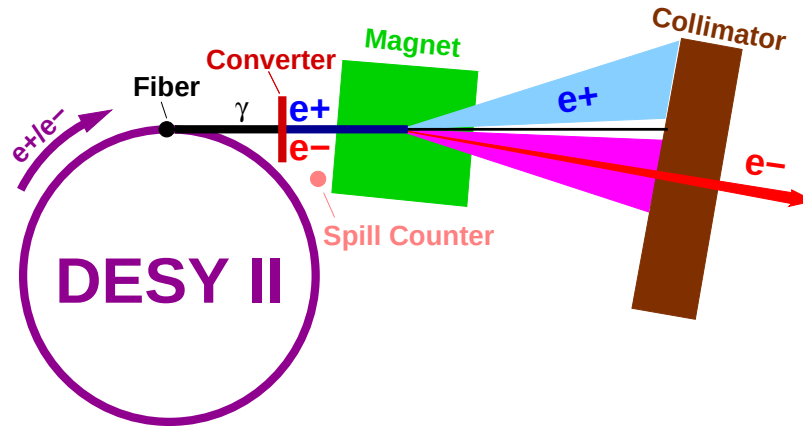


Figure 6.2 Schematic view of the DESY-II test beam facility [74].

horizontal fan by a dipole magnet to be collimated and delivered to the experimental areas. An illustration of the beam is shown in Figure 6.2. By adjusting the current of the magnet, the energy of the electron (positron) beam passing the collimator can be varied from a minimum of 1 GeV to a maximum of 6 GeV. The beam has an energy spread of $\sim 5\%$, a divergence of ~ 1 mrad, and a rate of $O(10)$ kHz.

The setup, shown in Figure 6.3, was installed in area TB21 and the test was carried out exploiting a positron beam with energies between 2 GeV and 4 GeV. The DUT module was mounted on a rotation stage and xy -stages. The REF module was fixed downstream. For both modules, the strips were oriented along the z -axis, which was also the rotation axis of the DUT. The distance L between the two modules was about 23 cm. Two scintillators, located downstream, provided the trigger signal to the modules. In the following, the sensors of the DUT will be referred to as S0 and S1 and the sensors of the REF will be referred to as S2 and S3.

The DUT and REF modules were installed inbetween six MIMOSA26 [79] sensors which compose the DATURA telescope [80]. However, the telescope data stream was

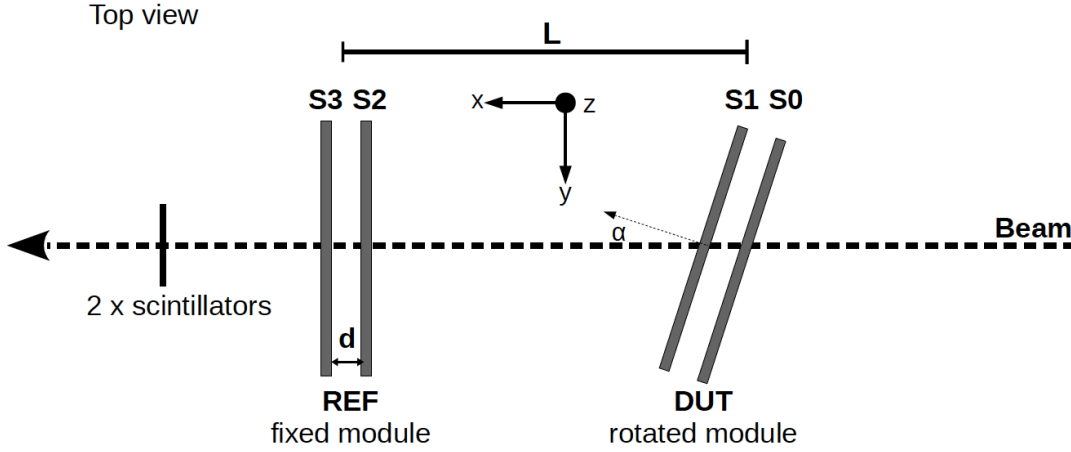


Figure 6.3 Schematic drawing of the test beam setup, showing the upper (S0) and lower (S1) sensors of the DUT, and the upper (S2) and lower (S3) sensors of the REF. The beam direction is from the right to left, traversing the two modules and the two trigger scintillators located downstream.

not synchronized during the data taking with the modules data stream. Unfortunately, attempts to perform the off-line synchronization were unsuccessful due to technical reasons. Therefore, no further use of the telescope data was made in the analysis.

6.1.3 Data acquisition setup

The DAQ setup used during the test beam is shown in Figure 6.4. As mentioned earlier, the trigger is provided by two scintillators which were placed downstream in the setup. The trigger signals from the scintillators were fed to a Trigger Logic Unit (TLU) [81] which is designed to receive and distribute these signals. A back-end (BE) Gigabit Link Interface Board (GLIB) [82] was interfaced to the TLU, in order to receive the trigger signals and provide them to the modules with a return LVDS back pressure signal. The TLU was configured to throttle the scintillators trigger if a back pressure signal was detected in which the BE board could either prevent data buffer overflows in the DAQ or pause data taking during or at the end of a run.

The BE was also configured with the logic needed for controlling the CBC2s, buffering and packaging the returning data streams, and transmitting the event data to the DAQ PC. Moreover, the BE provided the communication, through an optical fiber, with a front-end GLIB board, which was interfaced with the two mini-2S modules, and was configured to fulfill the roles of the CIC and the GBT ASICs [53].

The GLIB boards used in the modules DAQ are customizable electronics cards for data acquisition and evaluation purposes, based on the Xilinx Virtex 6 FPGA [64]. The card can be configured to interface with a range of external hardware via the use of

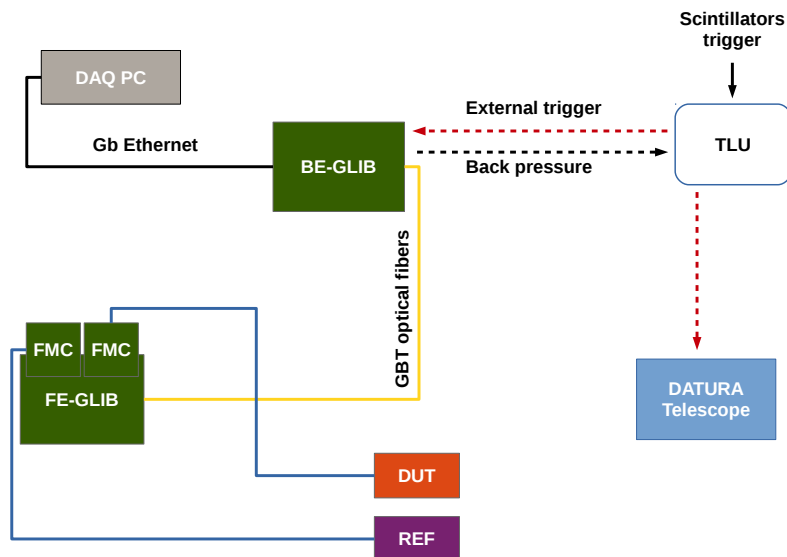


Figure 6.4 Schematic drawing of the DAQ setup. Modified from [83].

two on-board mezzanine headers, and can host up to four SFP+³ transceiver modules for data transmission. This configuration is meant to emulate the architecture that is being considered for readout and control of full size 2S modules.

The test beam DAQ system ran on a 40 MHz clock. For synchronization, the BE-GLIB measured the arrival time of the asynchronous trigger from the TLU, and allocated the 40 MHz clock into twelve time buckets, using a Time to Digital Converter (TDC) block. This block, implemented in the firmware of the BE-board, records the trigger arrival time with respect to the system clock. This is necessary for the data analysis where a selection on the TDC phase is required, to ensure the beam particle has arrived at a certain time with respect to the sampling clock on the CBC2s.

6.1.4 Recorded datasets

As mentioned in Chapter 5, the CBC2 chip is capable of providing two output streams, one with the stub information, and the second with the full hit information from the triggered events. For each event triggered by the TLU the information from both streams were stored. From the REF, only the event data stream was used, while from the DUT events data and stubs data were recorded for the off-line analysis. The DUT stub finding-logic was configured by setting the cluster width discrimination, explained in 5.4.2, to 3 strips, the coincidence window width to ± 7 strips (symmetrically around

³Small form-factor pluggable plus: an enhanced version of the SFP standard that supports data rates up to 16 Gbit/s.

the central strip), and the offset to 0 strips. Each time a cluster was found on S0, a window was seeded to find a correlation on S1.

After many commissioning runs for event and stub data latency optimization, the optimum settings were used for data taking runs, with about 200 k events recorded in each run. Runs relevant to the off-line analysis presented in this work included V_{CTH} scans of the DUT and angular scans. The V_{CTH} scans were performed in steps of 5 covering a range from 30 (high-threshold) to 120 (low-threshold) in units of analog-to-digital-conversion (ADC) counts. The V_{CTH} values can be expressed in terms of electrons using the following relation [84]

$$\text{Threshold}[e^-] = 380(120 - V_{CTH}) + 6440, \quad (6.1)$$

which is averaged over the chips of the same module. Therefore, the threshold scan of the DUT covered the range from $6440 e^-$ to $40640 e^-$. The angular scan was performed using different settings of the ϕ -rotation stage. For these runs, the beam energy was kept constant at 4 GeV.

6.2 Event Reconstruction

The analysis framework mentioned in the introduction of this chapter, is divided into two stages. In the first stage raw data are converted into ROOT readable data files using the CMSSW software. These files include all needed information (hit positions, cluster and stub information, meta-data). An analysis of the converted data is performed in the second stage.

In order to perform the data analysis a reconstruction of events is required. This includes noise suppression, off-line clustering, and the off-line alignment of the setup. A description of each of these steps is given in the following.

6.2.1 Noise suppression

The first step is an estimation of the intrinsic noise in the modules using randomly triggered events without beam. This reveal a limited number of noisy channels on both sensors of the REF. As a result, the corresponding channels generated hits in up to 70% of randomly triggered events. The affected strips are manually masked during data taking by raising their threshold values.

The hit distributions in the sensors in events with beam show that the strips neighboring the masked noisy strips are also slightly affected by noise. All the problematic channels for both sensors of the REF occupy a single region of about 30 strips in size, and thus the whole region is masked for the analysis. On the other hand, this study also

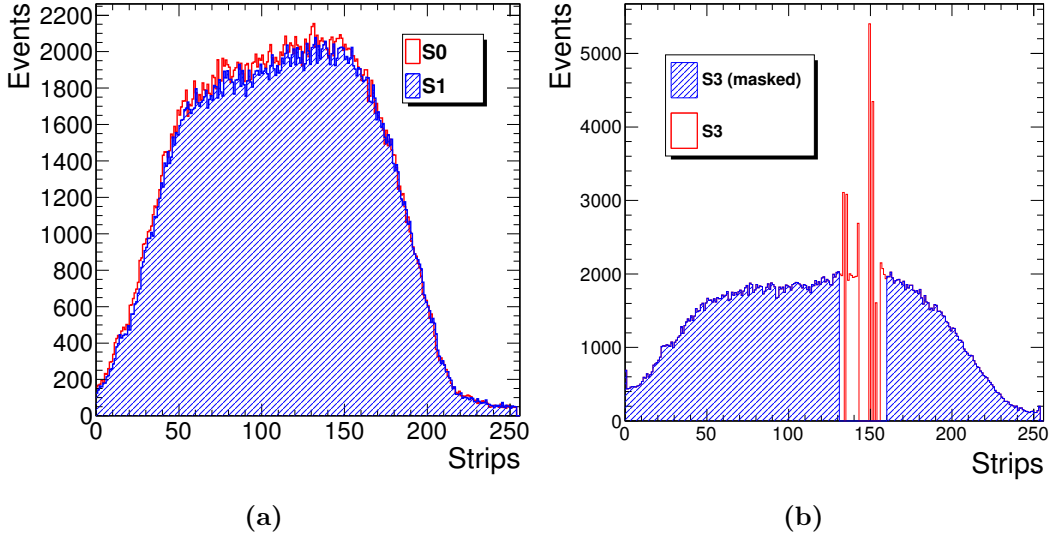


Figure 6.5 Number of hits per strip for the two DUT sensors S0 and S1 (a) and for sensor S3 of the REF before and after masking (b).

revealed that no DUT strips require masking. The beam profile distributions of the two DUT sensors, S0 and S1, and of one REF sensor, S3 (before and after the masking) are shown in Figure 6.5a and Figure 6.5b, respectively. S2 (not shown in the figures) has a similar behavior as S3, and the same masked region. These distributions show that both modules were well positioned in the beam. The hit distributions are also used to obtain the correlation between the sensors of the same module, and between the two modules. The two dimensional plots shown in Figure 6.6 indicate excellent hit correlation even before any event selection.

6.2.2 Clustering

As the CBC2 chips generate cluster and stub information, the same definitions are chosen for the off-line clustering. However, to obtain maximum precision, the cluster positions are calculated by an averaging algorithm explained below. The definitions are all in units of strips, and are only converted to length units where needed.

As the signal information provided by the CBC2 is binary, clusters are defined as a group of adjacent strips registering hits. The cluster width w is defined as the number of strips in the cluster and is expressed as

$$w = n_{\text{last}} - n_{\text{first}} + 1, \quad (6.2)$$

where n_{first} and n_{last} represent the first and the last strip in the cluster, respectively. This off-line derived quantity is important to understand the behavior of the diffusion process and the angular dependence of the charge cloud in the sensors, even though

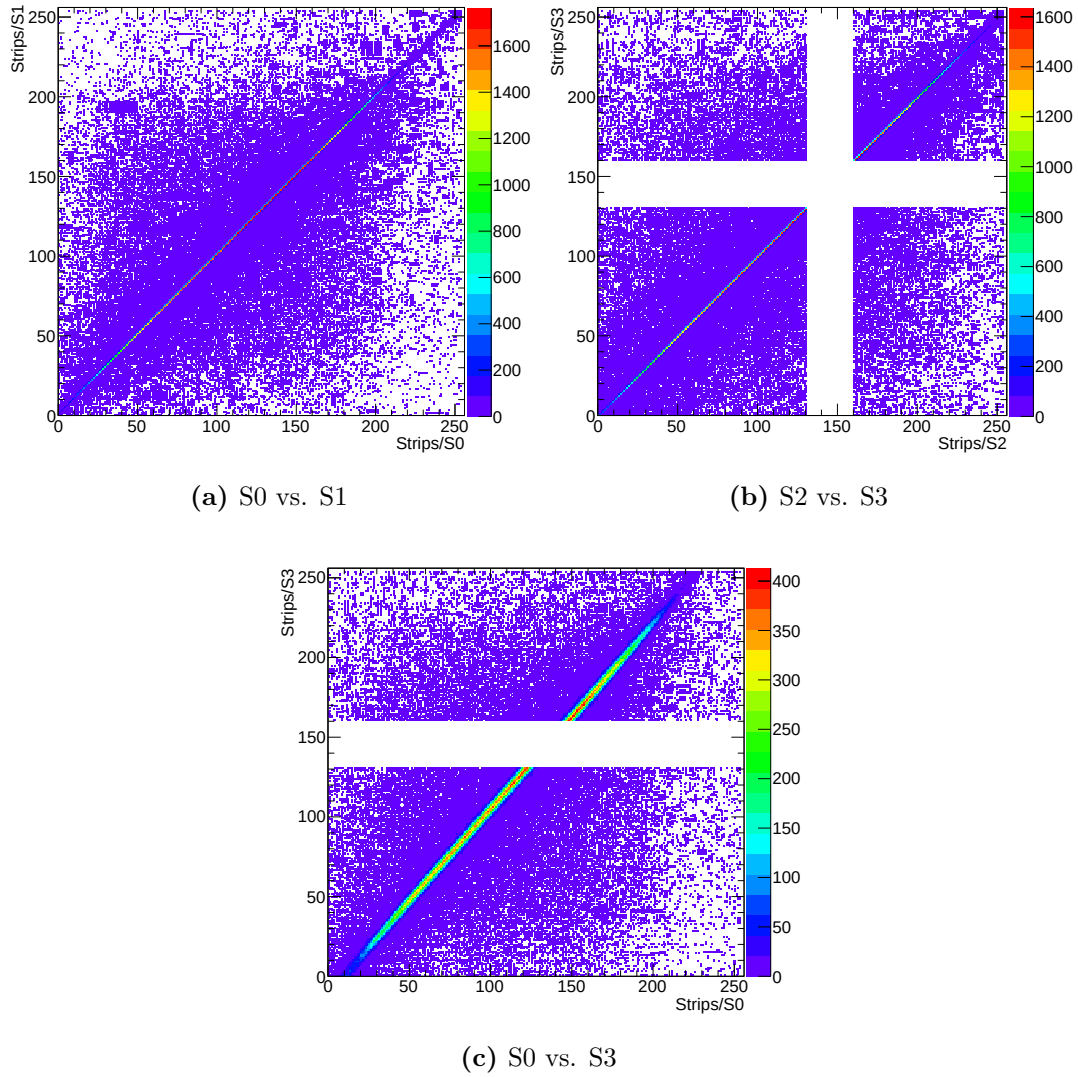


Figure 6.6 Two dimensional correlation plots as function of strip numbers. The correlation between the sensors of the DUT module (a) and of the REF module (b) are shown. Also, the correlation between the two modules (c) is shown using S0 and S3. The masked regions due to noisy strips can be seen in (b) and (c).

no charge information (pulse-height) is provided by the chip. Also, the off-line cluster width can be used for the evaluation of the CWD featured in the CBC2. The cluster position X is defined as the mean value

$$X = \frac{n_{\text{first}} + n_{\text{last}}}{2}. \quad (6.3)$$

The cluster width is given in units of full-strips, while the position has a half-strip precision. When both sensors of the module show exactly one cluster, stubs are reconstructed from the data stream and are referred to as off-line stubs. The off-line stub position A is defined as the mean cluster position per module

$$A = \frac{X_{\text{upper}} + X_{\text{lower}}}{2}, \quad (6.4)$$

where X_{upper} and X_{lower} are the cluster positions in the upper and lower sensor of the module, respectively. The off-line stub direction ΔX is defined as the difference between the cluster positions in the upper and lower sensor,

$$\Delta X = X_{\text{upper}} - X_{\text{lower}}. \quad (6.5)$$

This quantity has a similar definition as the one used by the CBC2 to generate a stub trigger signal. This means a trigger signal is generated if ΔX is within the analysis configured window size. The off-line stub direction is given in units of half-strips.

For some of the analysis steps described later, it is essential to select events where exactly one positron traversed all four sensors. Such events are selected by requiring exactly one cluster on each of the four sensors, and are therefore referred to as clean events. As shown by the cluster multiplicity plot given for S0 in Figure 6.7a, more than 80% of the events have exactly one cluster. The same quantity is given in logarithmic scale for all entries of the four sensors in Figure 6.7b.

6.2.3 Alignment of the DUT

For the off-line analysis it is important to precisely determine the alignment of the setup with respect to the beam. The angle of the DUT as stated earlier was adjusted using the rotation stage. To obtain the angular alignment, the off-line stub direction information ΔX is used. The off-line stub direction varies with the rotation of the DUT and this dependence is shown in Figure 6.8a. The mean value of ΔX at each rotation step is used to extract information about the alignment.

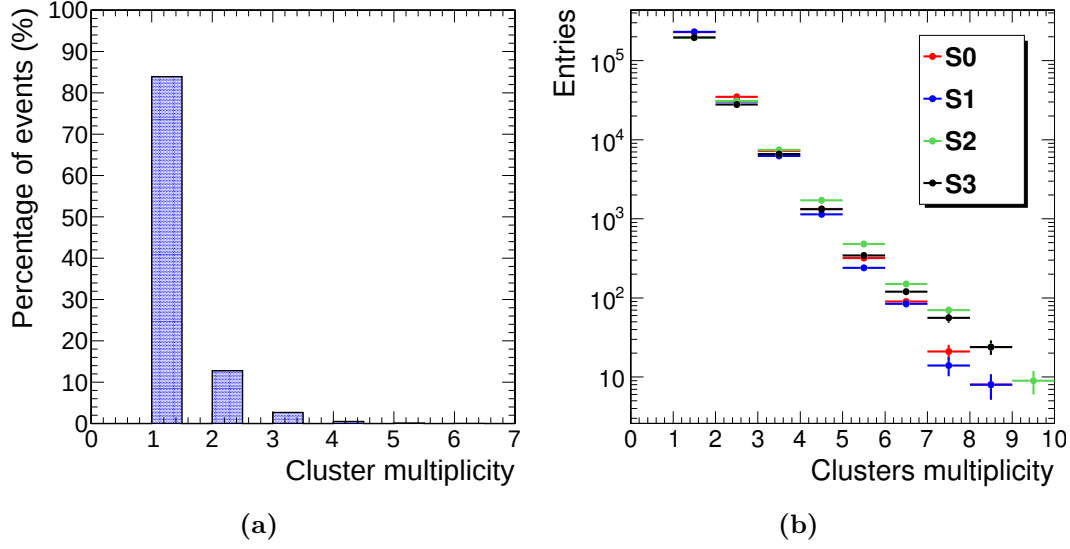


Figure 6.7 The cluster multiplicity for S0 given in percent (a), and the cluster multiplicity distribution of all sensors (b) shown in logarithmic scale.

If the rotational misalignment in the setup, and the translational misalignment between the DUT sensors are assumed to be zero, then ΔX behaves as

$$\Delta X = \frac{d}{p} \tan(\theta_{rot}), \quad (6.6)$$

where θ_{rot} is the angle as read off from the rotation stage, d the distance between the two sensors, and $p = 90 \mu\text{m}$ the strip pitch.

However, small errors can be expected in the assembly of the modules, leading to translational misalignment of the two sensors. Furthermore, errors can occur in the determination of the angle. Accounting for these uncertainties, the behavior of ΔX can be expressed as

$$\Delta X = \Delta X_0 + \frac{d}{p} \tan(\theta_{rot} + \theta_0), \quad (6.7)$$

where ΔX_0 is the translational misalignment, and θ_0 is the angular offset between the beam and the normal of the module at $\theta_{rot} = 0$.

The function in Equation 6.7 is used to fit the mean value of the ΔX distributions at different angles as shown in Figure 6.8b. The three free parameters of the fit are found to be $\Delta X_0 = -0.03 \pm 0.05$ strips, $d = 2.72 \pm 0.01$ mm and $\theta_0 = 2.1^\circ \pm 0.1^\circ$.

The obtained values reveal an excellent alignment between the two sensors, and therefore the value of ΔX_0 is set to zero. For the sensor separation the deviation from the nominal value of 2.75 mm is small, and $d = 2.72$ mm is used in the analysis. The beam incident angle α needs to be corrected by the estimated offset. A repetition of

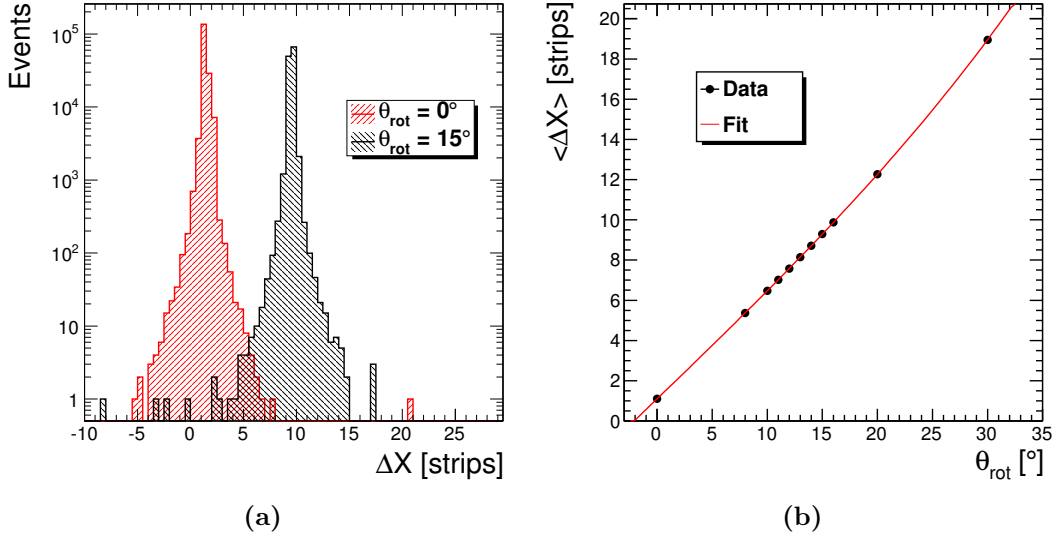


Figure 6.8 Distribution of the stub direction of the DUT in clean events for two different angles of the rotation stage (a) and mean stub direction as a function of the angle of the rotation stage including fit (b).

the fit while fixing the sensor misalignment to $\Delta X_0 = 0$ leads to a slightly smaller angle, and therefore it is set in the following to $\alpha = \theta_{rot} + 2^\circ$. The angle α is referred to as normal incidence when $\theta_{rot} = 0^\circ$.

6.3 Beam Parameters

The determination of the beam divergence is a necessity not only for obtaining the increase in beam diameter due to multiple scattering as the beam particles traverse the setup, but also to determine any possible misalignment of the two modules with respect to the beam axis. For this measurement only clean events are used. The difference D between the off-line stub position A (see Equation 6.4) on both modules is calculated, taking into account the different strip pitch sizes, and expressed as

$$D = (A_{DUT} \times p_{DUT}) - (A_{REF} \times p_{REF}). \quad (6.8)$$

The corresponding distribution of the beam divergence at normal incidence is shown in Figure 6.9, together with a Gaussian fit. The mean value of the fit represents the misalignment M between the two modules with around $598 \mu\text{m}$, while the width σ reflects the beam spread of $245 \mu\text{m}$. Knowing the distance L between the two modules, the angular measurement of the beam divergence Θ can be calculated as

$$\Theta = \tan^{-1} \left(\frac{\sigma}{L} \right) = 1.06 \text{ mrad}. \quad (6.9)$$

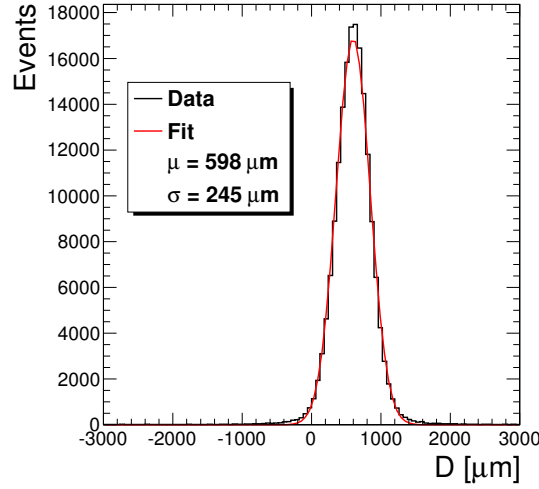


Figure 6.9 The beam divergence given as the distribution of the difference of stub positions of both modules using clean events, and normalized to the strip pitches. The Gaussian fit is shown in red. The mean of the fit reflects the misalignment between the two modules of $598\text{ }\mu\text{m}$ and the width σ is used to obtain an angular divergence of $\Theta = 1.06\text{ mrad}$.

This value is found to be in a very good agreement with the DESY-II beam specifications noted in Section 6.1.2.

The obtained beam divergence is used to extrapolate tracks from one module to the other. Thus, when correcting for the misalignment M , a cluster on one module should be found, within the beam divergence, in the region of $\pm \text{FWHM} \approx 2.35 \cdot \sigma \approx \pm 577\text{ }\mu\text{m}$ around the stub position on the other module. This is taken into account in the analysis whenever required.

6.4 Results

6.4.1 Cluster width

The cluster width is determined at different angle and threshold settings of the DUT. The cluster width distributions of one of the DUT sensors (S0) at different incident angles are shown in Figure 6.10a. For all angles a long tail of higher cluster widths is visible. This is expected and can be attributed to the delta-ray production in the silicon bulk and the radiative energy losses by positrons, which at the given energy dominates over ionization as discussed in Chapter 4. The mean value of the cluster width, shown in Figure 6.10b, for the two sensors of the DUT as a function of the incident angle, increases from around 1.1 strip at 2° to around 2.1 strips at 32° and it reveals that both sensors behave similarly.

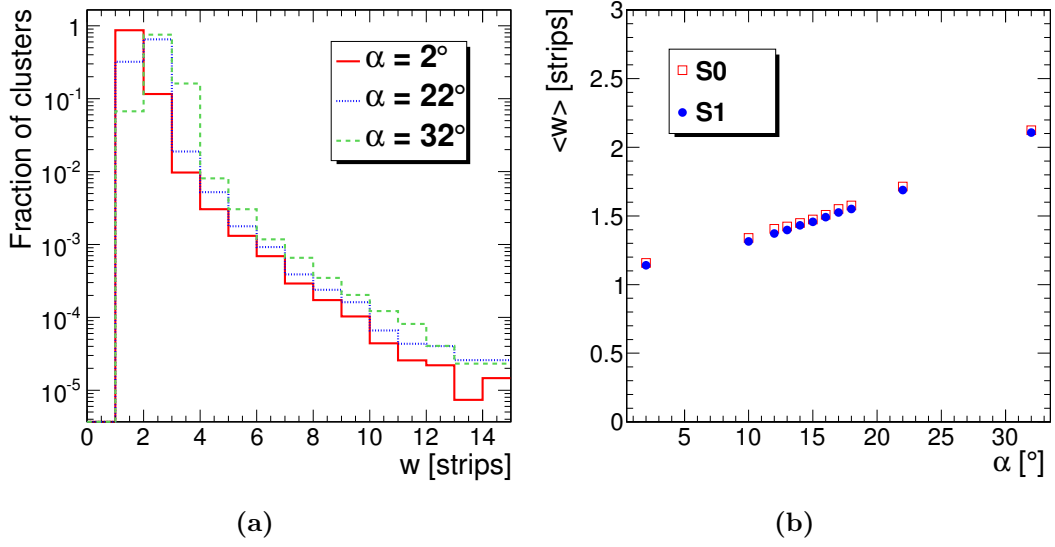


Figure 6.10 (a) Cluster width distributions for different incident angles on the DUT sensor S0. (b) Mean cluster width as a function of the beam incident angle for the sensors S0 and S1 of the DUT.

The fraction of clusters as a function of incident angle is shown in Figure 6.11a for various cluster sizes. At $\alpha = 2^\circ$, close to 87% are single-strip clusters, while about 12% are two-strip and the remaining approximately 1% are multi-strip clusters. The number of single-strip clusters decrease with incident angle and at around $\alpha = 16^\circ$ the fraction is close to the one for two-strip clusters, with 52% and 46%, respectively. For higher angles at $\alpha = 32^\circ$, the two-strip clusters dominate, reaching about 76%. A visible increase in three-strip clusters is observed between 22° and 32° , exceeding single-strip clusters. These values are within the geometrical expectations and are shown in the two dimensional plot in Figure 6.11b, with the mean cluster width superimposed.

It should be noted that wide clusters, with a width above five strips, do not show a strong dependence on the incident angle. This supports the delta-ray and low energy radiation interpretation, for which the propagation is independent of the incidence of the primary particle. In general, the choice of a value of 3 for CWD in the CBC2 for the trigger stubs proves to be reasonable for all angles, as this covers more than 99% of the clusters.

The mean cluster width at the optimized threshold of $V_{CTH} = 120$ ($6440 e^-$) is found to be slightly below 1.2 strips, with a long tail towards high strip multiplicity as can be seen in Figure 6.12a. On the other hand, for a higher threshold of $V_{CTH} = 70$ ($25440 e^-$), the clusters with sizes larger than one are strongly suppressed, and the mean cluster width is found to be around one. This behavior is expected, since for high thresholds less neighboring strips of the seed strip register a signal which is high enough. Furthermore, the cluster width was found to be uniform throughout the

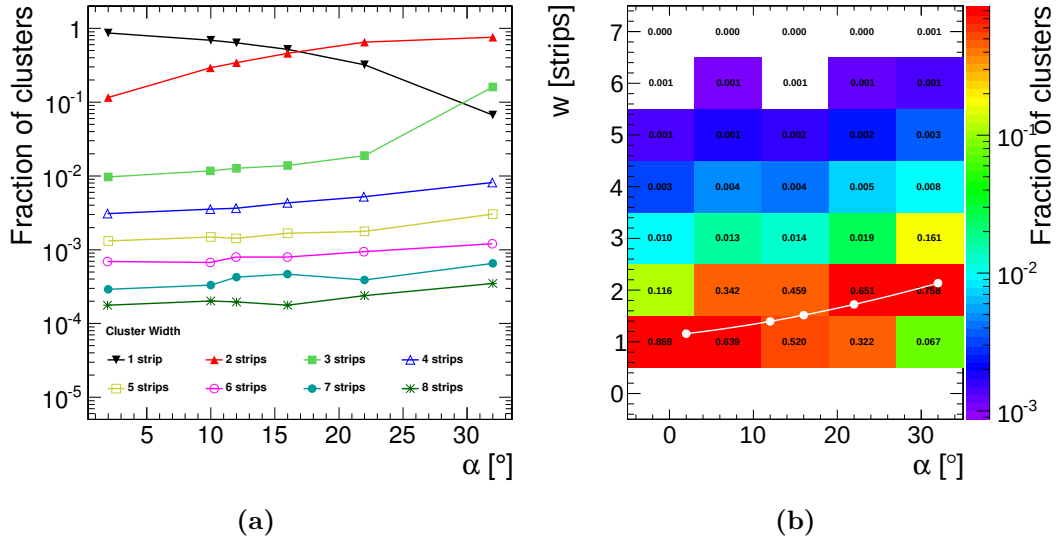


Figure 6.11 Fraction of clusters with different strip multiplicities shown as a function of incident angle for the DUT sensor S0 (a). The same information given in two dimensions (b) where the bins represent $\alpha = 2^\circ, 12^\circ, 16^\circ, 22^\circ$, and 32° , with the mean cluster width at each of these angles superimposed.

detector independent of V_{CTH} , except for some fluctuations towards the sensor edges due to statistical and edge effects. This is visible when the mean cluster width is plotted as a function of the cluster position, as shown in Figure 6.12b.

6.4.2 Cluster efficiency

In order to determine the cluster efficiency of a certain sensor, tracks are reconstructed using information from three sensors and extrapolated to the fourth sensor. In addition, edge effects are excluded by rejecting tracks pointing to a masked region or outside the active area of the sensor under study. Another general requirement is the number of TDC blocks used. The TDC phase distribution is shown in Figure 6.13a. For the efficiency studies events falling in the outer bins (5th and 12th bins) are excluded due to lower efficiency.

The efficiency is studied for the DUT, while the REF is only used for the track prediction. This selection is ensured by the following criteria for the sensors not under study:

- exactly one cluster on each sensor is required,
- cluster position X is required to be at least four strips from the edges and from the masked strips,
- for the REF, the off-line stub direction is required to be $|\Delta X| \leq 4$ strips,

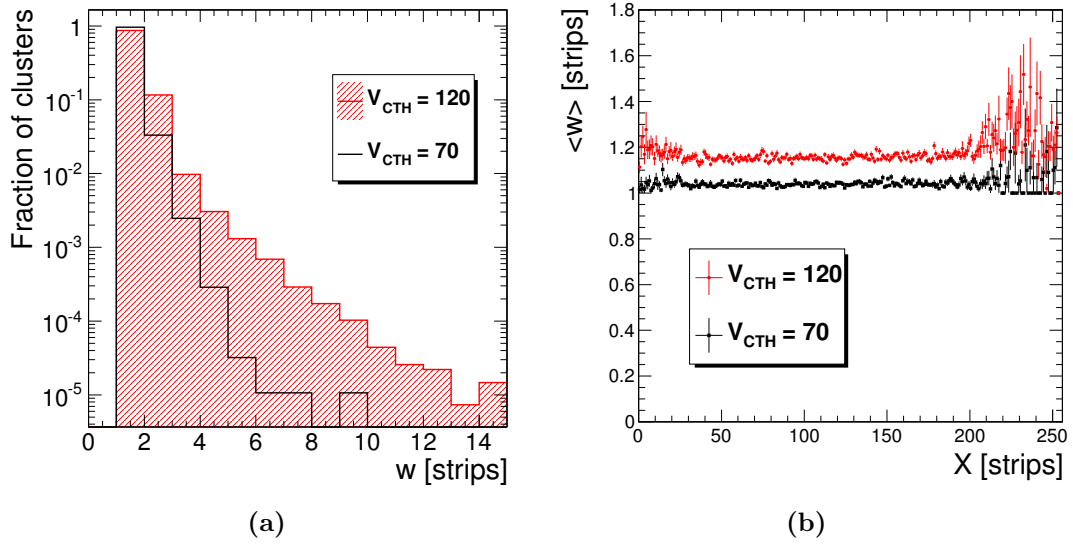


Figure 6.12 Cluster width distribution (a) and mean cluster width as function of the cluster position on the sensor (b) for two different V_{CTH} settings for the DUT sensor S0. The error bars indicate the statistical uncertainty.

- for the DUT sensor not under study, the cluster is required to be within the beam divergence with respect to the REF cluster.

The above criteria define the number of events for the denominator of the efficiency. Events enter the numerator if the DUT sensor under study has at least one cluster within a window of ± 4 strips around the cluster on the other DUT sensor.

The efficiency is studied for the different sensors, but also in different regions to search for variations between the two CBC2 chips on the module. This is achieved by using hits on one half of the sensor, and requiring again that the cluster position of the sensor not under study is at least four strips away from the sensor center to exclude edge effects. The efficiency is studied as a function of threshold by varying V_{CTH} of both CBC2 chips of the DUT in steps of 5 ADC counts in a range from 30 to 120 simultaneously. The extracted efficiency is not fully unbiased due to the cluster requirement on the DUT sensor not under study, which is also affected by the V_{CTH} setting. However, this requirement is needed for a reliable track prediction. The method gave valuable results when comparing efficiencies for different regions.

The efficiency at the optimized V_{CTH} value is determined for the DUT chips. The results are summarized in Table 6.2 and show that the efficiency is uniform across all sensors and chips and close to 100%. This is also reflected in the cluster efficiency as a function of the TDC phase shown in Figure 6.13b. At the optimal V_{CTH} setting, 100% efficiency is obtained for all TDC phase values used in this study. For higher

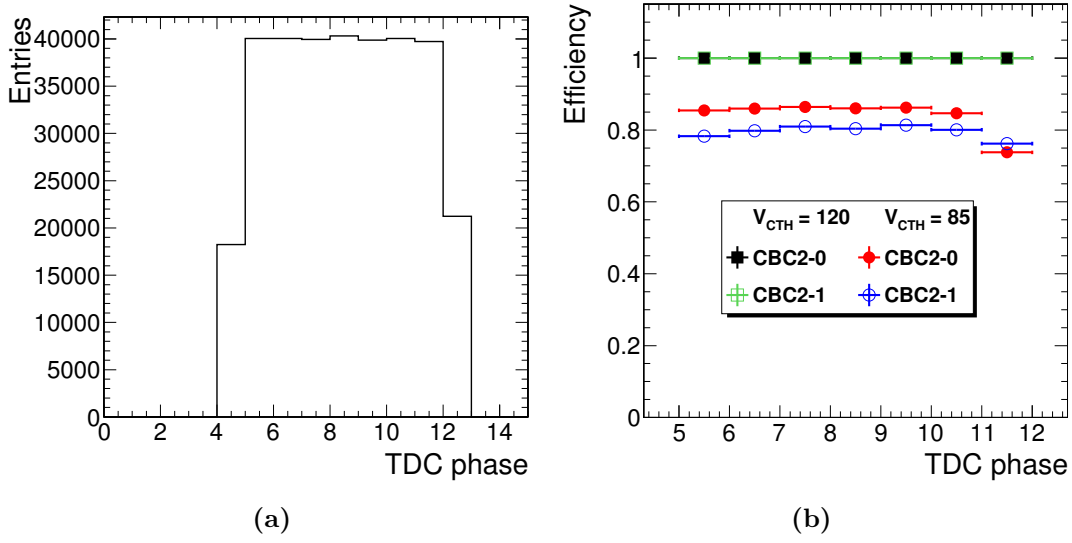


Figure 6.13 (a) TDC phase distribution as obtained for S0 at $V_{CTH} = 120$. (b) The per chip cluster efficiency at $V_{CTH} = 120$ and $V_{CTH} = 85$ as function of the TDC phase.

Sensor/Chip	CBC2-0	CBC2-1
S0	$99.97 \pm 0.01\%$	$99.97 \pm 0.01\%$
S1	$99.96 \pm 0.01\%$	$99.96 \pm 0.01\%$

Table 6.2 Efficiency of S0 and S1 per chip at a threshold of $V_{CTH} = 120$ ($6440 e^-$).

thresholds, at $V_{CTH} = 85$ ADC ($\sim 19700 e^-$), the efficiency drops by $\sim 20\%$. This study shows the different behavior of the DUT chips.

For the V_{CTH} scan of the DUT, per sensor and also per chip efficiencies are determined, and the s-curves are shown in Figure 6.14. The scan reveals that both sensors behave almost identically. However, when comparing the s-curve of the two chips, it appears that one chip has a systematically higher efficiency for lower V_{CTH} values. This is verified beforehand, by a characterization of the chips using chip-internal test pulses, estimating the electron equivalent for the V_{CTH} values, where small differences of the amplifier gains of different chips are obtained. This is expected and can be attributed to normal manufacturing variations.

Median charge

As mentioned in Chapter 4, when using a binary read-out, the pulse-height information corresponding to the collected charge is not available. Therefore, in order to estimate the full signal of the deposited charge, it is necessary to use the comparator threshold

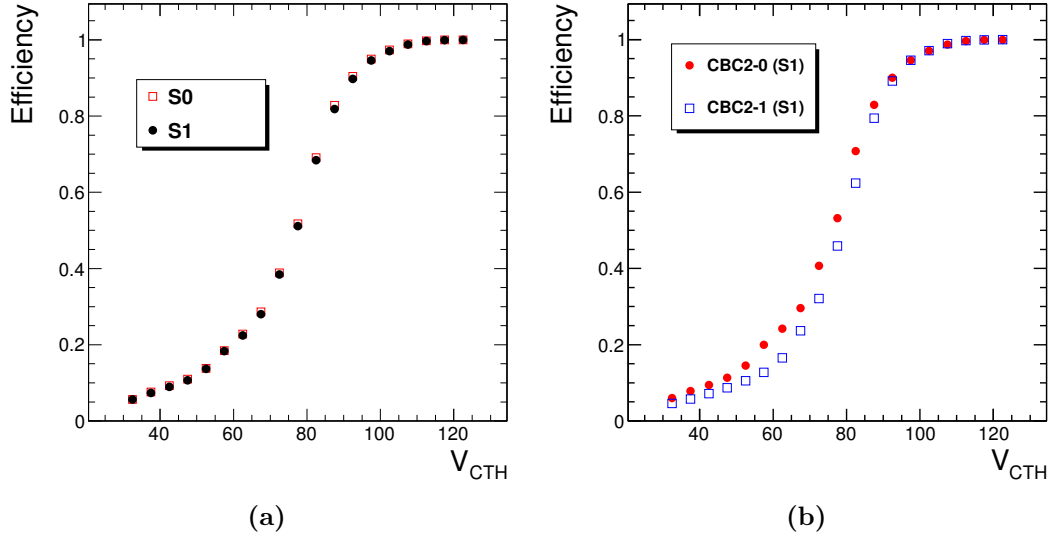


Figure 6.14 Cluster efficiency as function of V_{CTH} . (a) Per-sensor efficiency for DUT sensors S0 and S1. (b) Per-chip efficiency for the two chips (CBC2-0 and CBC2-1) connected to S1.

scan. The efficiency distribution, the s-curve, as a function of the threshold can be used to extract the integrated charge distribution, known as the median charge.

The median charge is defined as the charge measured at the threshold where 50% of the efficiency ϵ is achieved. It is obtained directly from fitting the s-curve by a complementary error function (erf) which takes into account the Landau distribution of the signal. The fit function is expressed as

$$\epsilon = \epsilon_{max} \cdot (1 - erf(x \cdot f(x))), \quad (6.10)$$

where,

$$f(x) = 1 + 0.6 \cdot \tanh(-\xi \cdot x), \quad (6.11)$$

and

$$x = \frac{V_{CTH} - Q_{med.}}{\sqrt{2} \cdot \sigma}. \quad (6.12)$$

In these functions, $Q_{med.}$, σ , ϵ_{max} , and ξ express the median charge, the width, the maximum efficiency, and the skew, respectively. Applying this fit to the s-curve of S0 and S1, $Q_{med.}$ is found to be at around $V_{CTH} = 77.5$ ADC ($\sim 22600 e^-$) with a width of $\sigma = 12.4$ ADC. The fits and the median charges of both sensors are shown in Figure 6.15.

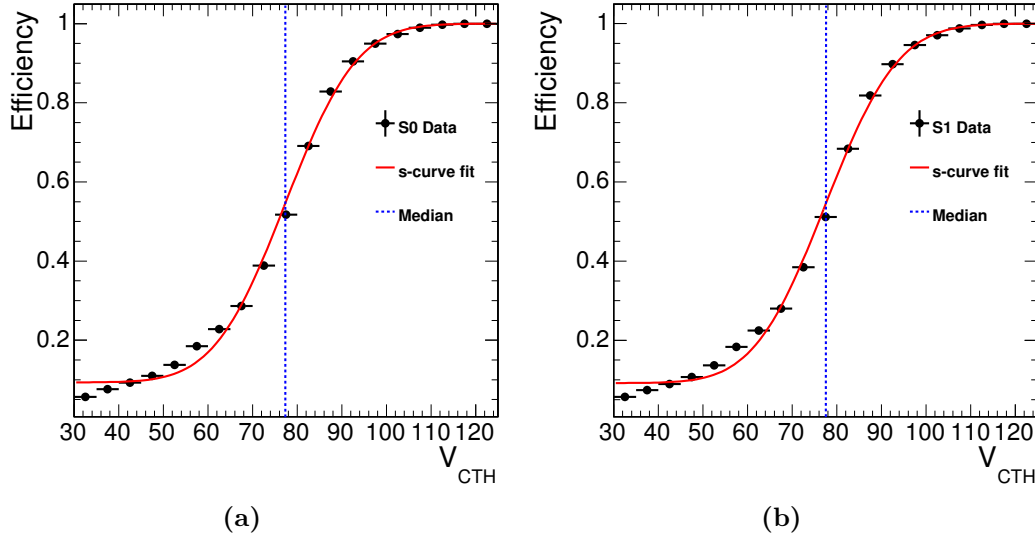


Figure 6.15 Cluster efficiency as function of V_{CTH} for DUT sensors S0 (a) and S1 (b). The obtained data points are fitted with an error function shown in red and the median charge is indicated by the blue line.

6.4.3 Stub efficiency

As stated previously, the CBC2 has a data stream dedicated to providing trigger data (stubs), corresponding to events with high- p_T tracks. Stubs are generated once the correlation logic of the CBC2 correlates clusters from both sensors of the DUT. In order to study the performance of the CBC2 correlation and its online stub efficiency, a rotation scan is performed. The aim of the rotation scan is to emulate the effect of the magnetic field on traversing charged particles. The beam incident angle α represents a particle with a certain curvature radius r in the transverse plane for a given radial position R of the module in the tracking detector following the equation $\sin(\alpha) = R/2r$.

When substituting r in Equation 5.2.1 and assuming a CMS-like magnetic field strength of $B = 3.8$ T, the relationship between the beam incident angle α and the transverse momentum p_T of the traversing particle can be then expressed as

$$p_T[\text{GeV}] \approx \frac{0.57 \cdot R[\text{m}]}{\sin(\alpha)}. \quad (6.13)$$

In order to measure the efficiency of the CBC2 correlation logic and the generation of stub triggers with as little bias as possible, no selection requirements are applied to the DUT. The following selection criteria are applied only to the REF:

- exactly one cluster on each of the two sensors (S2 and S3),
- the width of both clusters is $w \leq 3$ strips,

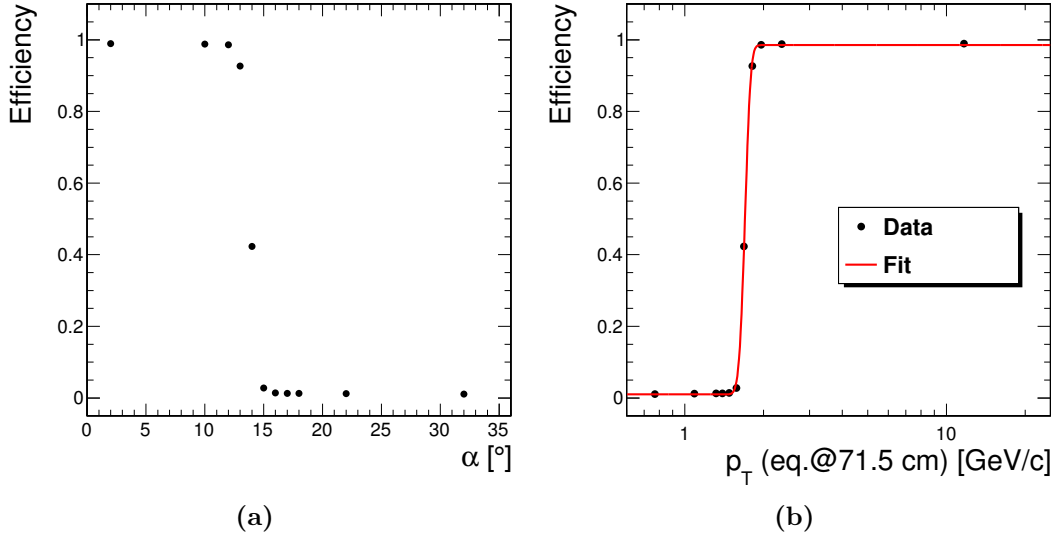


Figure 6.16 Trigger stub efficiency of the DUT as a function of beam incident angle (a) and as a function of p_T , calculated for a radial position of $R = 71.5$ cm in the Phase-II upgraded CMS outer tracking detector (b).

- cluster position X is at least 4 strips away from masked strips,
- cluster position X is at least 30 strips away from the module edges, ensuring the potential track being in the active sensor area also for higher rotation angles,
- the off-line stub direction is $|\Delta X| < 2$ strips.

This selection criteria on the REF rejects events where particles traverse the DUT and do not hit the REF module. It also reject events where an interaction might have occurred just upstream of the DUT, leading to a possible fake correlation. The efficiency is then defined as the number of stub trigger events from the DUT divided by the total number of selected events.

The beam incident angle is related to the stub direction, the strip pitch and the sensor separation as expressed in Equation 6.7. The CBC2 on the DUT is configured to generate stub triggers using a window size of ± 7 strips. For the known $p = 90 \mu\text{m}$ and the estimated $d = 2.72 \text{ mm}$, the efficiency should be constant and high for small angles, and is expected to start dropping at $\Delta X = 7$ strips corresponding to $\alpha \approx 13^\circ$, and to reach values around 0 for $\Delta X = 8$ strips corresponding to $\alpha \approx 14.8^\circ$. The efficiency as a function of α is shown in Figure 6.16a, and is in good agreement with the geometrical expectations. The efficiency for $\alpha \geq 15^\circ$ is close to, but not exactly zero, which could be related to multiple scattering and noise effects. For $\alpha \leq 12^\circ$ the CBC2 stub-finding logic is able to trigger on positrons with about 99% efficiency.

Figure 6.16b shows the expected module efficiency as a function of p_T if this module as to be placed at a radius $R = 71.5$ cm in the CMS tracking detector, using Equation 6.13.

As this prototype had $d = 2.72$ mm, the R is chosen to emulate the configuration of a module at a radial position of $R_{\text{design}} = 108$ cm with a sensor spacing of $d_{\text{design}} = 1.8$ mm, in the most recent layout of the CMS outer tracking detector.

The p_T threshold and resolution can be extracted by fitting the efficiency curve. An error function is used to perform the fit with four parameters: the mean value $p_T^{\text{trig.}}$ corresponding to the p_T threshold, the width $\sigma^{\text{trig.}}$ corresponding to the resolution of the threshold value, and the asymptotic minimum and maximum efficiencies $\epsilon_{\text{min.}}$ and $\epsilon_{\text{max.}}$, respectively. The fitted efficiencies yield an $\epsilon_{\text{min.}}$ of about 1% and $\epsilon_{\text{max.}}$ of about 99%. The module would be able to reject hits from particles with p_T below 1.70 GeV with a resolution $\sigma^{\text{trig.}}$ of 0.07 GeV. This would allow the CBC2 to suppress the large low- p_T minimum bias background events present in CMS and only pass hits from high transverse momentum candidates associated with hard scattering events for further processing.

6.5 Summary and Outlook

In summary, two fully functional mini-2S p_T -module prototypes equipped with CBC2 chips for read-out have been operated for the first time using positron test beam at DESY. This test aimed to study the performance of the p_T discrimination logic of the CBC2 chip and its capability to trigger on high- p_T tracks. Threshold and angular scans are performed to serve this goal.

The results have shown that the performance is well within expectations. The cluster width study revealed a good agreement with geometrical predictions. More than 99% of clusters are found to be within the CWD range, and the fraction of very broad clusters is below 1% even at high incident angles. At optimum threshold, the cluster efficiency is found to be uniform across the tested sensors and above 99%.

The trigger logic of such modules has been tested for the first time by emulating the p_T dependent track bending in the magnetic field via the rotation of the module. The trigger efficiency shows the desired behavior. The efficiency of identifying high- p_T tracks is around 99%. With the setup used, the separation from low- p_T tracks is excellent. Particles with a transverse momentum below 1.70 GeV can be rejected with a resolution of about 0.07 GeV.

These results provide a proof of concept of the functionality and the capability of the CBC2 chip. Following, the CBC2 has been put in several test beams with irradiated mini-2S modules and with full 2S module. Analysis of the measurements performed during these tests are ongoing.

The CBC3

Although the CBC2 has proven, by the studies presented, to perform well within the expectations, developments towards a new version, the CBC3, are ongoing. The CBC3 will feature changes and improvements concerning the front-end, the logic block, and the read-out control, the key elements of these changes and improvements are mentioned below, and more details can be found in [85].

Since the sensors to be used in the Phase-II outer tracking detector are of n-in-p type, the polarity in the front-end will be for electron read-out mode only, compared to the double polarity modes featured in the CBC2. A suppression circuit will be implemented in the hit detection logic, which will force the output of the logic to return to zero if the pulse length exceeds a pre-programmed number of clock cycles. In the current configuration of the CBC2, the hit detection logic is always seeded with the same sensor and the search for the correlation is performed on the second sensor. In the CBC3, a swap between the seed layer and the correlation layer will be possible.

In the stub finding logic of the CBC3, the CWD value is increased to a maximum of four adjacent strips instead of the maximum of three featured in the CBC2. The coincidence window size and the offset correction will be kept at the same values as in the CBC2, however a resolution of a half strip will be used.

Another important feature anticipated in the CBC3 is the stub bending information, which is defined as the offset between the cluster centroids on the upper and lower sensors of the module. The bending information will also have a half strip resolution and will be read-out synchronously with the stub address information. This feature is useful for the track finding since it provides information about the charge of the corresponding particle and gives an additional p_T estimation.

The pipeline memory cells will also be modified to improve their radiation hardness, compared to those featured in the CBC2. Moreover, the depth of the pipeline memory will be doubled to 512 bunch crossings, which corresponds to a trigger latency of about 12.8 μs . The buffer depth of 32 L1-triggered events will be maintained, however, the read-out rate will be increased to match the requirement of 320 Mb/s.

Further test beam measurements will be performed to verify the CBC3 design and performance, and to potentially allow an independent efficiency and resolution measurement using external tracks from a beam telescope.

Chapter 7

Introduction to Top Quark Physics

The top quark is by far the heaviest particle among all known elementary particles. Predicted in 1973 by Makoto Kobayashi and Toshihide Maskawa [86], the spin 1/2 particle was discovered in 1995 [87, 88] by the CDF [57] and DØ [89] experiments at the Fermilab¹ proton-antiproton collider, the Tevatron [90]. The top quark is the $I_3 = 1/2$ weak-isospin partner of the bottom quark (b quark) with electric charge $Q_t = 2/3 e$. Due to its large mass of $m_t = 173.34 \pm 0.27$ (stat.) ± 0.71 (syst.) GeV [91], the top quark manifests itself as an excellent probe for the SM in many different aspects.

With a mass almost 40 times larger than the b quark mass, and more than twice the W boson mass, the SM predicts a two-body decay of the top quark into W boson and a b quark ($t \rightarrow Wb$) with a branching fraction of almost 100%. This implies that in the SM, the CKM matrix element $|V_{tb}|$ is close to unity and thus can be accurately measured through studies of the top quark production. Moreover, due to its mass, it has a very short lifetime of $\tau_t \approx 5 \times 10^{-25} s$ such that it decays before it can form a hadronic bound state. This offers a unique opportunity to study bare quark properties. Furthermore, the production of the top quark at hadron colliders occurs dominantly in pairs ($t\bar{t}$) through the strong interaction, and as single top quark through the weak interaction. Therefore allowing to test the SM on the strong and the electroweak scales.

In this chapter the top quark production modes and its decays are discussed, and an overview on physics beyond the SM in the top quark sector is given.

¹Fermi National Accelerator Laboratory

7.1 Top Quark Production

At hadron colliders, the $t\bar{t}$ production mechanism via high energy interactions is mediated by the strong interaction, and since the top quark mass is much larger than the QCD scale, this mechanism can be described by the QCD-improved parton model [92]. Accordingly, the inclusive cross section $\sigma_{pp \rightarrow t\bar{t}}$ can be expressed using the factorization theorem, which represents a convolution of parton distribution functions PDFs $f_i(x_i, \mu_f^2)$ and the partonic cross section $\hat{\sigma}_{ij}$.

The factorization theorem separates the hadron interactions into short and long distance cross sections. This separation is defined by the factorization scale μ_f^2 . The short distance cross section describes the hard scattering via the partonic cross section for the participating partons i and j . It only involves high momentum transfer and can be calculated using perturbative QCD. The long distance cross section is described by the PDFs which resemble the probability to observe a parton i with a longitudinal momentum fraction x_i at the μ_f^2 scale. These PDFs cannot be calculated by perturbative QCD but can be extracted from deep-inelastic scattering experimental data [93, 94].

The inclusive $t\bar{t}$ production cross section in a pp collision at $\sqrt{s}$ is given by

$$\sigma_{pp \rightarrow t\bar{t}}(s, m_t) = \sum_{i,j=q,\bar{q},g} \int dx_i dx_j f_i(x_i, \mu_f^2) f_j(x_j, \mu_f^2) \cdot \hat{\sigma}_{ij \rightarrow t\bar{t}}(\hat{s}, m_t, \mu_f, \mu_r, \alpha_s), \quad (7.1)$$

where the sum takes into account all quark and gluon contributions with their momentum fractions x_i relative to the proton momenta which are described by the PDFs. The effective center-of-mass energy squared $\hat{s}$ is defined as $x_i x_j s$. The renormalization scale μ_r^2 is introduced to remove divergences which occur at higher order calculations [95].

At hadron colliders top quark pairs are at leading order (LO) mainly produced via gluon-gluon fusion $gg \rightarrow t\bar{t}$ or quark-antiquark annihilation $q\bar{q} \rightarrow t\bar{t}$. The ratio of these processes depends on the nature of the collisions and the center-of-mass energy. At the LHC, $gg \rightarrow t\bar{t}$ is the dominant process with a ratio of about 90%. The LO Feynman diagrams of these processes are shown in Figure 7.1. Next-to-leading order (NLO) processes such as quark-gluon scattering or gluon-gluon fusion with additional gluon radiation or virtual corrections also contribute to the $t\bar{t}$ production.

The production of the top quark at hadron colliders is not limited to the pair production mode, but it can also be produced singly via the electroweak interaction. Three possible processes at LO are associated with the production of single top quarks: via the W boson-gluon fusion process (dominant), which involves a virtual t -channel W boson; via the exchange of a W boson in the s channel; and via the production in association

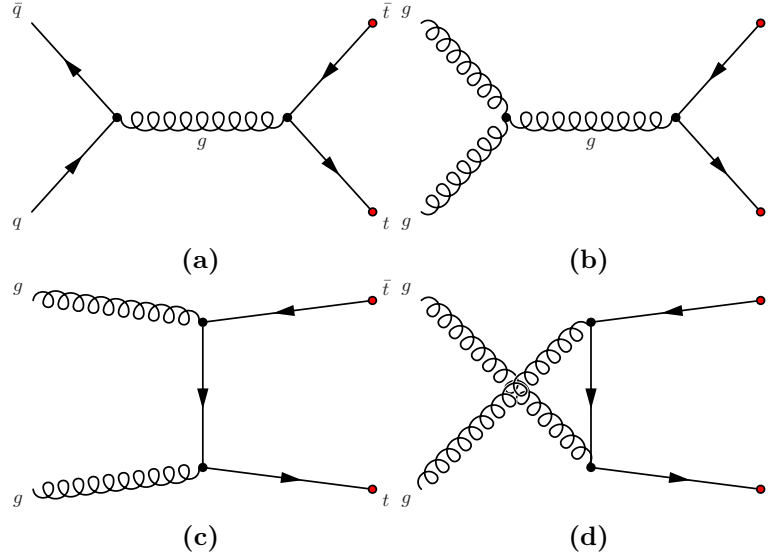


Figure 7.1 Leading order Feynman diagrams of the $t\bar{t}$ production. Possible processes at the LHC are (a) quark-antiquark annihilation and gluon fusion processes in the: s channel (b), t channel (c), and u channel (d). From [96].

with a W boson (the tW process). The LO Feynman diagrams of these processes are shown in Figure 7.2.

7.2 Top Quark Decay

As stated in the introduction of this chapter, the top quark decays dominantly into Wb . In the SM the decay of the top quark into Ws and Wd is also allowed, but suppressed with respect to Wb by the squared CKM matrix elements $|V_{ts}|$ and $|V_{td}|$, which are orders of magnitude smaller than $|V_{tb}|$ [4].

The top quark final state is governed by the decay of the W boson. The W boson decays 2/3 of the time into quark-antiquark pair $q\bar{q}$ in three different color variants, and 1/3 of the time into pairs of leptons $l\nu_l$ assuming lepton universality. Therefore, each W boson has the possibility to decay into one of nine different fermion pairs.

The $t\bar{t}$ system has three final state decay channels: (i) the fully hadronic channel with a ratio of 4/9, where both W bosons decay into a quark-antiquark pair; (ii) the semi-leptonic channel with a ratio of 4/9, where one W boson decays into a lepton pair and the second decays into a quark-antiquark pair, and (iii) the di-leptonic channel with a ratio of 1/9, where both W bosons decay into lepton pairs. The three channels are shown below with the exact contribution[97]:

$$(i) \quad t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow q\bar{q}'bq''\bar{q}'''\bar{b}, \quad (46.2\%)$$

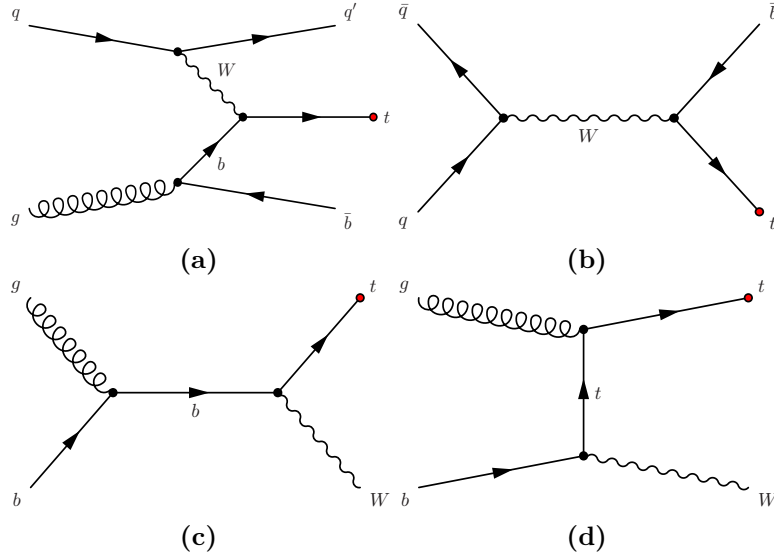


Figure 7.2 The leading order Feynman diagrams of the single top quark production. Possible processes at the LHC are the t channel (a), the s channel (b), and the tW channel (c, d). From [96].

$$(ii) \quad t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow q\bar{q}'bl^-\bar{\nu}_l\bar{b} + l^+\nu_lbq''\bar{q}'''\bar{b}, \quad (43.5\%)$$

$$(iii) \quad t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow l^+\nu_lb l'^-\bar{\nu}_{l'}\bar{b}. \quad (10.3\%)$$

For the $t\bar{t}$ production cross section measurement presented in this thesis, the di-lepton final states are considered. While l refers to e , μ , and τ , in the analysis only the decays into e and μ are considered. The di-leptonic channel has the lowest branching ratio, however, it suffers the least from background contamination.

7.3 Top Quark in the SM and Beyond

Various theory predictions and parameters can be probed by accurately measuring the top quark properties. For instance, the precision of the CKM matrix elements, the QCD strong coupling constant α_s , and the PDFs can be improved by studying the $t\bar{t}$ and single top quark inclusive cross sections.

Furthermore, the top quark plays a crucial role in the Higgs boson studies. Since the top quark mass scale is close to the electroweak symmetry breaking scale (the vacuum expectation value $v = 246$ GeV), the Yukawa coupling y_t between the Higgs boson and the top quark is close to unity and is given as

$$y_t = \frac{\sqrt{2}m_t}{v} \approx 1. \quad (7.2)$$

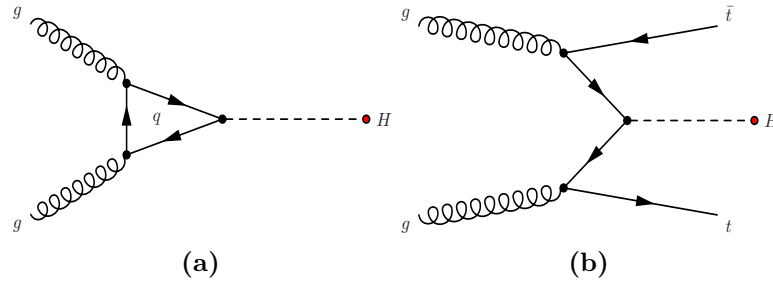


Figure 7.3 Feynman diagrams of Higgs boson production. (a) Via a quark loop which dominantly is a top quark, and (b) in association with $t\bar{t}$ pairs. From [96].

Due to this strong coupling, one of the main Higgs boson production processes at the LHC, the gluon-gluon fusion process, is dominantly realized via top quark loops as shown in Figure 7.3a. In addition, the Higgs boson production can also occur in association with a $t\bar{t}$ pair, in the $t\bar{t}H$ process, as shown in Figure 7.3b.

Different models extending the SM also rely heavily on the measurements of the top quark, namely on the measurement of the $t\bar{t}$ production cross section. For example, many scenarios predict heavy electrically neutral bosons with masses up to a few TeV, strongly coupling to $t\bar{t}$ pairs. Models such as the Two-Higgs-Doublet Model (2HDM) [98] predict pseudo-scalars (e.g. a heavy neutral Higgs boson A , $m_A > m_{Higgs}^{SM}$ in 2HDM) which can decay into $t\bar{t}$. Other models with a spin-1 vector boson (e.g. the hypothetical massive Z' boson), or even a spin-2 vector boson (e.g. graviton) could also involve $t\bar{t}$. Any of the above models could be a possible candidate for new sources of top quark production, and would thus appear as an enhancement of the top quark cross section.

Chapter 8

Simulation of Collision Events

High energy physics analyses rely heavily on the comparison between experimentally obtained data and simulation. At the LHC the simulation of proton-proton collisions must predict and describe precisely the interaction processes including the initial states of the colliding particles and the final states, in addition to the detector response for these interactions. Therefore, simulation is a necessity in every aspect of the analysis chain, from calibrating the detector and studying its performance, to predicting and modeling the expected physics signals and their backgrounds. The Monte Carlo (MC) technique [99], a fundamental method based on numerical integration using random number generators, is widely used for this purpose.

The simulation chain, shown in Figure 8.1, starts with the matrix element calculation of the hard scattering processes of interest and their final states. A relevant example of such processes is the gluon-gluon fusion associated with $t\bar{t}$ decaying into four leptons and two b quarks ($gg \rightarrow t\bar{t} \rightarrow \bar{l}\nu\bar{b} l\bar{\nu}b$). The following step, is the generation of the parton showers, which occur mainly due to QCD radiation emitted by the accelerated final state partons. At a certain energy scale, parton showers lead to the hadronization process where hadrons are generated. On top of the hard scattering and the parton showers, proton beam remnant interactions, known as the underlying events, take place and thus are also included in the simulation. The simulation of the detector response to the collisions products is the final step of the simulation chain.

In this chapter the event generation is introduced. The matrix element generation, parton showering, hadronization, and the underlying events simulation in addition to the detector response simulation will be described. Finally, a summary of the simulated samples used in the measurement of the $t\bar{t}$ production cross section is given.

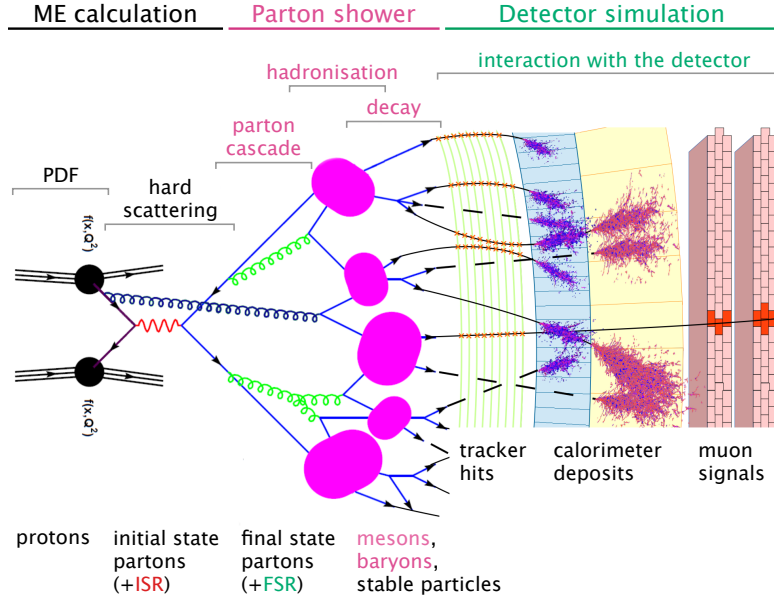


Figure 8.1 Sketch showing the simulation chain starting with the matrix element calculations based on the PDFs input, followed by the parton showering, and the detector simulations. From [96].

8.1 Event Generation

The generation of collision events is performed by separating the phase space for the partons into two disjoint regions. The first region accounts for the hard scattering where the calculation of the matrix element of the considered processes is performed. In the second region a complementary approximation based on the parton showers modeling takes place. This approach is guided by the QCD factorization theorem described in Chapter 7 and it depends on the energy scale.

Many simulation programs are exploited for the collision event generation based on the MC technique. For instance, PYTHIA8 [100] and Herwig++ [101] are both well established multi-purpose event generators, which are capable of simulating SM processes as well as processes based on theories beyond the SM. Both generators feature a wide range of hard scattering processes for the LO matrix element calculation, however they have different approaches for parton shower and hadronization treatment.

8.1.1 Matrix element generation

The calculation of the matrix elements of the hard scattering processes is performed at fixed order of α_s where the final states of the process of interest are produced from the initial partons. It applies an integration over the PDF distributions, which

predetermine the initial state of the collision, and from which the momenta of the incoming partons are randomly chosen.

Due to the limitation of the computational speed and the complexity of the calculation, additionally produced partons from initial and final state radiation (ISR and FSR) are usually not addressed in the matrix element calculation, but they are accounted for in the next stage which is the parton shower generation.

8.1.2 Parton shower generation

The hard scattering processes involve large momentum transfer resulting in the acceleration of partons. Just as accelerated electric charges emit QED radiation (photons), the accelerated colored partons emit QCD radiation in the form of gluons. Radiation due to the acceleration is not limited to a single emission, and therefore many gluons are radiated. Unlike the neutral photons, the emitted gluons themselves carry color charge and they further contribute by additional radiation leading to parton showers. These showers are predicted by QCD and they provide higher order corrections to the hard processes, however they are not precisely calculated. An approximation scheme is used instead and is implemented in parton shower programs. This scheme takes into account the dominant contributions at each order, which are mainly associated with collinear parton splitting or soft (low-energy) gluon emission.

The probability of emissions resulting from the leading contributions can be obtained using the following expression

$$dP_a(z, \mu^2) = \frac{d\mu^2}{\mu^2} \frac{\alpha_s}{2\pi} P_{a \rightarrow bc}(z) dz, \quad (8.1)$$

where parton a splits into partons b and c with a virtuality¹ scale μ^2 and with parton b carrying a fraction z of the momentum of parton a . Emissions with very soft or very collinear partons, associated with $\mu \rightarrow 0$, are not experimentally detectable, thus an effective cut-off of the order of a few hundreds of MeV is introduced to screen the tendency of μ toward 0. The upper limit on the initial virtuality is set by the momentum transfer scale Q of the hard process $\mu^2 < Q^2$, and thus the shower evolves with Q^2 of the parent parton and terminates once the virtuality has fallen to the cut-off or the hadronization scale where $\mu^2 \approx Q_{min}^2 \sim 1 \text{ GeV}^2$.

Parton shower approximation does not only take into account the collinear-enhanced real parton emissions at each order in perturbation theory, but it also accounts for virtual (quantum loop) effects of the same order. Such effects are included in the

¹Each parton is characterized by virtuality scale μ^2 , in terms of energy scale which gives an approximate sense of time-ordering to the shower evolution.

probability of not splitting during evolution which is described by the Sudakov form factor [102, 103].

Different schemes accounting for the relation between μ^2 and Q^2 are used in different showering algorithms. PYTHIA8 for example chooses $Q^2 = \mu^2 = p_T^2$ and orders emissions according to the invariant mass of the parent parton. While on the other hand Herwig++ chooses $Q^2 = \mu^2/(z(1-z))$ equivalent to $2E_a(1 - \cos \theta)$, and orders emissions according to energy of the parent parton E_a and the splitting angle θ between the parent and the emitted parton. Both choices are equivalent at the level of double leading logarithms (NNLL), however, they result in different estimations.

8.1.3 Hadronization models

As the parton shower evolution becomes closer to the cut-off energies and the radiated partons travel further from the interaction point, the event generation enters the non-perturbative regime where $\alpha_s \approx 1$. The rise of α_s at such low energy makes the separation among the partons impossible, and leads to the formation of the observed color-neutral final state hadrons. Hadronization of the partons is dominated by color confinement [104] and is independent of the hard scattering process.

String hadronization model

The string model (also known as the Lund fragmentation model) [105, 106] is a phenomenological model used in PYTHIA8 for hadronization based on lattice QCD [107] simulations. After the parton shower, the potential energy of color sources, such as heavy quark-antiquark pairs, increases linearly with their separation. This leads to the occurrence of a gluonic self-attraction force, compressed in a tube-like (string) configuration. Usually the string endpoints are quarks, but gluons can also contribute. Further increase in the distance between the partons causes the potential energy of the string to increase until it is large enough to produce a new quark-antiquark pair, breaking the string into two fragments. Several iterations depending on the energy are performed until individual string segments are associated to hadrons.

Cluster hadronization model

The cluster hadronization model [108] is adopted by Herwig++. It is also known as the pre-confinement model, and is based on the color pre-confinement property of QCD [109]. At evolution scales much lower than the hard process scale $\mu \ll Q$, parton showers are clustered in color-neutral groups. The clusters invariant mass distribution is independent of the nature and scale of the hard process, but depends on μ and the fundamental QCD scale Λ_{QCD} . At the hadronization scale this model forces the

gluons to split into quark-antiquark pairs which form color-neutral clusters with their corresponding color partners. These clusters then decay into the observed final state hadrons via a quasi-two-body decay.

8.1.4 Matching matrix elements and parton showers

When both matrix elements and parton shower event generation are performed using the same generator (e.g. PYTHIA8) no complications concerning event matching occur. On the contrary, when different generators are used, matching of the two can lead to double counting of events due to the same emissions being produced simultaneously by both generators, i.e. events which are generated as LO+shower can be also of the NLO type. Many approaches are implemented in order to handle the event matching with a smooth transition while avoiding the event double counting.

A matching scheme is used in POWHEG (POsitive Weight Hardest Emission Generator) [110]. The POWHEG approach allows generation of hard processes with next to leading order accuracy independent from the shower simulation algorithm. Its output can be interfaced with all modern showering programs that support the *Les Houches Interface* [111] for User Generated Processes (e.g. PYTHIA8, Herwig++, etc.) which perform all subsequent showers and hadronization. Here, the double-counting of events is avoided by reweighing the parton shower model according to the matrix element terms such that it only acts in the phase space defined by the leading order expansion term.

Another approach to solve the problem of double counting is featured in the unified framework, the so-called MadGraph5_aMC@NLO [112], for LO and NLO event generation. The basic idea of this approach is to subtract the approximated cross section, which is implemented in the shower simulation, from the exact NLO cross section [113], and therefore removing the unwanted parton-shower contributions.

8.1.5 Underlying event

In hadron-hadron collisions, besides the interaction between the two partons responsible for the hard scattering, there may occur an additional soft or semi-hard interaction which cannot be neglected. The occurrence of such event is due to the interaction between the beam remnant partons. For instance, in a proton beam a parton, say an u quark in the initial state contributing to the hard scattering, would leave behind an ud di-quark beam remnant with color charge, and therefore is color-connected to the hard scattering and forms part of the same fragmenting system. Contributions to the final energy may also come from additional gluon radiation from either the initial-state

or final state partons. These contributions, which do not depend on the two partons responsible for the hard scattering, define the so-called underlying event.

To account for the underlying event when a hard scattering is present, an event generator must model the impact parameter structure of hadron-hadron collisions. When the impact parameter is large, i.e. the collision is peripheral, it indicates a low probability of a hard parton-parton interaction and few multiple interactions. On the other hand, a small impact parameter indicates a central collision, with a higher probability of a hard interaction, and several multiple interactions. Thus, the presence of a hard scattering is correlated with more multiple interactions and a higher level of underlying event activity. At the LHC, proton-proton differential data measured in minimum-bias and hard QCD processes are used to tune the generator parameters (e.g. in PYTHIA8 and Herwig++) to be used in modeling the underlying event.

8.2 Detector Simulation

In addition to the event generators which help in understanding the physics of interactions between different particles, detector simulation is also essential for providing an understanding of the detector response to these interactions. A special software package, GEANT4 (GEometry ANd Tracking) [114], is utilized for that purpose. It is fully integrated with the CMS software framework and it includes the full detector geometry and performance information. This package allows the modeling of particle interactions with the different detector materials as well as the effect of the CMS magnetic field and the detector's electronic response. The MC generated events are passed to GEANT4 which includes all the above mentioned effects in addition to CMS trigger emulation. Depending on conditions, as luminosity, bunch spacings, etc., parameters can be tuned in order to optimize the agreement between collision data and simulation.

8.3 Simulated Samples

In this section the signal and background samples used in the measurement of the inclusive $t\bar{t}$ production cross section are summarized. The previously described MC techniques and tools are utilized in the production of these sample.

The signal sample (in the following referred to as nominal) of $t\bar{t}$ decaying to W^+b and $W^-\bar{b}$ where both W^+ and W^- decay to an electron or a muon and a neutrino is produced using the next-to-leading order POWHEG(v2). The PS, hadronization, and the underlying events are generated with PYTHIA8 (v8.205) [115] with the CUETP8M1 tune [116] for the underlying events. The top quark mass m_t used in this sample is 172.5 GeV and the Q^2 scale is defined as $m_t^2 + p_{T,t}^2$, where $p_{T,t}$ is the top quark

Sample	Matrix element + Parton showering
$t\bar{t}$ signal/background	POWHEG+ PYTHIA8
tW (single top)	POWHEG+ PYTHIA8
WW, ZZ, ZW (di-bosons)	PYTHIA8 + PYTHIA8
W +jets	MG5_aMC@NLO + PYTHIA8
Z +jets (Drell-Yan)	MG5_aMC@NLO + PYTHIA8
$t\bar{t}$ + W/Z	MG5_aMC@NLO + PYTHIA8

Table 8.1 Summary of the simulated background samples and their corresponding matrix element and parton shower generators.

transverse momentum. The NNPDF3.0 NLO PDF set [117] is used in the simulation calculations.

In addition to the nominal sample, alternative $t\bar{t}$ simulation samples are produced using different generators and with varied parameters. These samples are generated to determine the uncertainty in the measurement owing to the theoretical assumptions on the modelling of the $t\bar{t}$ events, as well as for comparisons with the measured distributions. This will be discussed further in Chapter 10.

The $t\bar{t}$ production events in the di-lepton channel can be mimicked by many different background processes. These backgrounds are simulated with MG5_aMC@NLO, POWHEG, or PYTHIA8, depending on the process. The MG5_aMC@NLO generator in its v5-2.2.2 [112] version is used to simulate Drell–Yan events (referred to as Z +jets, in the following), and W boson production with additional jets (W +jets, in the following). Single top quark events representing the dominant, non- $t\bar{t}$ background (tW channel) are simulated using POWHEG(v1) [118, 119] and the event yields are normalized to the approximate NNLO cross sections [120]. Di-bosons (WW , ZZ , and ZW) events are generated using PYTHIA and the events are normalized to the NLO cross sections [121]. MG5_aMC@NLO is used in simulating the $t\bar{t}$ events produced in association with a Z or a W boson. The parton showering, hadronization, and underlying events of all backgrounds are simulated using PYTHIA. The simulated samples include additional interactions per bunch crossing (pileup), with the distribution matching that observed in data, with an average of about 11 collisions per bunch crossing. The summary of the simulated processes and their corresponding generators is given in Table 8.1.

All simulated signal and background samples are processed with GEANT4 for the simulation of the CMS detector response, and are normalized to the data integrated luminosity. The simulated samples with their corresponding theory predicted cross sections are summarized in Table D.1. The object reconstruction and event selection introduced in next chapter are performed simultaneously on both data and simulation samples.

Chapter 9

Object Reconstruction and Event Selection

The first step in carrying out the $t\bar{t}$ cross section measurement is to reconstruct the physics objects (leptons, photons, missing transverse energy, and jets), and to perform the selection of events according to the requirements. These objects are reconstructed based on the combined information from the CMS sub-detectors, and using an optimized algorithm known as the Particle Flow (PF) algorithm [122].

Following the reconstruction, events are selected based on the decay topology of the $t\bar{t}$ pair, where each top quark decays into a W boson and a b quark. Only the cases in which both W bosons decayed to an electron or a muon and a neutrino are considered. These decays imply the presence of isolated leptons, missing transverse energy from the undetected neutrinos, and highly energetic jets. The heavy-quark content of the jets is identified through b-tagging techniques.

The $t\bar{t}$ cross section measurement in this thesis is performed using data collected with the CMS detector during 2015 at $\sqrt{s}=13$ TeV. The datasets are certified beforehand by the Data Quality Monitoring (DQM) process [123, 124] and provided for physics analysis. In this work, the used datasets correspond to a total integrated luminosity of 2.2 fb^{-1} . The certified data samples are summarized in Table D.2.

The object reconstruction and selection of events presented in this chapter are similar to those used for the measurement of the $t\bar{t}$ di-lepton differential cross section at 8 TeV [125], and will be referred to as **baseline** selection.

9.1 Trigger Selection

The HLT trigger paths introduced in Section 3.2.6 are a necessary ingredient of the event selection. As a first step, events are selected using trigger paths requiring combinations of two leptons (electron or muon) with minimal reconstruction criteria. Such events can present as potential candidates for $t\bar{t}$ decaying into two leptons in the final state. The trigger selection is applied to data and simulation events.

For the ee combination, the chosen trigger path requires two electrons with transverse momentum greater than 12 GeV and 17 GeV, respectively. In the case of $e\mu$, two HLT paths are used. One path has transverse momentum thresholds of 17 GeV and 12 GeV for muons and electrons, respectively, while the second path has 8 GeV and 17 GeV, respectively. For $\mu\mu$, also two paths are used with both having the same transverse momentum thresholds for the two muons, 8 GeV and 17 GeV, respectively, but they differ in the reconstruction requirement. When more than one path is used, events are required to pass at least one of the two paths. The trigger paths used for the different di-lepton combinations are given in Table D.3.

The di-lepton trigger efficiency $\epsilon_{trigger}$ is calculated using a data driven technique based on cross-trigger paths [126], weakly correlated with the di-lepton triggers used in the analysis. The efficiency is calculated as the ratio of events passing the cross triggers, the di-lepton trigger, and the event selection over the number of events passing only the cross-triggers and the event selection. In particular, the trigger paths chosen are based on missing transverse energy, which are weakly correlated with di-lepton triggers, and at the same time they provide sufficient number of events for the calculation. Efficiencies are derived from data and simulation, as a function of the leptons pseudorapidity. The calculated efficiencies are found in general to be higher than 0.96 for $e^\pm\mu^\mp$, 0.95 for $e^\pm e^\mp$, and 0.92 for $\mu^\pm\mu^\mp$.

The trigger efficiency in simulation is corrected to describe the efficiency measured in data via a scale factor given as

$$SF_{trigger} = \frac{\epsilon_{trigger}^{data}}{\epsilon_{trigger}^{MC}}. \quad (9.1)$$

The corresponding values are given as a function of $|\eta_{lep1}|$ and $|\eta_{lep2}|$ of the two leptons as shown in Appendix A.1.

9.2 Primary Vertex Reconstruction

At every bunch crossing several proton-proton collisions take place, yielding several collision points per event (vertices), referred to as *pileup*. It is important to pre-

cisely reconstruct these vertices in order to select the one corresponding to the hard interaction.

Collision vertex candidates are identified using the track information from the pixel and the strip tracking detectors. Each vertex is reconstructed using a set of associated tracks. These tracks are selected based on their distance from the vertex candidate in the z direction, their compatibility with the beam spot, number of hits in the tracking detector, and the track fit quality. The quality of each vertex is obtained using a three dimensional vertex fitter [127] which assigns a weight for each track representing the probability of the track to be arising from the vertex under study.

A vertex is considered valid if the sum of the associated track weights is larger than four. Events with at least one valid vertex are considered for the analysis only if the vertex position is within 24 cm from the nominal interaction point along z and within 2 cm from the beam axis in the transverse plane. If several vertex candidates pass this criteria in an event, the one with the highest p_T^2 of the associated tracks is considered as the primary vertex while the rest as pileup vertices.

In data, the number of vertices per event, also referred to as the average event multiplicity, is measured based on the total proton-proton inelastic cross section and the instantaneous luminosity. However, in simulation the multiplicity is estimated based on predefined assumptions of the collision conditions. This leads to differences with respect to data. In order to correct for these differences, the simulation events are reweighed using the data-to-simulation ratio of the event multiplicity. The effect of the reweighing is shown in Figure 9.1.

9.3 Lepton Reconstruction and Selection

The main signature of the process under study is the presence of two leptons in the final state. In this thesis, only $t\bar{t}$ events with W bosons decaying into electron or muon and a neutrino are considered as signal, and any other $t\bar{t}$ final state (eg. $t\bar{t}$ leptonic decay via τ leptons, fully hadronic decays, or semi-leptonic decays) are considered background. The identification and isolation criteria of muons and electrons in addition to the selection requirements of the two leptons are given in the following.

9.3.1 Lepton identification

Muon candidates are reconstructed using the combined information from the muon system and the tracking detector. A track fitting is performed on the hits from the subdetectors. Muons reconstructed with the combined information are known as *global muons*.

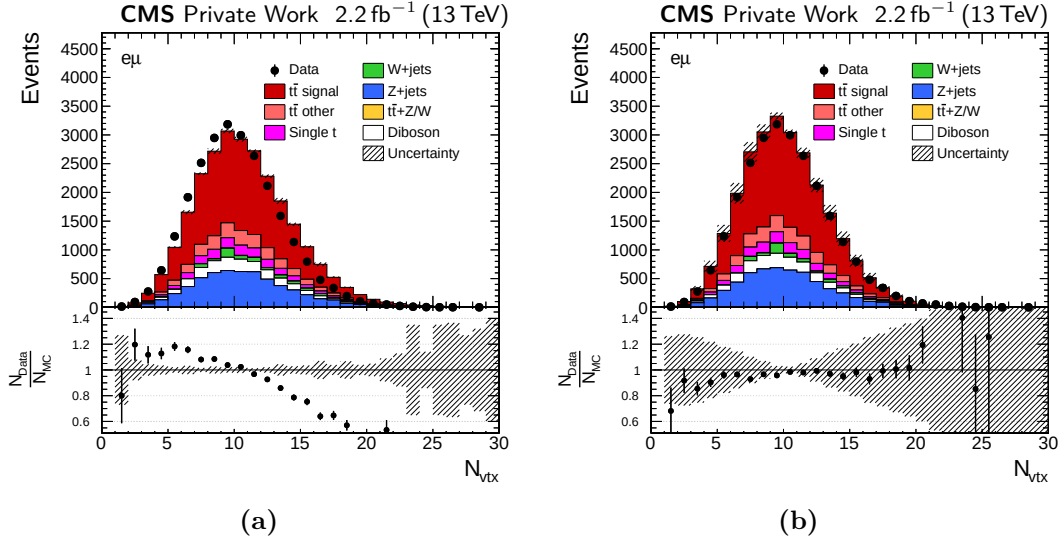


Figure 9.1 Distributions of the reconstructed vertices before (a) and after (b) the vertex reweighing. The distributions are obtained for data and simulation after the trigger and di-lepton event selections (see Section 9.3). The data-to-simulation ratio is shown. The hatched bands represent the total uncertainties in the simulation (see Chapter 10).

The selection criteria of global muons is further tightened based on fulfilling the following identification requirements:

- at least one valid hit in the pixel detector,
- more than five valid hits in the strip tracking detector layers,
- at least one hit in the muon system,
- at least one muon station with hits matched to a track from the tracking detector,
- global muons track fit with $\chi^2/ndf < 10$.

To ensure the selection of prompt muons (muons coming from the hard process), the track from the tracking detector is further constrained by cuts on the transverse impact parameter with respect to the beam spot $d_0 < 0.2 \text{ cm}$ and $d_Z < 0.5 \text{ cm}$. Such requirements serve in suppressing the fake rate coming from objects misidentified as prompt muons (e.g muons from leptonic or semi-leptonic Kaon/pion decays) and ensure the selection of high purity prompt muons.

Electron candidates are reconstructed using the track information from the tracking detector combined with the energy deposition information from the ECAL system. The reconstruction can be performed either by using the track as a seed which is then extrapolated into the ECAL, or by starting from the energy deposited in the ECAL and searching for a corresponding track.

Electrons can be mimicked by certain processes occurring in the detector which have to be excluded from the analysis. For example, e^-e^+ pairs created through photon conversion close to the beam pipe, could be wrongly assigned to a *real electron (positron)* coming from the hard process. In this case, one of the differences to distinguish electrons from misidentified particles, *fake electrons*, is the bremsstrahlung emission. Electrons coming from the hard scattering processes are likely to radiate more photons than fake electrons. Even though this emission is taken into account in the fitting of the electron track, using the Gaussian-sum filter (GSF) [128], this property alone is not sufficient to be used as a discriminator.

Therefore, in addition to the fit requirements, the quality of the reconstructed electron is governed by an identification criteria based on a set of variables, summarized in Appendix C. These variables incorporate:

- the track position with the missing number of hits in the tracking detector,
- the ECAL cluster information of energy deposition and position,
- the energy measured in the calorimeter versus the momentum measured by the tracking detector,
- the fraction of energy deposited in the HCAL,
- a veto for electron candidates originating from photon conversion.

The gap separating the ECAL barrel from the end-cap disks (Section 3.2.4) is taken into account in the reconstruction, and thus the definition of the electron identification is divided accordingly into two categories as a function of pseudorapidity.

MVA-based and Cut-based identification

The variables used in the definition of the electron identification can be handled in two different ways: either based on a multi-variate-analysis (MVA) technique or based on predefined requirements, *cuts*.

When using the MVA-based identification, the electron variables are fed into a multi-variate-analysis based on boosted decision tree (BDT) training in order to build a unified discriminant variable. The training is performed on signal and background samples in several bins of p_T and η . The BDT discriminant is provided for three different working points corresponding to loose ($\sim 60\%$ efficiency), medium ($\sim 70\%$ efficiency), or tight ($\sim 80\%$ efficiency) identification criteria. The advantage of using the BDT for the electron identification is that it allows the reduction of fake electrons without degrading the identification efficiency.

The cut-based identification uses most of the previously mentioned variables, but only a simple cut value for each variable is applied. The cut-based identification is usually

used when no MVA alternative is provided. It is less time and computational power consuming, but does not provide the same discrimination power as the MVA, for the same background rejection fraction.

In this analysis, the cut-based identification with medium working point yielding $\sim 70\%$ selection efficiency is used. However, once an MVA alternative became available and for comparisons of systematic uncertainties and background rejection, the measurement is repeated using the MVA-based identification, and the effect is discussed in Chapter 10.

9.3.2 Lepton isolation

In order to ensure the purity of the prompt leptons corresponding to the hard scattering process an additional criterion is applied. This criterion, known as isolation, rejects leptons produced via semi-leptonic decays, QCD events, and hadrons misidentified as leptons, using an isolation variable $I_{rel.}$. This variable, compares the sum of energies of photons, charged hadrons, and neutral hadrons deposited within a cone of $\Delta R = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2}$ around the lepton, to the transverse momentum of the lepton, and is expressed as

$$I_{rel.} = \frac{\sum_{\text{photons}} E + \sum_{\text{charged had.}} E + \sum_{\text{neutral had.}} E}{p_{T,l}}. \quad (9.2)$$

In this analysis, $I_{rel.} < 0.15$ is used for muons with a $\Delta R < 0.4$. For electrons the isolation is included as one of the cut-based identification criteria by requiring $I_{rel.} < 0.0766$ and 0.0678 in the barrel and the end-cap regions, respectively, in a cone size of $\Delta R < 0.3$. Also for electrons, the pileup effects due to unclustered objects depositing energy in the ECAL are taken into account and subtracted using the so-called effective area factor [129].

9.3.3 Lepton identification and isolation efficiencies

The lepton identification and isolation efficiencies (ϵ^{id} , ϵ^{iso}) are calculated using a data driven method known as *Tag&Probe*. In this method, events are selected with two oppositely charged, same flavor, leptons having their invariant mass m^{ll} within the region of the Z boson peak ($76 < m^{ll} < 106$ GeV). One of the leptons, referred to as *tag*, is selected with a tight criteria to ensure a good pre-selection of events, while the second, referred to as *probe*, is selected with a looser criteria, usually consistent with the selection criteria used in the measurement. The identification efficiency is then obtained as the ratio of the number of probes passing the identification criteria over the number of all probes. For isolation, the efficiency is obtained as the ratio of the number of probes passing the isolation and the identification criteria over the

number of all probes passing the identification criteria. These numbers are obtained, after background subtraction, by fitting the invariant mass of the tag and probe lepton pairs. The electron and muon identification and isolation efficiencies are derived as a function of the p_T and η of the leptons. More details about the Tag&Probe method and the electron efficiency calculation can be found in Appendix C.1.

The lepton scale factors SF_{lepton} used for the correction of the expected number of events due to efficiency differences observed with respect to data, are derived as

$$SF_{lepton} = \frac{\epsilon_{id}^{data} \times \epsilon_{iso}^{data}}{\epsilon_{id}^{MC} \times \epsilon_{iso}^{MC}}. \quad (9.3)$$

The electron and muon scale factors used in this analysis are given in Appendix A.2.

9.3.4 Lepton pair selection

In this analysis the phase-space for leptons is defined within $|\eta| < 2.4$ and $p_T > 20 \text{ GeV}$. Only events with two oppositely charged and well isolated leptons in the defined phase-space are selected. Within an event, the lepton pair with maximum sum of transverse momentum is considered as the product of the $t\bar{t}$ decay. With such selection criteria, events can be assigned to three different channels according to the flavor of the leptons forming the pair, i.e. $e^\pm e^\mp$, $\mu^\pm \mu^\mp$, or $e^\pm \mu^\mp$.

In addition, a di-lepton invariant mass m^l threshold of 20 GeV is applied in the three di-lepton channels. This requirement serves in rejecting low-mass Drell-Yan [130] and QCD multi-jet events. Furthermore, only in the same flavor channels ($e^\pm e^\mp$, $\mu^\pm \mu^\mp$), where Drell-Yan processes dominate, an additional mass requirement is applied. All events with di-lepton invariant mass falling in the Z -boson peak region ($76 \text{ GeV} < m^l < 106 \text{ GeV}$) are rejected. The m^l distributions in the $e^\pm \mu^\mp$ and $\mu^\pm \mu^\mp$ channels after the trigger and the di-lepton selection are shown in Figure 9.2.

9.4 Missing Transverse Energy

The colliding protons do not carry a transverse momentum component and therefore, due to momentum conservation, the final state collision products must not as well. This can be employed in determining the missing transverse momentum $\vec{E}_T^{miss}$ due to neutrinos which cannot be directly measured in the detector. The $\vec{E}_T^{miss}$ is defined as the negative vector sum of the measured transverse momentum of all reconstructed final state particles in an event. Its magnitude, referred to as missing transverse energy

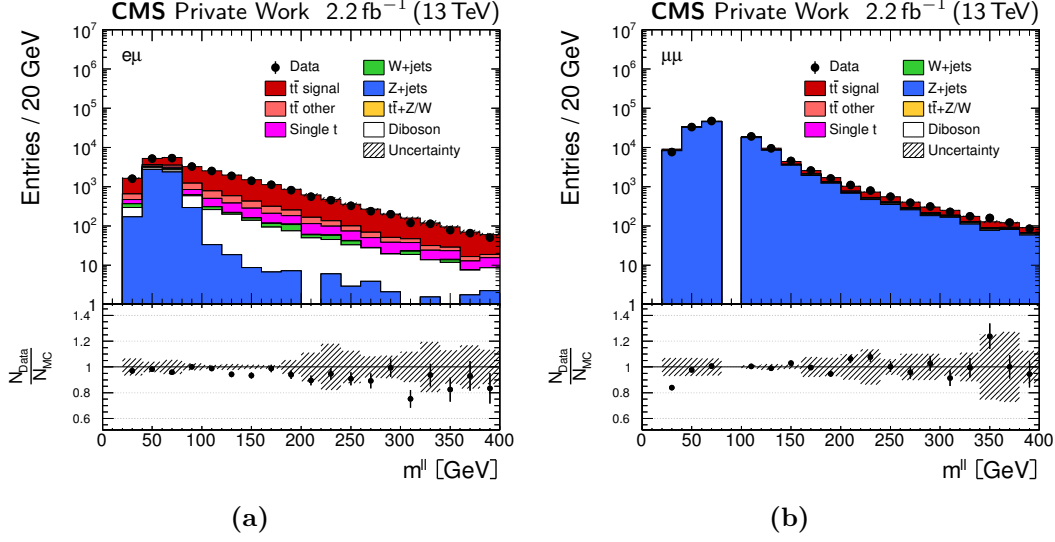


Figure 9.2 Distributions of the di-lepton mass m^{ll} in the $e^\pm\mu^\mp$ (a) and $\mu^\pm\mu^\mp$ (b) channels. The distributions are obtained for data and simulation after the trigger and di-lepton event selections. The data-to-simulation ratio is shown. The hatched bands represent the total uncertainties (see Chapter 11).

E_T^{miss} , can be expressed as

$$E_T^{miss} = \sqrt{\sum_i (E_x^i)^2 + \sum_i (E_y^i)^2}, \quad (9.4)$$

where the index i refers to each object of the event.

The $t\bar{t}$ events have significantly higher E_T^{miss} compared to background processes (e.g. $Z \rightarrow ee/\mu\mu$ processes, where no neutrinos are expected in the final state). Therefore, the requirement of $E_T^{miss} > 40$ GeV serves in reducing background events significantly in the same flavor channels. This requirement is not applied on the $e^\pm\mu^\mp$ channel since this channel is already dominated by the $t\bar{t}$ signal events after the jet requirement described in the following section.

9.5 Jets Reconstruction, Calibration, and Selection

The hadronization of quarks and gluons, described in Section 8.1.3, in the final state leads to the formation of sets of particles clustered along the direction of the hadronizing parton, known as *jet*. The reconstruction of objects forming the jet provides the necessary information about the original parton, which is vital for the event selection. For this purpose, the measurement information from the HCAL and the tracking

detector are used. Jet algorithms combine these information and use the four-momenta of all input objects in the reconstruction.

Several algorithms have been developed to perform the jet reconstruction [131–135]. In this analysis, the anti- k_t algorithm [136] is used. This algorithm features collinear and infrared safety properties, which assure that collinear splitting of jet components or their soft emissions do not influence the result of the jet reconstruction. The anti- k_t algorithm is a sequential clustering algorithm, which merges objects into clusters according to their distances from each other d_{ij} and from the beam d_{iB} as can be expressed

$$d_{ij} = \min(k_{t_i}^{-2}, k_{t_j}^{-2}) \frac{\Delta_{ij}^2}{R^2}, \quad (9.5)$$

$$d_{iB} = k_{t_i}^{-2}, \quad (9.6)$$

where i corresponds to a particle with a transverse momentum k_{t_i} and j corresponds to an object (can be a particle or a pseudo-jet) with a transverse momentum k_{t_j} , R is the cone size parameter of the algorithm, and Δ_{ij}^2 is the angular separation between i and j . The algorithm starts by identifying the smallest of distances, if it is d_{ij} then i and j are merged and the iteration continues, however, if it is d_{iB} then i is considered a jet and removed from the iteration. This is iteratively repeated over all the objects of each event. The cone size parameter used in the clustering of jets in this analysis is $R = 0.4$.

The properties of the reconstructed jets in simulated events could suffer significant deviations with respect to data. This is mainly due to effects such as the calorimeter response, where non-linear and non-uniform behavior of the HCAL are not properly accounted for in simulation. Pileup effects could also play a role in introducing some differences by leading to jet energy excess for example. Moreover, differences can arise due to missing energy from undetected neutrinos or from particles falling outside the jet cone. In order to account for these differences, a sequential calibration procedure is applied [137].

The calibration begins by the removal of the excess of jet energy due to pileup in data and simulation separately. This correction is derived using minimum-bias data events. This step is followed by removing the non-uniformity in η and the non-linearity in p_T from the simulation generated jets using correction derived from QCD simulation events. Finally, residual data driven corrections from Z+jets and di-jet events are applied on data only in order to minimize any remaining differences.

In order to account for differences in the jet energy resolution (JER) between data and simulation a correction factor is applied. This factor is data driven obtained using di-jet events in the transverse plane of the detector and applied as function of $|\eta|$ on

$ \eta $ range	[0-0.5]	[0.5-0.8]	[0.8-1.1]	[1.1-1.3]	[1.3-1.7]	[1.7-1.9]	[1.9-2.5]
JER factor	1.10	1.12	1.10	1.10	1.12	1.10	1.16
$+1 \cdot \sigma$	1.11	1.15	1.11	1.14	1.13	1.13	1.20
$-1 \cdot \sigma$	1.08	1.09	1.08	1.07	1.10	1.07	1.11

Table 9.1 Summary of the jet energy resolution correction factors and its uncertainties in different η ranges of reconstructed jets.

simulated events. It is defined as the ratio of the measured jet p_T over the simulated jet p_T . The values as function of $|\eta|$ utilized in this analysis are summarized in Table 9.1.

The presence of hadronic activity in the final state of the $t\bar{t}$ events due to the b quarks can be used as an advantage in order to distinguish these events from Drell-Yan and other non- $t\bar{t}$ events. Therefore, the requirement of jets in the event significantly enhances the $t\bar{t}$ signal over background. In this analysis events with at least two well reconstructed and calibrated jets are only considered if they are within $|\eta| < 2.4$ and with $p_T > 30$ GeV. The selected jets must also satisfy a loose identification requirement, which constrains the number of neutral and charged constituents of a jet, and their corresponding neutral and charged hadronic and electromagnetic energy fractions [138].

An additional criterion is applied over all jets in an event in order to ensure that jets overlapping with selected leptons are excluded. This is performed by requiring a minimum separating distance of $\Delta R(\text{jet}, \text{lepton})$ between any jet and a selected lepton. In this analysis jets are rejected if $\Delta R < 0.4$.

9.6 Identification of b Quark Jets

Events used in this analysis are expected to contain two b quark jets. Thus it is essential to efficiently identify and distinguish jets originating from b quarks, from those originating from c quark, light flavor quarks (u, d, s), or gluons. This identification is referred to as b-tagging.

The hadronization of the b quark in the final state leads to the formation of b -hadrons (e.g. B-mesons). These hadrons have a relatively long lifetime ($\sim 1.6 \times 10^{-12}$ s), and thus a traveling distance in the silicon tracking detector before they decay. Therefore, events with b quarks in the final state will contain in addition to the tracks pointing to the primary vertex, additional tracks pointing to the b -hadron decay vertex known as the secondary vertex. Owing to the pixel detector these vertices can be identified with high accuracy and good resolution.

This analysis exploits the so-called *Combined Secondary Vertex* (CSV) algorithm for b-tagging [139]. It utilizes the secondary vertex and tracks information as input, and

WP	discriminator	light-jets misidentification [%]	b-jets efficiency [%]
loose	≥ 0.460	~ 10	$\sim 80-85$
medium	≥ 0.800	~ 1	$\sim 65-75$
tight	≥ 0.935	~ 0.1	$\sim 50-60$

Table 9.2 The CSV b-tagging discriminator values for the three working points of the b-tagging algorithm. The efficiencies of b-jets identification is shown together with the light-jet misidentification efficiency.

provides a CSV discriminant variable as output. The CSV discriminant has values from 0.0 to 1.0. Three working points (WPs) loose, medium, and tight, are defined in this range, each corresponding to a different result in terms of misidentification rate. A higher value of the CSV variable means that a jet is more likely to be a b-jet, and vice-versa. The working points and their corresponding efficiencies of b-tagging, and light-jets/gluons misidentification as b-jets, are summarized in Table 9.2.

The efficiency of the CSV algorithm is estimated in data and QCD multijet events [140]. Differences between data and simulation are corrected using b-tagging scale factor SF_{b-tag} . This factor is derived as the data over simulation efficiency ratio for every b-tagging working point and jet flavor as a function of the jet kinematics ($|\eta|$, p_T). In order to account for the different kinematics of the $t\bar{t}$ events and the QCD multijet events, b-tagging efficiency using $t\bar{t}$ signal events $\epsilon_{b-tag}^{t\bar{t},MC}$ is calculated. The status of each selected jet is then updated according to the values of SF_{b-tag} and $\epsilon_{b-tag}^{t\bar{t},MC}$. If a jet is already b-tagged, but has a

$$1 - SF_{b-tag} > 0, \quad (9.7)$$

it is downgraded to an untagged jet. On the contrary, if a non b-tagged jet has

$$\frac{1 - SF_{b-tag}}{1 - 1/\epsilon_{b-tag}^{t\bar{t},MC}} \geq 0, \quad (9.8)$$

it is upgraded to a b-tagged jet.

In this analysis, a medium working point is chosen for the b-tagging, which corresponds to an efficiency for tagging a b-jet of about 65-75% (see Table 9.2), while the probability to misidentify light-flavor or gluon jets as b-jets is around 1%. The b-tagging and misidentification efficiencies at a medium working point are shown in Figure 9.3. Events in data and simulation are selected if they contain at least one b-tagged jet.

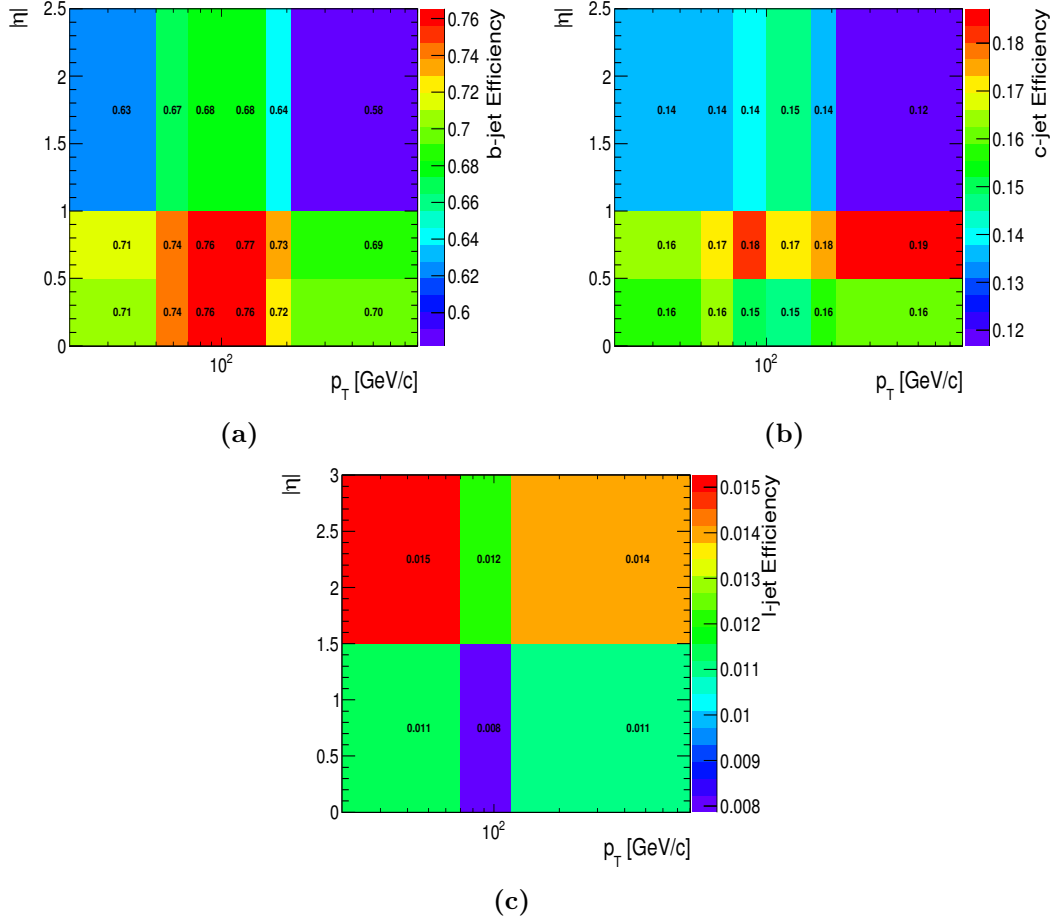


Figure 9.3 Two dimensional distributions of the b-tagging efficiency of the (a) b-jets, and the mis-tagging efficiency of (b) c-jets, and (c) light-jets, presented as a function of $|\eta|$ and p_T of the jets. These efficiencies are derived from the $t\bar{t}$ simulation events in the $e^\pm\mu^\mp$ channel at a medium b-tagging working point.

9.7 Selection Summary and Control Distributions

The goal of the event selection described earlier in this chapter is to reject as much as possible background events while maintaining a high fraction of $t\bar{t}$ signal events. A summary of the baseline event selection is listed below:

- Events are filtered using di-lepton triggers which require the presence of two electrons, or two muons, or an electron and a muon.
- Pileup removal is performed by requiring the events to contain at least one valid primary vertex. Events failing this requirement are excluded.
- Events are required to have two oppositely-charged, well isolated leptons with $p_T > 20$ GeV and within $|\eta| < 2.4$. For this analysis, only electrons and muons are considered. This criteria leads to separation of signal events into three channels, $e^\pm e^\mp$, $e^\pm \mu^\mp$ and $\mu^\pm \mu^\mp$.
- For events to be considered further they have to pass a threshold of 20 GeV on the lepton pair mass m_{ll} . In addition, only for the same flavor channels ($e^\pm e^\mp$ and $\mu^\pm \mu^\mp$), events with m_{ll} falling in the Z-peak region are excluded.
- Events must contain at least two well reconstructed and calibrated jets with a loose identification criteria. These jets must be within $|\eta| \leq 2.4$ and with $p_T \geq 30$ GeV.
- An $E_T^{miss} > 40$ GeV requirement applied to the same flavor channels.
- Finally, events are required to have at least one b-tagged jet with the medium working point (discriminator value > 0.800).

The baseline selection will be used for the inclusive $t\bar{t}$ production cross section measurement in Chapter 10, and for evaluation it will also be compared to different selection scenarios.

After the full event selection the total number of selected data events is found to be 2504, 9889, and 3872 in the $e^\pm e^\mp$, $e^\pm \mu^\mp$, and $\mu^\pm \mu^\mp$ channels, respectively. About 80% of the events in the three channels correspond to the $t\bar{t}$ signal. The most significant background, the $t\bar{t}$ -other (including events from $t\bar{t}$ leptonic decay via τ , fully hadronic decays, or semi-leptonic decays) amounts to 12-13% of the total selected events. The dominant non- $t\bar{t}$ background is the single-top process (tW) with 4%, followed by the Z+jets process with about 3% in the same flavor channels and 0.5% in the $e^\pm \mu^\mp$ channel. The total contribution of the $t\bar{t}$ production in association with W/Z boson, the di-bosons, and W+jets processes is less than 0.5% in all channels. Data and simulation events after applying the full selection and corrections are summarized in Table 9.3, in addition to the relative contribution of each simulation process. The event yield after each selection step are given in Table D.5.

A set of control distributions of different variables are shown in the following to evaluate the description of data by simulation. Simulation events are scaled to the data integrated luminosity of 2.2 fb^{-1} . All data-to-simulation corrections described earlier are applied to the simulation events. The p_T distributions of all selected leptons are shown for the $e^\pm e^\mp$, $e^\pm \mu^\mp$, $\mu^\pm \mu^\mp$, and the combined channels in Figure 9.4. The p_T spectrum of the selected lepton pairs and their mass distribution are shown in Figure 9.5, and Figure 9.6, respectively. The E_T^{miss} distribution is shown in Figure 9.7. The jet multiplicity and p_T spectrum of all selected jets are shown in Figure 9.8 and Figure 9.9, respectively. The multiplicity distribution of the b-tagged jets is shown in Figure 9.10. In general, data are well described by the simulation, where differences are mostly covered by the $t\bar{t}$ signal shape uncertainties described in Chapter 10.

	Channel		
	$\mu^\pm \mu^\mp$	$e^\pm \mu^\mp$	$e^\pm e^\mp$
Sample	Fraction of events (%)		
$t\bar{t}$ signal	79.9	81.9	79.2
$t\bar{t}$ other	12.8	12.9	12.1
$t\bar{t}+Z/W$	0.2	0.2	0.2
tW	4.3	4.3	4.5
di-boson	0.2	0.1	0.1
W+jets	0	0	0
Z+jets	2.5	0.5	3.1
	Number of vents		
Total simulation	3789	10303	2693
Data	3872	9889	2504

Table 9.3 Composition of different simulation processes with respect to the number of selected data events after the full event selection. In addition the total number of selected data and simulation events are given.

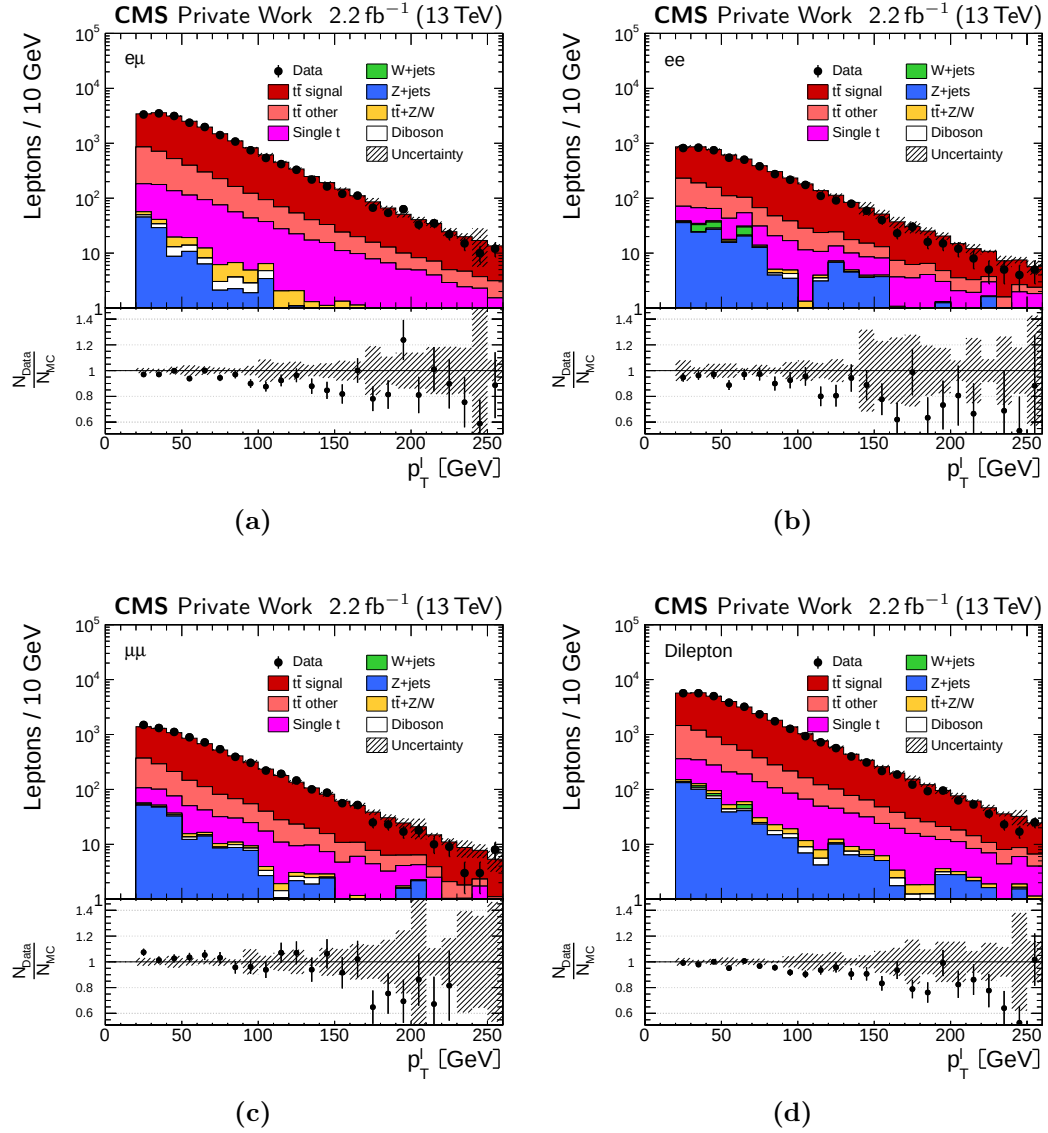


Figure 9.4 Distributions of the lepton p_T in the $e^\pm\mu^\mp$ (a), $e^\pm e^\mp$ (b), $\mu^\pm\mu^\mp$ (c), and combined dilepton (d) channels. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

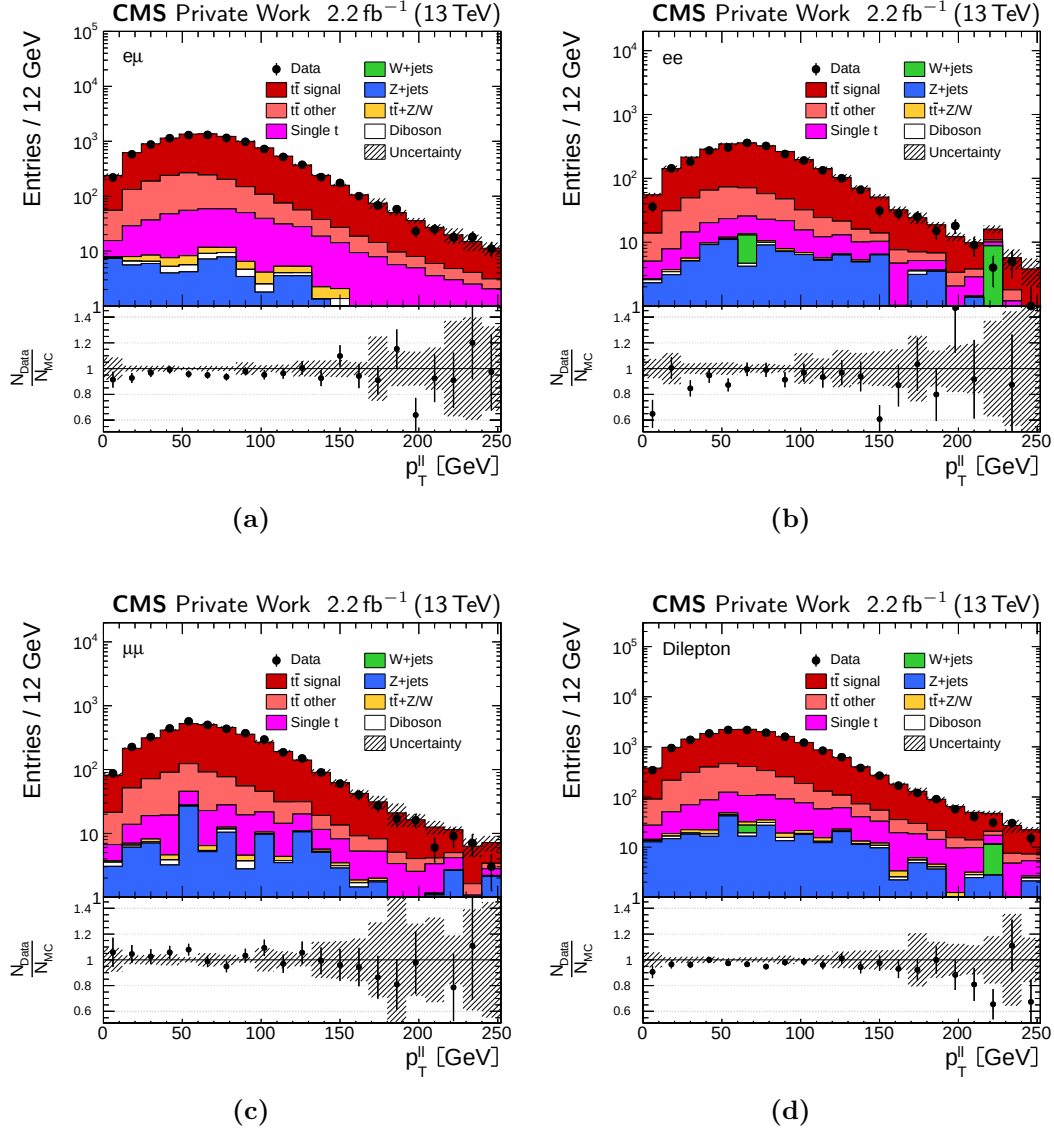


Figure 9.5 Distributions of the di-lepton p_T in the $e^\pm\mu^\mp$ (a), $e^\pm e^\pm$ (b), $\mu^\pm\mu^\mp$ (c), and combined di-lepton (d) channels. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

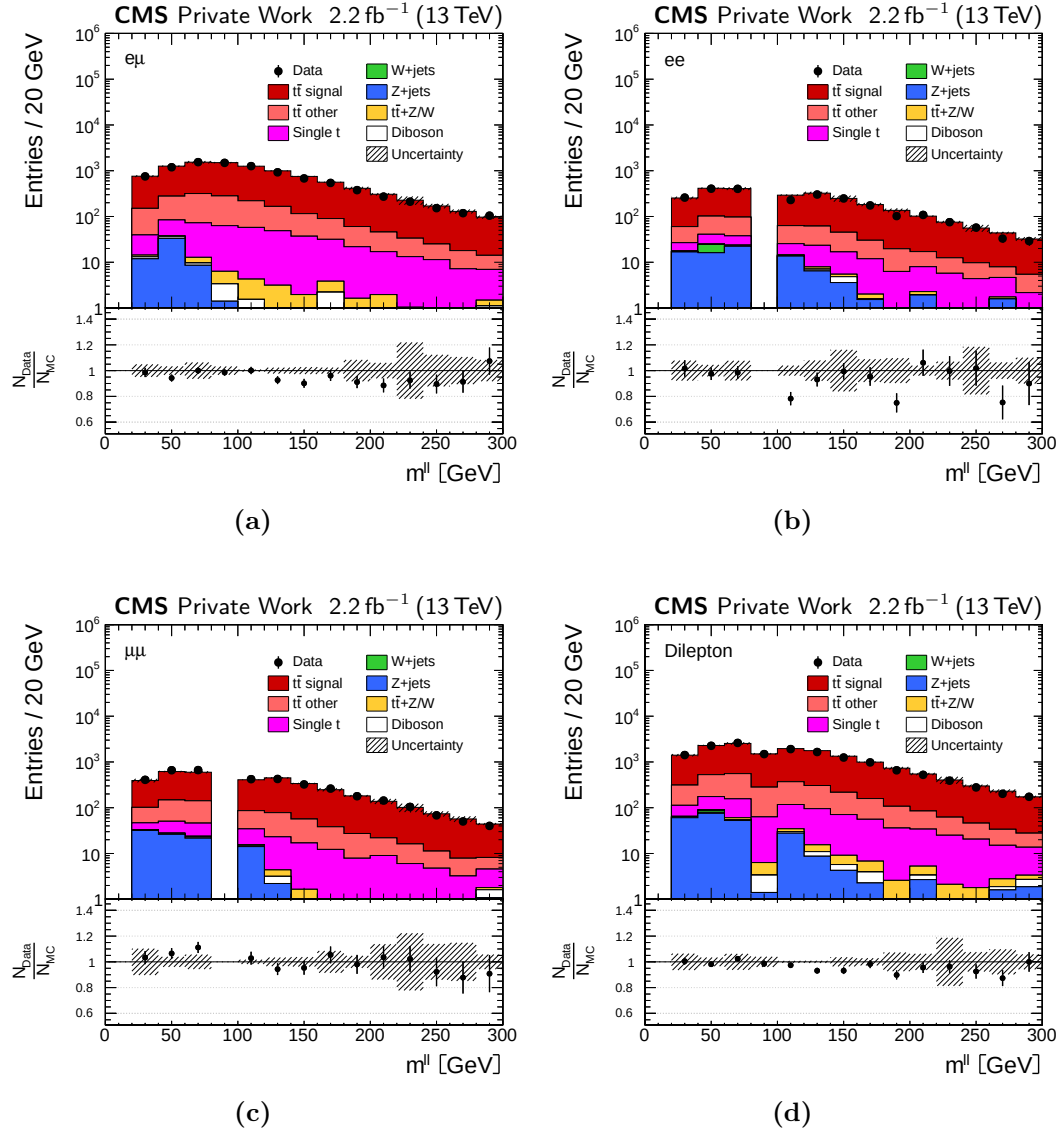


Figure 9.6 Distributions of the di-lepton mass in the $e^\pm\mu^\mp$ (a), $e^\pm e^\mp$ (b), $\mu^\pm\mu^\mp$ (c), and combined di-lepton (d) channels. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

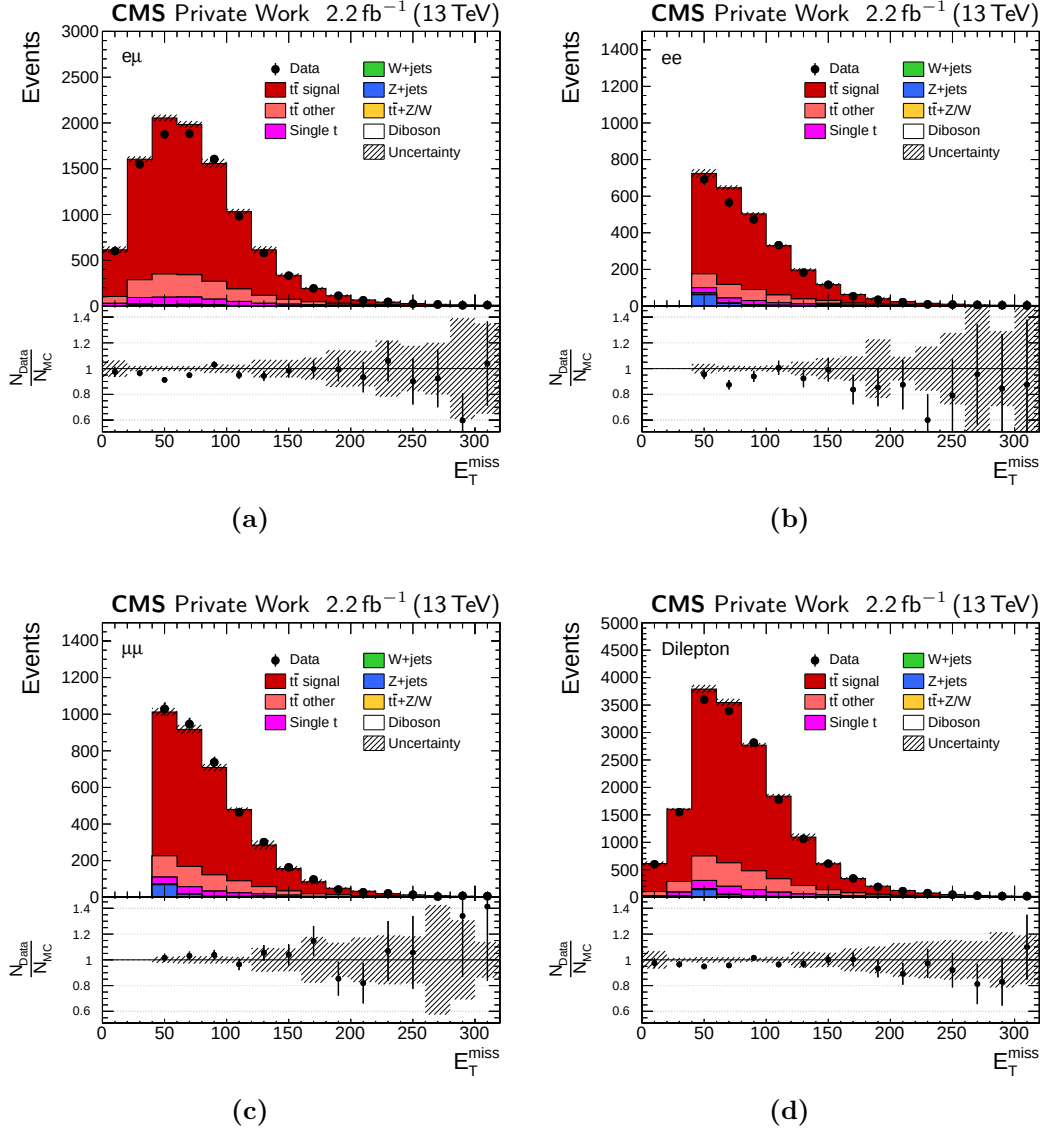


Figure 9.7 Distributions of E_T^{miss} in the $e^\pm\mu^\mp$ (a), $e^\pm e^\mp$ (b), $\mu^\pm\mu^\mp$ (c), and combined di-lepton (d) channels. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

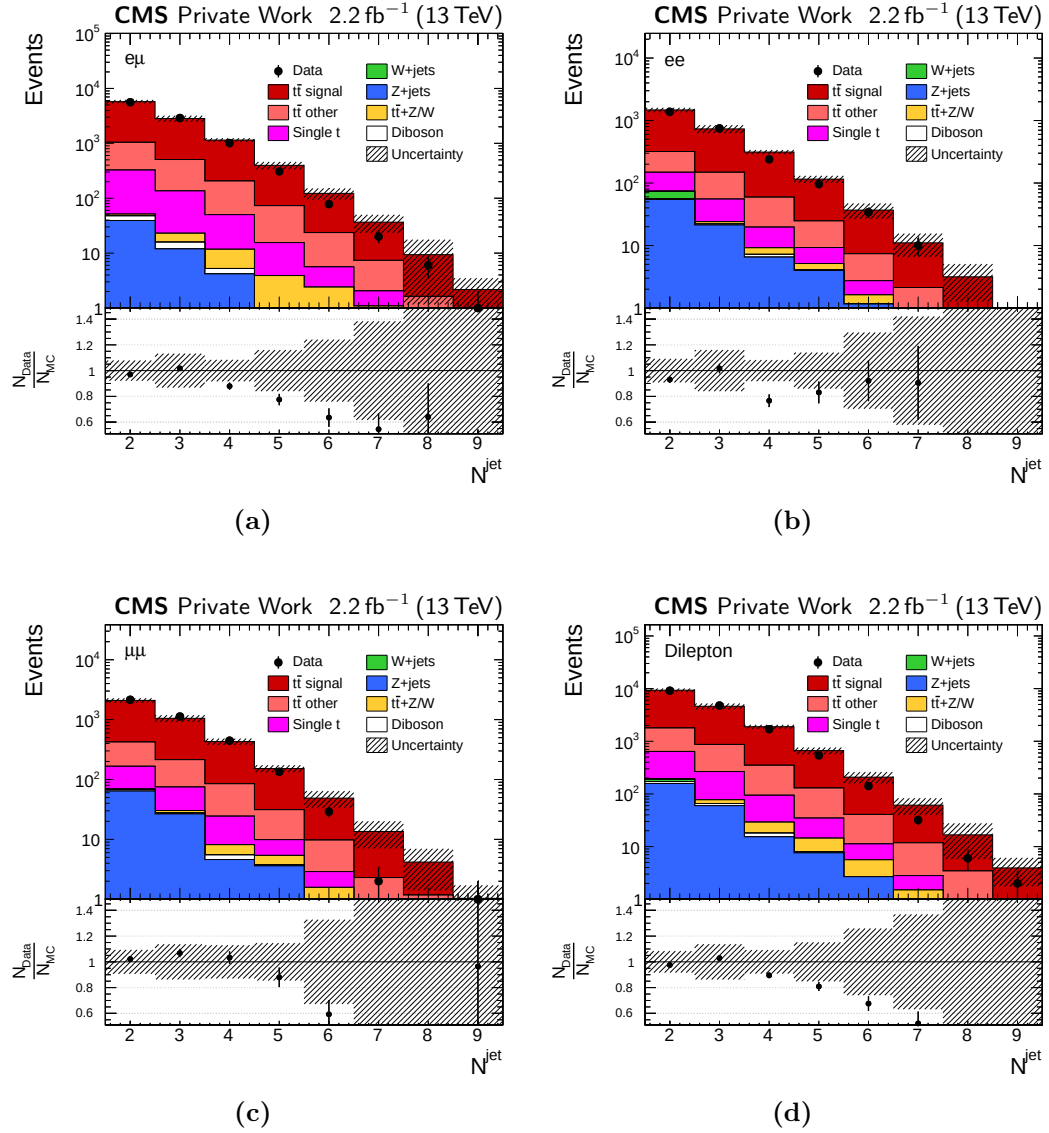


Figure 9.8 Distributions of the jet multiplicity in the $e^{\pm}\mu^{\mp}$ (a), $e^{\pm}e^{\mp}$ (b), $\mu^{\pm}\mu^{\mp}$ (c), and combined di-lepton (d) channels. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

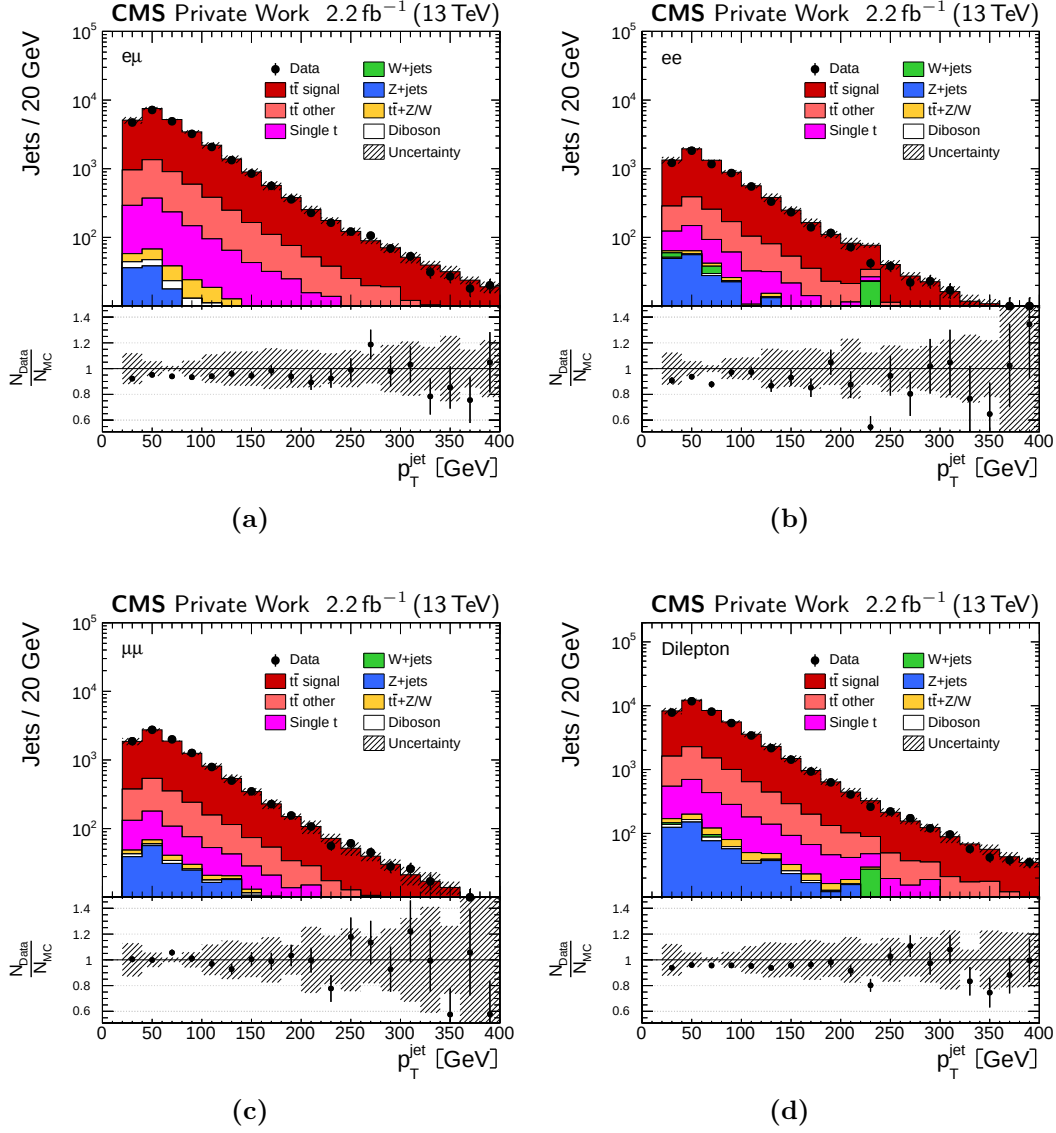


Figure 9.9 Distributions of the jet p_T in the $e^\pm\mu^\mp$ (a), $e^\pm e^\mp$ (b), $\mu^\pm\mu^\mp$ (c), and combined di-lepton (d) channels. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

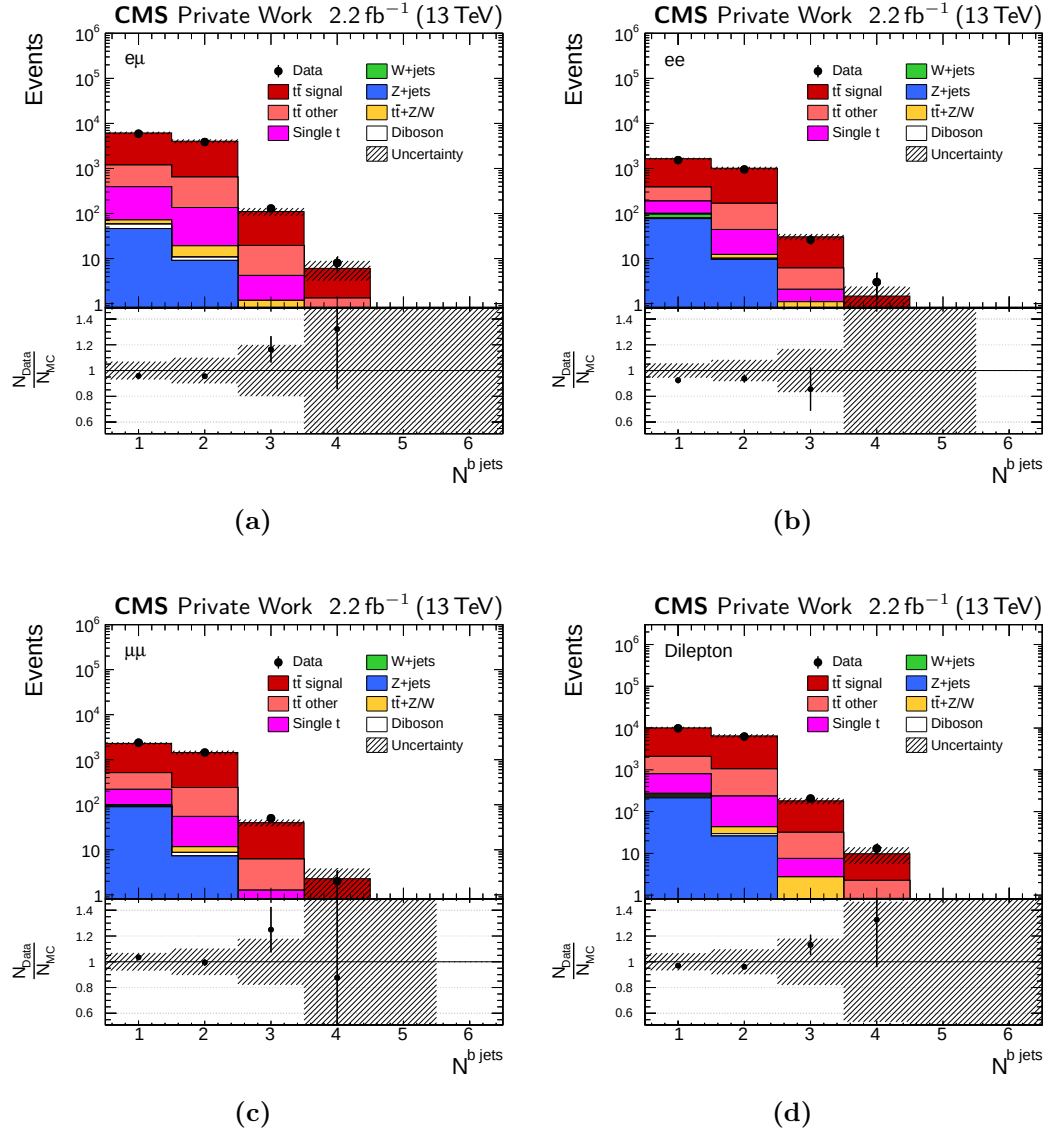


Figure 9.10 Distributions of the b-jet multiplicity in the $e^\pm\mu^\pm$ (a), $e^\pm e^\pm$ (b), $\mu^\pm\mu^\pm$ (c), and combined di-lepton (d) channels. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

Chapter 10

Inclusive $t\bar{t}$ Cross Section Measurement at $\sqrt{s} = 13$ TeV

The inclusive $t\bar{t}$ production cross section has been previously measured at 1.96 TeV by the CDF and D0 collaborations using $p\bar{p}$ collision data [141], and at 7 TeV and 8 TeV by the ATLAS and CMS collaborations at the LHC [142, 143] using pp collision data. The larger energy of $\sqrt{s}=13$ TeV at the LHC provides the opportunity to perform this measurement at an unprecedented energy regime. At $\sqrt{s}=13$ TeV, CMS has performed the measurement only in the $e^\pm\mu^\mp$ di-lepton channel [144] while ATLAS has measured it using all channels [145]. Measurements in the semi-leptonic channel have also been performed by the two collaborations [146, 147]. These measurements are found to be in agreement with the SM predictions. A selection of the most precise cross section results are given in Figure 10.1.

In this work, the event counting method described in Chapter 9 is exploited providing the first measurement of the cross section in the $e^\pm\mu^\mp$ and the same flavor di-lepton channels at $\sqrt{s}=13$ TeV using data collected by CMS. The measurement in the $e^\pm\mu^\mp$ di-lepton channel serves as a cross check for the CMS official result.

As part of this work, and in order to evaluate the chosen event selection, the measurement is performed using different scenarios featuring variations in the electron identification and the b-tagging selection criteria. The results obtained for all scenarios are compared to the ones obtained using the baseline selection and to the theoretical predictions. Furthermore, for an improved treatment of the signal modeling uncertainties, an approach based on b-jets reweighting, is implemented and exploited throughout the analysis.

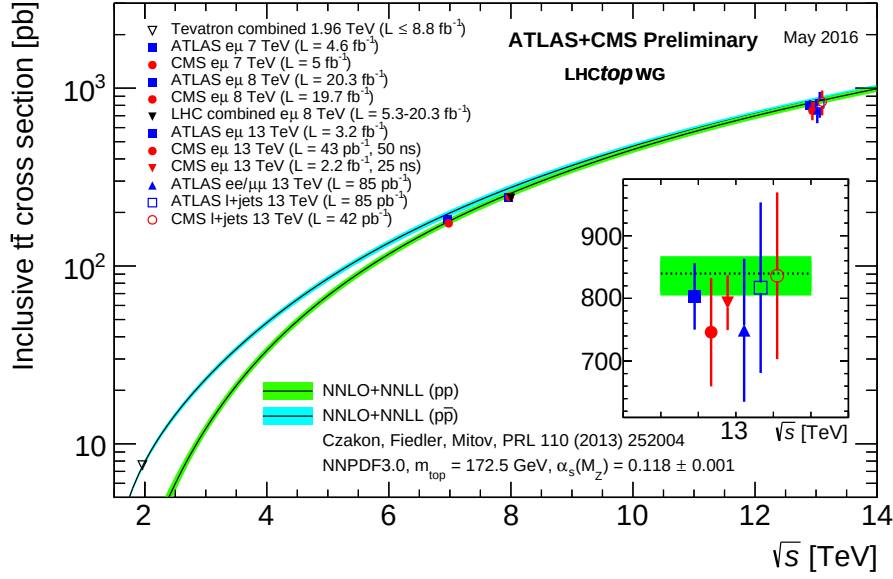


Figure 10.1 Summary of LHC and Tevatron measurements of the $t\bar{t}$ production cross section as a function of $\sqrt{s}$ compared to the NNLO QCD calculation complemented with NNLL re-summation (top++2.0) [148–152]. The theory band represents uncertainties due to renormalization and factorization scale, parton density functions and the strong coupling. The measurements and the theory calculation is quoted at $m_t = 172.5$ GeV. Measurements made at the same energy are slightly offset for clarity. From [153].

10.1 Definition of the Cross Section

The inclusive $t\bar{t}$ cross section is obtained in the three di-lepton channels, $e^\pm e^\mp$, $e^\pm \mu^\mp$, and $\mu^\pm \mu^\mp$, after performing the full event selection using the following expression

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{non-t\bar{t}}^{MC}}{\epsilon \cdot L \cdot BR} \cdot f_{sig}, \quad (10.1)$$

where N_{data} is the number of selected events in data, $N_{non-t\bar{t}}^{MC}$ is the estimated number of all non- $t\bar{t}$ background events, which apart from Drell-Yan (see Section 10.2), are estimated from simulation. In the denominator, L stands for the total integrated luminosity of the analyzed datasets, BR is the branching ratio of a W boson decaying leptonically, and ϵ is the total efficiency of the reconstruction and selection of di-lepton events. It is defined as the detector efficiency ϵ' multiplied by the phase-space acceptance A , and is expressed as

$$\epsilon = \epsilon' \cdot A. \quad (10.2)$$

The acceptance is defined by the p_T and η selection requirements on the leptons and jets. It is determined from the signal $t\bar{t}$ simulation events, and it extrapolates the measurement from the visible phase-space to the full phase-space. The visible phase-space is defined as the kinematic region with detector coverage. This region is constrained by the kinematic (p_T and η) requirements on the leptons and jets selection. The full phase-space is the full kinematic region, i.e. with no constraints. The measurement in the full phase-space would only be possible by the extrapolation from the visible phase-space and using simulation generated events. Therefore, the acceptance is expressed as the fraction,

$$A = \frac{N_{V_{ps}}^{gen.}}{N_{F_{ps}}^{gen.}}, \quad (10.3)$$

of simulation events generated in the visible phase-space $N_{V_{ps}}^{gen.}$ over the number of events generated in the full phase-space $N_{F_{ps}}^{gen.}$. Whereas the detector efficiency is defined as the ratio of the number of reconstructed events $N_{V_{ps}}^{rec.}$ over generated events $N_{V_{ps}}^{gen.}$ in the visible phase-space, and can be expressed as

$$\epsilon' = \frac{N_{V_{ps}}^{rec.}}{N_{V_{ps}}^{gen.}}. \quad (10.4)$$

The signal fraction f_{sig} is a factor used to account for the fraction of background events arising from $t\bar{t}$ processes with non-prompt di-lepton decays. The signal fraction is defined as

$$f_{sig} = \frac{N_{t\bar{t}\text{-signal}}}{N_{t\bar{t}\text{-signal}} + N_{t\bar{t}\text{-other}}}, \quad (10.5)$$

where $N_{t\bar{t}\text{-signal}}$ is the number of $t\bar{t}$ di-lepton signal events after the full event selection, and $N_{t\bar{t}\text{-other}}$ is the number of $t\bar{t}$ events with non-prompt di-lepton decays. Therefore, the use of f_{sig} avoids the dependency of the measurement on the $t\bar{t}$ cross section used in the normalization of the $t\bar{t}$ simulation samples.

The obtained N_{data} using $L = 2.2 \text{ fb}^{-1}$ integrated luminosity and $N_{non-t\bar{t} \text{ bkg}}^{MC}$ are summarized per channel in Table 10.1 with the corresponding ϵ , BR , and f_{sig} .

10.2 Background Determination

Drell-Yan is one of the main background processes mimicking the di-lepton final states of the $t\bar{t}$ events in the same flavor channels. In this analysis the Drell-Yan background is estimated with a data-driven method known as $R_{out/in}$ used in [154, 144].

This method exploits the events excluded by the analysis selection requirements on the di-lepton invariant mass $76 < m_{ll} < 106 \text{ GeV}$. The vetoed events are used as a control

Channel	N_{data}	N_{bkg}	ϵ [%]	BR [%]	f_{sig} [%]
$e^\pm e^\mp$	2504	234.1	9.9	1.15	86.7
$e^\pm \mu^\mp$	9889	534.6	19.5	2.28	86.4
$\mu^\pm \mu^\mp$	3872	273.8	14.0	1.13	86.1
Combined	16265	1042.5	15.8	4.56	86.4

Table 10.1 Summary of the measured number of events in data and simulation per channel after the full event selection. In addition, the analysis efficiency, the branching ratios and the signal fraction are given in percent.

region where further requirements of $E_T^{miss} > 40$ GeV and at least two jets are applied. Then the obtained number of Drell-Yan events in simulation is scaled to the obtained number in data, such that both data and simulation will have the same number of events inside the Z-peak region.

The number of Drell-Yan events observed outside the Z-peak region can be estimated using the following formula

$$N_{out}^{l^+l^-,obs} = R_{out/in}^{l^+l^-} (N_{in}^{l^+l^-} - \frac{1}{2} N_{in}^{e\mu} k_{ll}) \quad \text{for } ll = e^\pm e^\mp \text{ or } \mu^\pm \mu^\mp, \quad (10.6)$$

where $R_{out/in}^{l^+l^-,MC}$ is the ratio of number of events outside the Z-peak region $N_{DYMC}^{l^+l^-,out}$ over the number of events inside the Z-peak region $N_{DYMC}^{l^+l^-,in}$. This ratio is derived using the Drell-Yan simulated sample. Equation 10.6 accounts for the non-Drell-Yan background inside the Z-peak region in the same flavor channels. This is achieved by measuring the number of events in the Z-peak region in the $e^\pm \mu^\mp$ channel $N_{in,data}^{e\mu}$ and subtracting it from the measured number in the same region of the same flavor channel $N_{in,data}^{ll}$. It takes into account, via the k_{ll} factor, the differences in the efficiency between muon and electron reconstruction and selection. The k_{ll} factor can be determined using the number of events in the Z-peak region passing the standard di-lepton and jet selections, but with no E_T^{miss} cut applied. It is found to be for the $e^\pm e^\mp$ and $\mu^\pm \mu^\mp$ events as

$$k_{ee} = \sqrt{\frac{N_{in}^{e^+e^-}}{N_{in}^{\mu^+\mu^-}}} = 0.81, \quad (10.7)$$

$$k_{\mu\mu} = \sqrt{\frac{N_{in}^{\mu^+\mu^-}}{N_{in}^{e^+e^-}}} = 1.24. \quad (10.8)$$

The global Drell-Yan scale factors $SF_{DY_{ee}}$ and $SF_{DY_{\mu\mu}}$ are obtained to be 0.93 and 0.95, respectively. For the $e^\pm \mu^\mp$ channel it is determined as $SF_{DY_{e\mu}} = \sqrt{SF_{DY_{ee}} \times SF_{DY_{\mu\mu}}}$ and is found to be 0.94. These scale factors are applied to the Drell-Yan background simulation events.

The contributions of other backgrounds originating from di-bosons processes, $W + \text{jets}$, as well as tW and $t\bar{t} + Z/W$ events are determined from simulation.

10.3 Systematic Uncertainties

Apart from the statistical uncertainties, the precision of the $t\bar{t}$ cross section measurement is affected by different sources of systematic uncertainties. They are categorized under two types, experimental, arising from detector effects, and theoretical, arising from different theoretical assumptions on the modeling of the $t\bar{t}$ signal. Systematic uncertainties are determined by varying the corresponding sources (efficiency, resolution, etc.) by ± 1 standard deviation (σ) of their uncertainties. For each variation, the inclusive $t\bar{t}$ cross section is recalculated, and the obtained result is compared to the nominal measurement $M_{nom.}$. The average of the up and down variation, M_{up} and M_{down} respectively, with respect to $M_{nom.}$ are assigned as an uncertainty for each corresponding source, and can be expressed as

$$\delta_i = \frac{1}{2}(|M_{up} - M_{nom.}| + |M_{down} - M_{nom.}|). \quad (10.9)$$

All sources of uncertainty are assumed to be uncorrelated, and the total uncertainty δ_{total} on the cross section is obtained by the quadratic summation of all individual contributions δ_i as

$$\delta_{total} = \sqrt{\sum_i \delta_i^2}. \quad (10.10)$$

The different sources of experimental and theory related uncertainties and their impact on the cross section measurement are discussed in the following.

10.3.1 Experimental uncertainties

The experimental uncertainties are obtained by the variation of the data-to-simulation corrections discussed in Chapter 9. The uncertainties associated to those corrections are obtained by varying the scale factors by their uncertainties, $\pm 1\sigma$. In the following a summary of the experimental uncertainties is given for the $e^\pm e^\mp$, $e^\pm \mu^\mp$, and $\mu^\pm \mu^\mp$ channels.

Di-lepton trigger efficiency

The trigger scale factors $SF_{trigger}$ applied as a function of the two leptons pseudorapidity ($|\eta_{lep1}|, |\eta_{lep2}|$), as described in Section 9.1, are varied within their uncertainties. These uncertainties include the statistical and systematic uncertainties, typically of the order

of 1-3%, arising from the cross-trigger method (see Section 9.1). The variations result in an uncertainty of 1.5% in the $e^\pm\mu^\mp$ and the $\mu^\pm\mu^\mp$ channels, and 1.7% in the $e^\pm e^\mp$ channel.

Pileup and luminosity

The correction of the pileup distribution in simulation is evaluated by weighting the simulation events using the total inelastic proton-proton cross section. This cross section is obtained from the minimum bias data events and it amounts to around 80 mb [155]. The systematic uncertainty arising from the data-to-simulation correction is derived by varying the inelastic proton-proton cross section by $\pm 5\%$. The uncertainty due to this variation is found to be 0.2% in the $e^\pm\mu^\mp$ channel and around 0.1% in the same flavor channels.

CMS uses a pixel cluster counting method for the luminosity measurement. For the data collected in 2015 the overall uncertainty in the measured integrated luminosity is estimated to be 2.7% [156].

Lepton efficiency

Differences in simulation with respect to data in the lepton efficiencies are corrected using the lepton scale factors SF_{lepton} . The uncertainties of these efficiencies are obtained by varying the Tag&Probe method requirements, such as the tag selection criteria, the fit functions for signal and background, and the Z window. The estimated uncertainty of the cross section measurement after applying the variation of the lepton scale factors is about 3.6% in the $e^\pm e^\mp$ channel, 3% in the $e^\pm\mu^\mp$ channel and 2.5% in the $\mu^\pm\mu^\mp$ channel.

Jet energy correction and resolution

The jet energy correction uncertainty on the cross section measurement is determined by the variation of the uncertainties of the jet calibration in different bins of η and p_T . The analysis is repeated with the corresponding variations of the jet momenta in the simulated sample. The variation in each case is propagated to the missing transverse energy and the cross section is recalculated. The obtained uncertainties are 2.8% in the $e^\pm e^\mp$, 2.6% in the $e^\pm\mu^\mp$, and 2.7% in the $\mu^\pm\mu^\mp$ channels.

The uncertainty due to the jet energy resolution is determined by the variation of the JER by the uncertainties given in Table 9.1. The obtained uncertainties are less than 0.1% of the total cross section in all channels.

b-tagging efficiency

The b-tagging and misidentification uncertainties are determined from the variation of the corresponding scale factors within their uncertainties. The jet flavor is taken into account in the variation. Since c jets are considered to be correlated with b jets, while the light jets are not, the variation is performed separately for heavy jets (c and b) and light jets (u, d, s, and gluon jets). The difference with respect to the nominal result is found to be between 1.4% and 1.5% in all channels for the b-tagging and mis-tagging of c-jets, while the light jets mis-tagging uncertainty is found to be less than 0.1% in all channels.

Background normalization

The Drell-Yan background is normalized using the $R_{out/in}$ method described in Section 10.2. A $\pm 30\%$ uncertainty due to this normalization is estimated. Accordingly, the effect on the inclusive cross section in the $e^\pm e^\mp$ and $\mu^\pm \mu^\mp$ is 1.1% and 0.8% respectively, while in the $e^\pm \mu^\mp$ channel it is 0.2%.

For other backgrounds, such as tW , W +jets, and di-boson events, an uncertainty of $\pm 30\%$ is assumed. The up and down variation of this uncertainty has an impact on the total cross section of 2% in the $e^\pm e^\mp$ channel, 1.5% in the $e^\pm \mu^\mp$ and the $\mu^\pm \mu^\mp$ channels.

10.3.2 Signal modeling uncertainties

The impact of theoretical assumptions on the $t\bar{t}$ cross section measurement is determined by repeating the analysis, while replacing the nominal $t\bar{t}$ signal simulation sample by alternative samples. These samples, produced with varied signal modeling parameters with respect to the nominal sample, allow to study the effect of the theoretical assumptions on the measurement. A summary of all $t\bar{t}$ signal samples used in determining the modeling uncertainties is given in Table 10.2.

Hard process Q^2 scale

The hard scattering processes depends on the definition of the renormalization and factorization scales ($Q^2 = \mu_f^2 = \mu_r^2$). The hard scattering process of the nominal $t\bar{t}$ sample is generated by POWHEG as mentioned earlier. In POWHEG, Q^2 is given as $m_t^2 + p_{T,t}^2$, where m_t is the top mass and $p_{T,t}$ is the top transverse momentum. The nominal value of Q is varied up and down by a factor of two to determine the scale uncertainty. This variation is simultaneously considered for parton showering using dedicated $t\bar{t}$ signal samples. The average uncertainty due to the scale variation on

Sample	ME + PS	Parameters
Nominal	POWHEG + PYTHIA8	$Q^2 = m_t^2 + p_{T,t}^2$ $m_t = 172.5$
Q^2 Scale up	POWHEG + PYTHIA8	$4 \cdot Q^2$
Q^2 Scale down	POWHEG + PYTHIA8	$\frac{1}{4} \cdot Q^2$
Top mass up	POWHEG + PYTHIA8	$m_t = 175.5$ GeV
Top mass down	POWHEG + PYTHIA8	$m_t = 169.5$ GeV
Generator	MG5_aMC@NLO + PYTHIA8	-
PS & Hadronization	POWHEG + Herwig++	-

Table 10.2 Summary of the different $t\bar{t}$ simulated samples used for the estimation of the signal modeling uncertainties. The nominal sample is the reference for comparison. Each of the other samples has a varied parameter compared to nominal. The matrix element (ME), parton showering (PS) and hadronization models are given together with the varied parameters.

the measured cross section value is obtained to be 0.4%, 1.7%, and 1.5% in the $e^\pm\mu^\mp$, $e^\pm e^\mp$, and $\mu^\pm\mu^\mp$ channels, respectively. These values are obtained after applying the b-jet reweighting discussed in Section 10.3.3.

Generator

This uncertainty is determined by comparing the analysis result using the nominal process, where POWHEG is used as the LO matrix element generator, with NLO sample generated using MG5_aMC@NLO (v5-2.2.2) [112]. Both samples are interfaced to PYTHIA8 for the parton shower and hadronization. The uncertainties in the measured cross section due to the choice of the ME generator are estimated to be 1.6% in the $e^\pm\mu^\mp$ channel and $\sim 1.2\%$ in the same flavor channels. These values are obtained after applying the b-jet reweighting discussed in Section 10.3.3.

Parton showering & Hadronization

In order to obtain the uncertainty arising from the parton showering and the hadronization model, a sample with POWHEG as a matrix element generator interfaced to Herwig++ (v2.7.2) [101] is used. The result of the measurement using this sample is compared to the result from the nominal sample where PYTHIA8 is used. This variation allows the comparison between the cluster hadronization model and the Lund fragmentation model (Section 8.1.3) and their impact on the cross section measurement. This impact is found to be 1.8% in the $e^\pm\mu^\mp$ channel, and around 0.4% in the same flavor channels. These values are obtained after applying the b-jet reweighting discussed in Section 10.3.3.

Parton distribution function

The uncertainty arising due to the parton distribution function is estimated by reweighting the nominal $t\bar{t}$ signal events according to the 100 eigenvalues of the NNPDF3.0 error set. The maximum difference between the result evaluated using the central and the uncertainty eigenvalues is considered as the PDF uncertainty. The impact of this uncertainty on the inclusive cross section is estimated to be of the order of 0.5% in all channels.

Top quark mass

In order to account for the experimentally measured top quark mass uncertainties, the result of the analysis using the nominal sample with $m_t = 172.5$ GeV, is compared to the results obtained using samples with $m_t = 169.5$ GeV and $m_t = 175.5$ GeV. Since the uncertainty on the measured top quark mass is less than 1 GeV [91], the resulting uncertainty of the variation is scaled accordingly. The mass uncertainty with respect to the measured cross section is estimated to be 1% in the $e^\pm\mu^\mp$ channel and $\sim 1.4\%$ in the same flavor channels.

10.3.3 b-jets reweighting

The b-tagging efficiencies obtained using samples with varied parameters, generators, or hadronization models, are found to have differences with respect to the ones obtained using the nominal sample. The differences vary from $\sim 1\%$ at a loose b-tagging working point up to $\sim 2\%$ and $\sim 4\%$ at medium and tight working points, respectively. A chosen set of b-jet efficiency plots shown in Figure 10.2 and Figure 10.3 using different signal modeling samples reflects the differences with respect to the efficiencies obtained for the nominal sample. Therefore, in order to estimate the signal modeling uncertainties in an unbiased way, by excluding the effects of the b-tagging discriminator and only accounting for the modeling effects an additional correction is needed.

This correction is applied by replacing the b-tagging efficiency $\epsilon_{b-tag.}^{MC,Var.}$ obtained from the varied signal modeling samples by the efficiency from the nominal sample $\epsilon_{b-tag.}^{MC,Nom.}$. This replacement requires a correction factor which is applied as a global weight for every b-jet in an event and is derived as

$$w_{b-jet} = \frac{\epsilon_{b-tag.}^{MC,Nom.}}{\epsilon_{b-tag.}^{MC,Var.}}. \quad (10.11)$$

For every b-jet found in an event, the event weight is updated by the multiplication with w_{b-jet} . Since the misidentification rate of a c-jet or a light-jet in an event is significantly lower than the b-jets tagging efficiency especially for medium and tight

working points, and because their difference among different samples is in agreement within uncertainties, their weights w_{c-jet} and w_{l-jet} are set to unity.

This correction is applied when determining the uncertainties due to Q^2 scale, matrix element generator, and hadronization variations. It is expected, excluding statistical fluctuations, that disentangling the b-jet discriminator effect from these signal modeling variations would lead to a reduction of the uncertainty, specially of the Q^2 scale uncertainty. The effect of the b-jets reweighting on the signal modeling uncertainties, and the total systematic uncertainty is given in the next section.

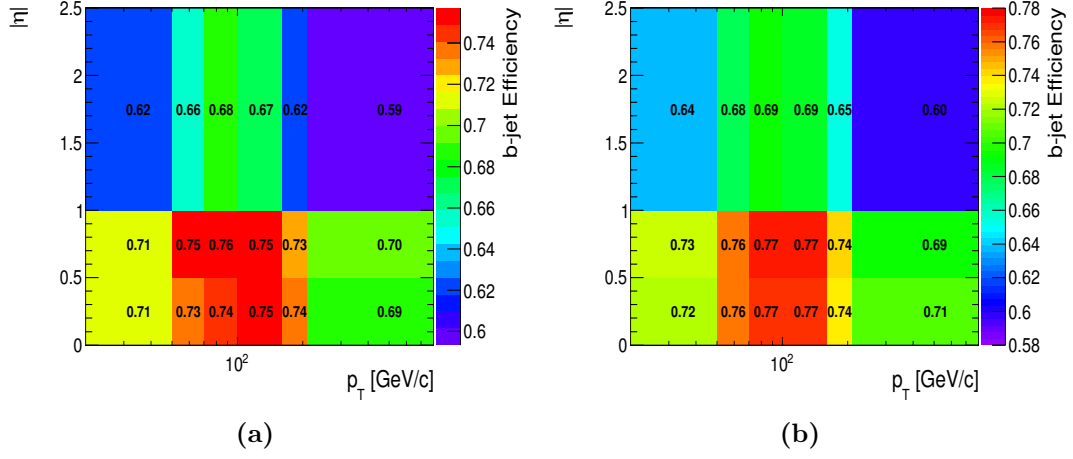


Figure 10.2 Two dimensional distribution of the b-tagging efficiency obtained at a medium b-tagging working point in the $e^\pm\mu^\mp$ channel for (a) the MG5_aMC@NLO sample, and (b) the Q^2 scale up sample presented as a function of $|\eta|$ and p_T of the jet. Variations with respect to the efficiencies obtained for the nominal sample, shown in Figure 9.3a, can be seen.

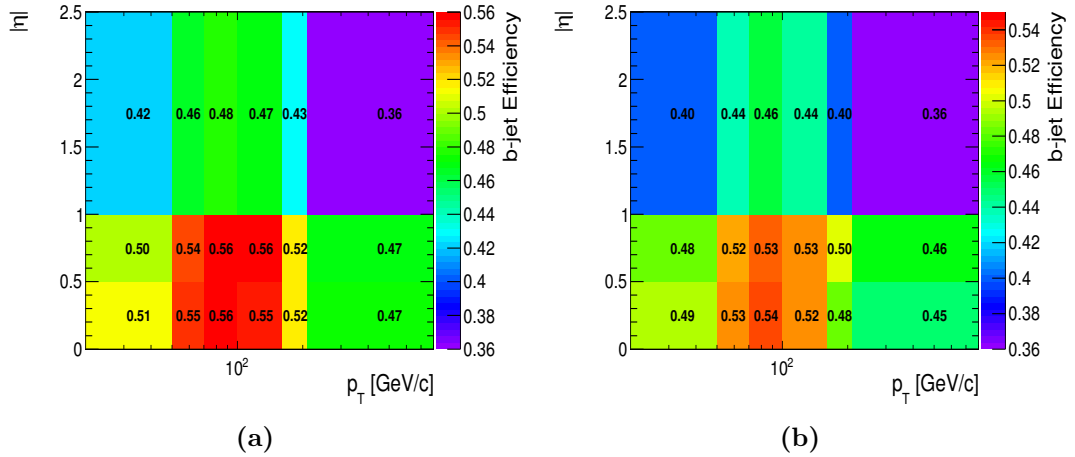


Figure 10.3 Two dimensional distribution of the b-tagging efficiency obtained at a tight b-tagging working point in the $e^\pm\mu^\mp$ channel for (a) the nominal sample, and (b) Q^2 scale down sample presented as a function of $|\eta|$ and p_T of the jet. Variations up to 4% can be seen.

10.3.4 Summary of systematic uncertainties

The total systematic uncertainty in the $t\bar{t}$ cross section measurement is estimated to be 6.6%, 5.9%, and 5.6%, in the $e^\pm e^\mp$, $e^\pm \mu^\mp$, and $\mu^\pm \mu^\mp$ channels, respectively, after the b-jet reweighting is applied. The dominant uncertainties are found to be arising from the lepton identification and isolation efficiencies and from the jet energy scale in the three channels. The summary of all systematics per channel is given in Table 10.3 including comparison between the signal modeling uncertainty values before and after the b-jets reweighting. In general, the b-jets reweighting led to a decrease of $\sim 2\%$ to 4% in the total systematic uncertainty in the different channels.

Differences in signal modeling uncertainties between different channels, before and after the b-jets reweighting, are related to statistical uncertainties, event selection efficiency, and mainly to the description of data by simulation. Distributions of the b-jets multiplicity, shown in Appendix B, for different channels and signal modeling uncertainties before and after the reweighting reflect these differences.

Sources of uncertainty	$e^\pm e^\mp$	$e^\pm \mu^\mp$	$\mu^\pm \mu^\mp$
Experimental (%)			
Trigger	1.7	1.5	1.5
Pileup	< 0.1	0.2	< 0.1
Lepton	3.6	3.0	2.5
JES	2.8	2.6	2.7
JER	< 0.1	< 0.1	< 0.1
Background	2.0	1.5	1.5
DY Background	1.1	0.2	0.8
b-tagging	1.5	1.4	1.5
Luminosity	2.7	2.7	2.7
Total experimental	6.1	5.4	5.2
Theoretical (%)			
Top mass	1.5	1.0	1.3
Hadronization	0.3 (0.3)	1.8 (1.8)	0.4 (4.8)
Generator	1.1 (2.7)	1.6 (1.1)	1.3 (0.8)
Scale Q^2	1.7 (5.8)	0.4 (5.7)	1.5 (6.0)
PDF	< 0.5	< 0.5	< 0.5
Total theoretical	2.6 (6.6)	2.3 (6.2)	2.2 (7.8)
Total systematics (%)	6.6 (9.0)	5.9 (8.2)	5.6 (9.4)
Statistical (%)	2.2	1.1	1.7

Table 10.3 Summary of the experimental and theoretical uncertainties in the three channels obtained using the baseline event selection. The values are given in percent with respect to the measured cross section in each channel. The values in brackets corresponds to the uncertainties obtained if no b-jets reweighting is applied.

10.4 $t\bar{t}$ Cross Section Using the Baseline Selection

The $t\bar{t}$ cross section for the three di-lepton channels are measured for a top quark mass of $172.5 \text{ GeV} \pm 1 \text{ GeV}$ and obtained as

$$\sigma_{t\bar{t}}^{ee} = 780 \pm 17 \text{ (stat.)} \pm 52 \text{ (syst.) pb}, \quad (10.12)$$

$$\sigma_{t\bar{t}}^{e\mu} = 817 \pm 9 \text{ (stat.)} \pm 48 \text{ (syst.) pb}, \quad (10.13)$$

$$\sigma_{t\bar{t}}^{\mu\mu} = 878 \pm 15 \text{ (stat.)} \pm 50 \text{ (syst.) pb}. \quad (10.14)$$

The differences between the central values of the three channels are mainly related to the differences in the detector and the selection efficiencies. The systematic uncertainties are obtained after the b-jets reweighting is applied.

The combined cross section of the $e^{\pm}e^{\mp}$, $e^{\pm}\mu^{\mp}$, and $\mu^{\pm}\mu^{\mp}$ channels is also measured. The three channels are considered to be statistically independent, due to the unambiguous event selection. Thus, the combined cross section can be obtained as a summation of the individual results weighted by their statistical uncertainties [157], and can be expressed as

$$\sigma_{t\bar{t}}^{combined} = \sum_i \frac{\left(\frac{\sigma_i}{\delta\sigma_i^2}\right)}{\frac{1}{\delta\sigma_i^2}}, \quad (10.15)$$

where i is the individual channel, and $\delta\sigma_i$ is its corresponding statistical uncertainties.

The statistical uncertainty of the combined cross section is the inverse quadratic summation of $\delta\sigma_i$ and can be expressed as

$$\delta\sigma_{combined} = \frac{1}{\sqrt{\sum_i \frac{1}{\delta\sigma_i^2}}}. \quad (10.16)$$

The systematic uncertainties of the combined cross section are determined by comparing the central value of the combined result, using the nominal sample, with the combined result for a certain systematic variation. All systematic uncertainties discussed earlier are used for the combined measurement. The combined inclusive cross section with the corresponding statistical and systematics uncertainties is

$$\sigma_{t\bar{t}}^{di-lepton} = 823 \pm 7 \text{ (stat.)} \pm 50 \text{ (syst.) pb}, \quad (10.17)$$

for a top quark mass of $172.5 \text{ GeV} \pm 1 \text{ GeV}$.

In Figure 10.4 the combined di-lepton $t\bar{t}$ cross section is shown together with the obtained results in the $e^{\pm}e^{\mp}$, $e^{\pm}\mu^{\mp}$, and $\mu^{\pm}\mu^{\mp}$ channels. In addition, the results are compared to the most precise SM prediction, based on calculations up to NNLO +

NNLL accuracy, determined using the Top2.0++ framework [158]. The results are found to be in good agreement with the predictions.

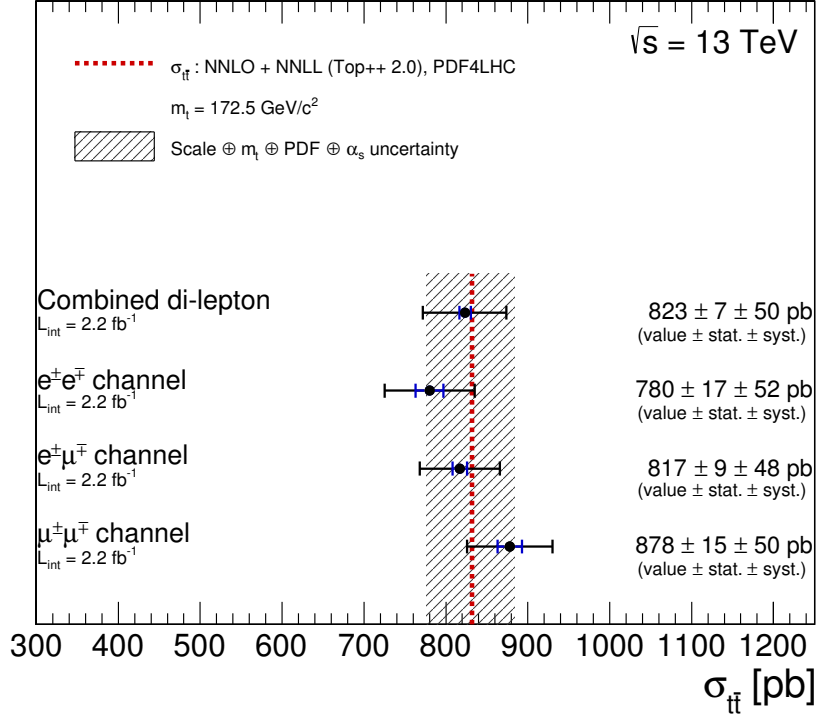


Figure 10.4 The inclusive $t\bar{t}$ cross section results obtained in the $e^\pm e^\mp$, $e^\pm \mu^\mp$, and $\mu^\pm \mu^\mp$ channels together with the di-lepton combination. The results are shown with the statistical and systematic (including luminosity uncertainty) uncertainties. The outer error bars correspond to the total uncertainties while the inner error bars indicate the statistical uncertainty. The vertical line and band represent the central value of the predicted cross section and the total uncertainty respectively.

10.5 Comparison with Different Selection Scenarios

In order to evaluate the used selection scenario and to look for possible optimization, several other scenarios are compared. In each of these scenarios, one of the following criterion is changed each at a time, with respect to the baseline selection:

- cut-based electron identification and isolation replaced by MVA-based,
- loose or tight b-tagging working points instead of medium (see Table 9.2),
- selection of at least two b-jets instead of at least one b-jet.

For each case the systematic uncertainties are recalculated accordingly. For signal modeling uncertainties, the b-jets reweighting correction is applied.

The statistical, experimental, theoretical, and total uncertainties are summarized per channel in Figures 10.5a, 10.7a, and 10.9a and compared to the baseline analysis uncertainties. The corresponding cross sections obtained for each case are shown in Figures 10.5b, 10.7b, and 10.9b. The breakdown of all systematics sources is given per channel in Figure 10.6, Figure 10.8, and Figure 10.10. The impact of the b-jet reweighting on the signal modeling uncertainties can be clearly seen for all selection scenarios in comparison to the values obtained if no correction is applied (see Figure B.13).

Electron identification: In general, a slight improvement of the accuracy of the measurement is obtained when using the electron MVA-based identification, where a reduction of 0.4% on the total uncertainty is achieved in the channels with electrons in the final state, i.e. $e^\pm e^\mp$ and $e^\pm \mu^\mp$. This is related to the lower uncertainties in the electron scale factors obtained using the MVA-based identification, which is reflected as a reduction in the lepton and background uncertainties.

A looser b-tagging working point: Using a loose b-tagging working point increases the selection efficiency and thus, lowers the statistical uncertainty. It also reduces the b-tagging uncertainty, due to the lower uncertainties in the b-tagging scale factors at this working point. However, it degrades the accuracy of the measurement by 0.2% to 0.9% in the different channels mainly due to background uncertainties and Q^2 scale uncertainties compared to the baseline analysis.

A tighter b-tagging working point: On the other hand, using a tight b-tagging working point decreases the background and the JES uncertainties by around 0.2% each, however, this decrease becomes less important when compared to the combined increase in the statistical and b-tagging uncertainties due to tighter selection of b-jets.

Moreover, the modeling and hadronization uncertainties also increase compared to the baseline analysis. The scale uncertainty is found to significantly decrease in the same flavor channels compared to the medium working point, but the opposite is found for the $e^\pm\mu^\mp$ channel. The different behavior in the $e^\pm\mu^\mp$ channel could be related to statistical fluctuations. In general, tightening the b-tagging selection increases the total uncertainty by 0.2% to 1.5% in the different channels.

At least two b-jets: The selection of at least two b-jets ensures less background contamination and therefore decreases the background uncertainty, but at the same time it significantly increases the b-tagging uncertainty. This selection is also found to significantly increase all signal modeling uncertainties despite the use of the b-jet reweighting, due to the larger acceptance corrections.

From the outcome of this study it can be concluded that the use of the MVA-based electron identification and isolation together with the criterion of at least one b-jet tagged using a medium working point yields an improvement of the measurement precision in the $e^\pm e^\mp$ and $e^\pm\mu^\mp$ channels and performs similar to the baseline scenario in the $\mu^\pm\mu^\mp$.

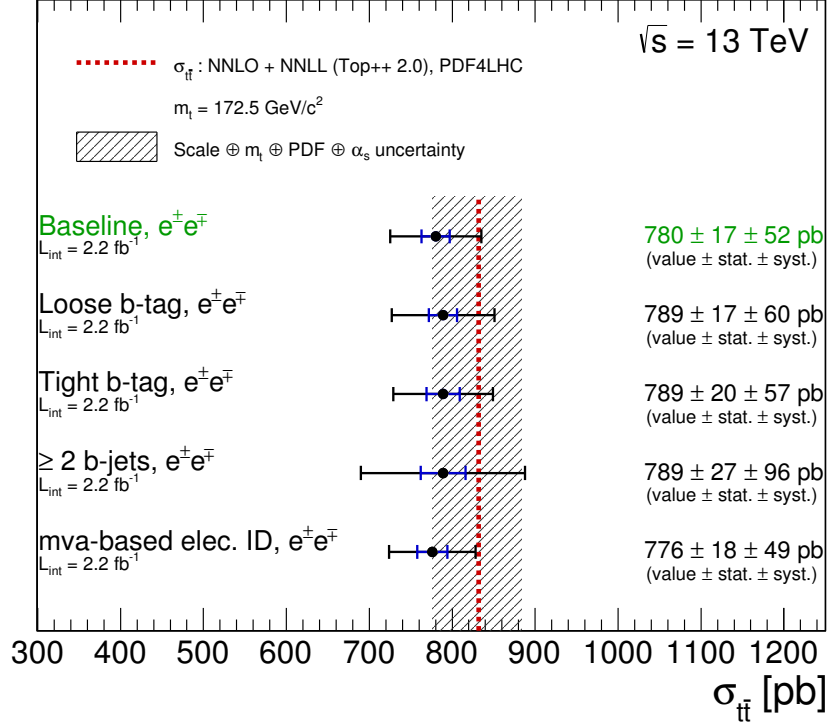
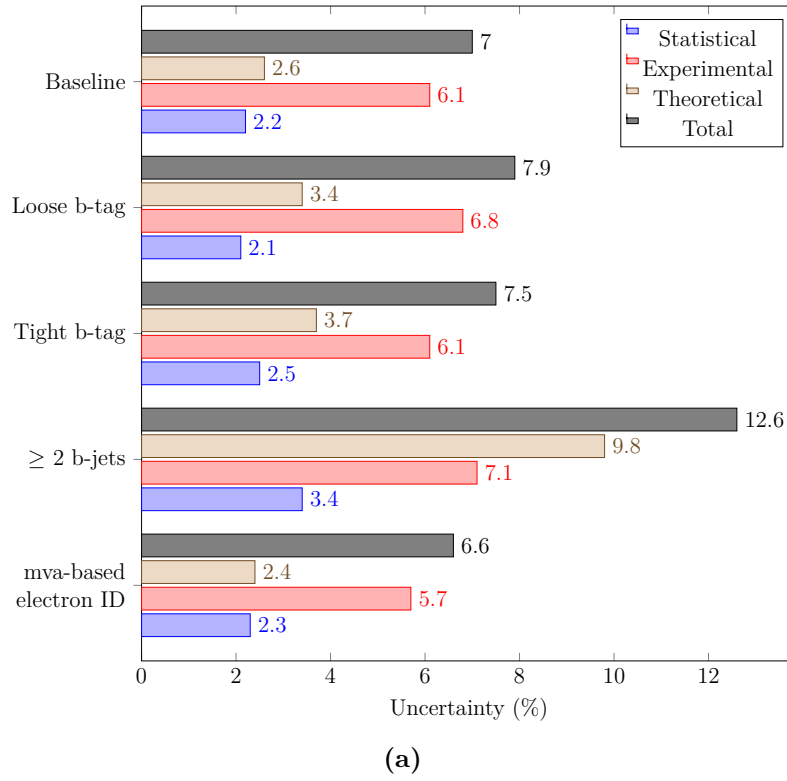


Figure 10.5 The obtained uncertainties (a) and cross sections (b) at different selection scenarios compared to the baseline analysis in the $e^\pm e^\mp$ channel.

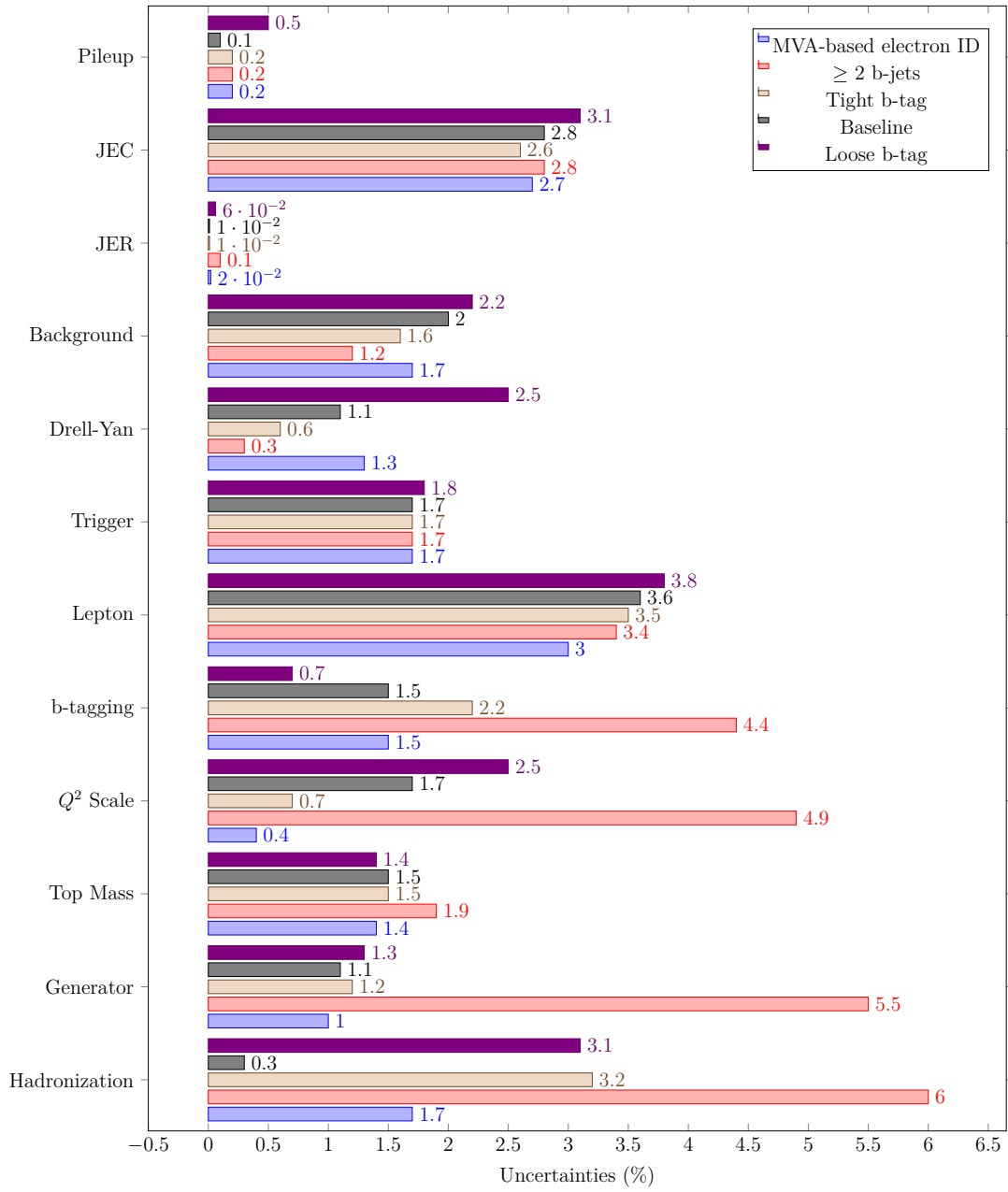


Figure 10.6 The breakdown of the systematic and experimental uncertainties obtained for different selection scenarios in the $e^\pm e^\mp$ channel.

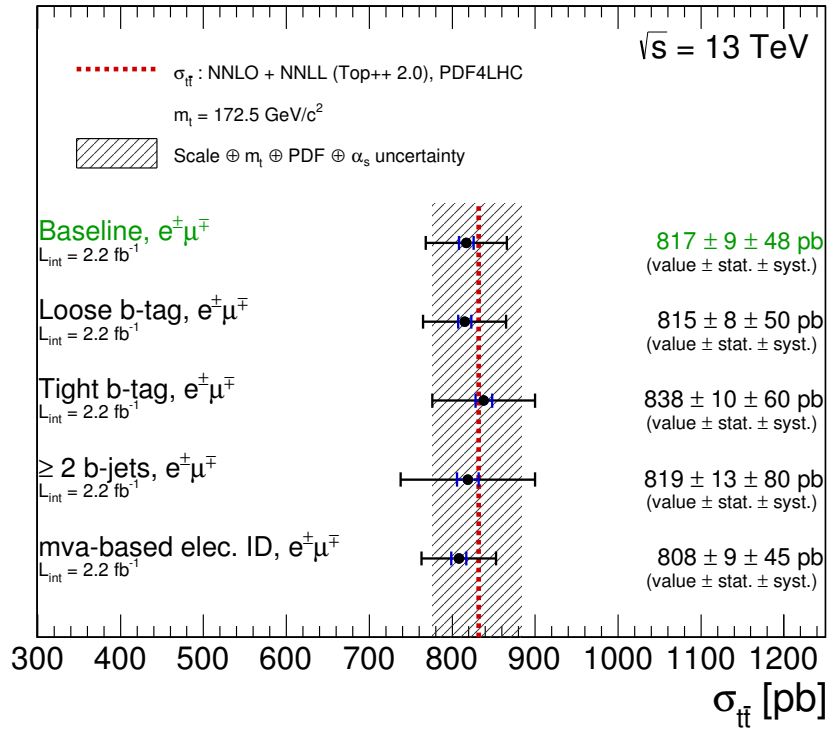
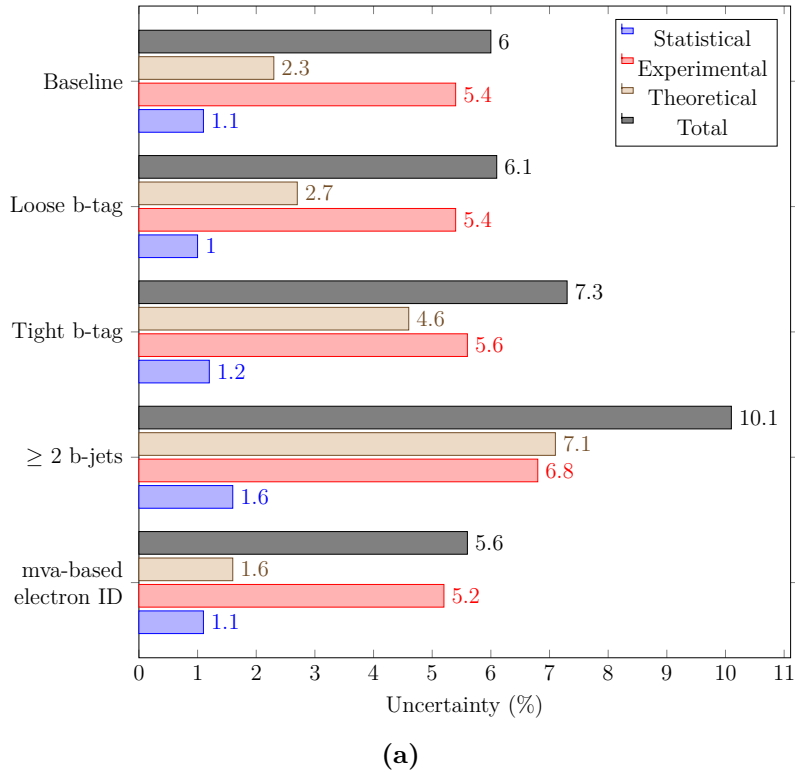


Figure 10.7 The obtained uncertainties (a) and cross sections (b) at different selection scenarios compared to the baseline analysis in the $e^\pm\mu^\mp$ channel.

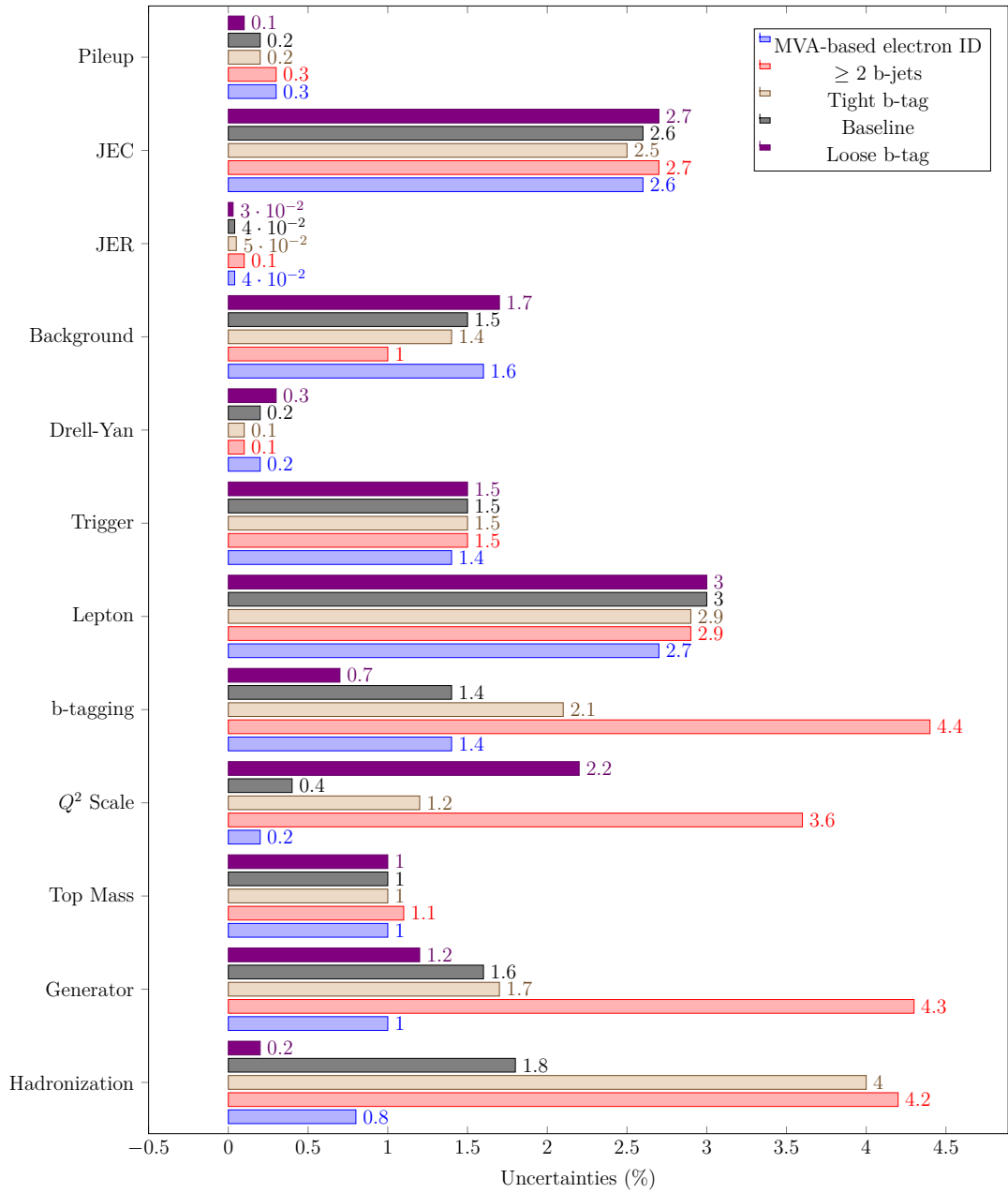


Figure 10.8 The breakdown of the systematic and experimental uncertainties obtained for different selection scenarios in the $e^\pm\mu^\mp$ channel.

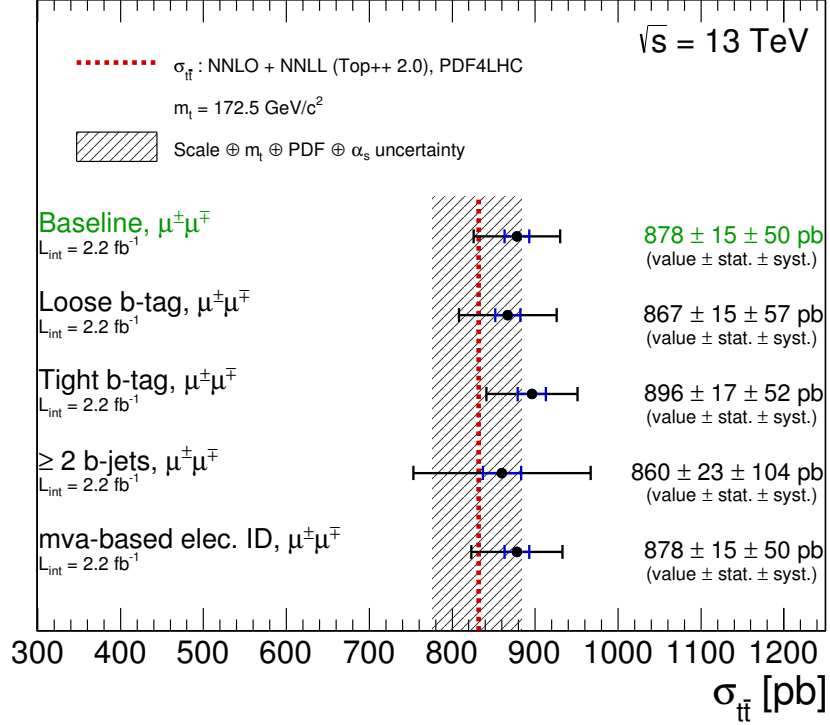
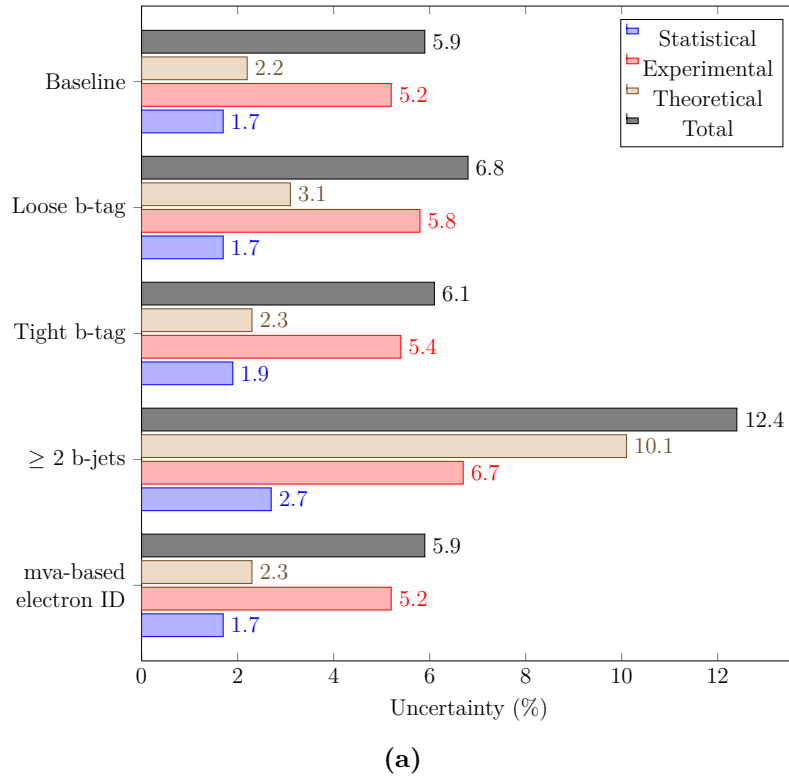


Figure 10.9 The obtained uncertainties (a) and cross sections (b) at different selection scenarios compared to the baseline analysis in the $\mu^\pm\mu^\mp$ channel.

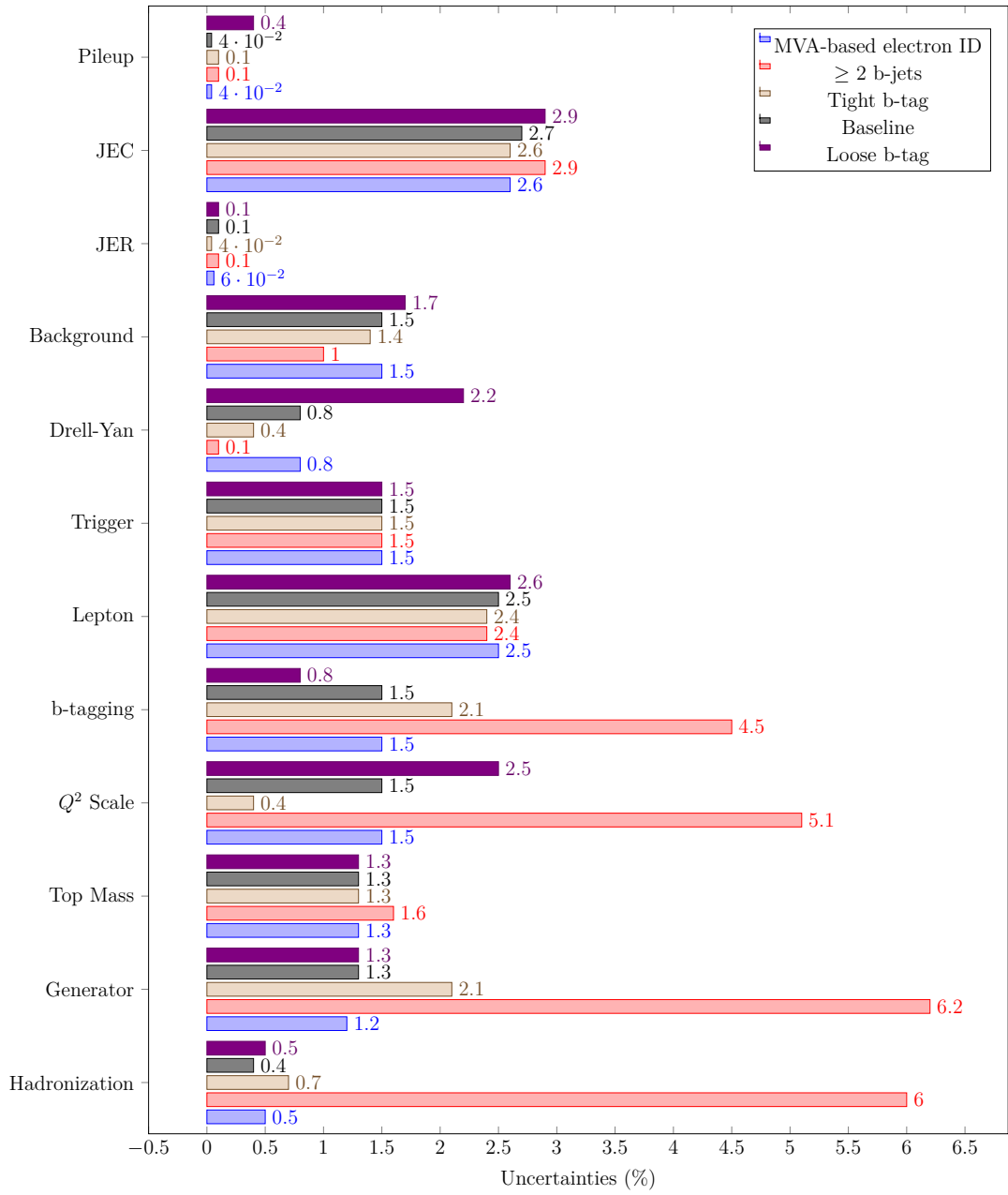


Figure 10.10 The breakdown of the systematic and experimental uncertainties obtained for different selection scenarios in the $\mu^\pm\mu^\mp$ channel.

10.6 Comparison to Other Results

The results of this work are found to be in agreement, within uncertainties, with two independent CMS measurements carried out at the same energy. The two measurements are performed in the $e^\pm\mu^\mp$ channel exploiting two dataset corresponding to 42 pb^{-1} [144] and 2.2 fb^{-1} [159]. Both used an event-counting method, selecting events containing oppositely charged electrons and muons, with two or more jets. The first measurement required no b-tagging while the second required at least one of the jets to be tagged as originating from a b quark. The respective obtained cross sections with the statistical and systematic uncertainties including luminosity uncertainty are

$$\sigma_{t\bar{t},e\mu}^{\text{CMS}}(42\text{ pb}^{-1}) = 746 \pm 58 \text{ (stat.)} \pm 64 \text{ (syst.) pb}, \quad (10.18)$$

$$\sigma_{t\bar{t},e\mu}^{\text{CMS}}(2.2\text{ fb}^{-1}) = 792 \pm 8 \text{ (stat.)} \pm 43 \text{ (syst.) pb}. \quad (10.19)$$

Even though the second measurement uses the same method and dataset as the measurement performed in this work (see Equation 10.13), the cross section central values are found to have a difference of 25 pb. This difference is related to the additional single lepton trigger paths used in the event selection of the official measurement in addition to the different treatment of non-Drell-Yan background, and to the non-prompt leptons. The official measurement includes in the selection of events electrons and muons from the τ lepton decays. The latter source of difference was verified as part of this work. The verification is performed by treating the $t\bar{t}$ -other events corresponding to the non-prompt leptons as signal. The efficiency, acceptance, and branching ratio are updated accordingly, using the values obtained in the official measurement. This resulted in diminishing the difference between the two measurements from 25 pb to about 5 pb. The difference in the systematic uncertainties between the two measurements is related to the top quark mass uncertainty included in this work but not in the official measurement.

The results are also found to be in agreement with two recent measurements performed by the ATLAS collaboration at $\sqrt{s} = 13$ TeV exploiting datasets with 78 pb^{-1} [160] and 3.2 fb^{-1} [145] of integrated luminosity, respectively. In these measurements the $t\bar{t}$ cross section is determined by counting the numbers of events with exactly one $e^\pm\mu^\mp$ pair and exactly two b-tagged jets. The background contributions are estimated using a combination of simulation and data-driven methods. In this measurement the cross section and the b-tagging efficiency are obtained simultaneously using a likelihood minimization method. The ATLAS measurements in the $e^\pm\mu^\mp$ channel using the 78 pb^{-1} and 3.2 fb^{-1} datasets are found to respectively be

$$\sigma_{t\bar{t},e\mu}^{\text{ATLAS}}(78\text{ pb}^{-1}) = 825 \pm 49 \text{ (stat.)} \pm 60 \text{ (syst.) pb}, \quad (10.20)$$

$$\sigma_{tt,e\mu}^{\text{ATLAS}}(3.2 \text{ fb}^{-1}) = 818 \pm 8 \text{ (stat.)} \pm 36 \text{ (syst.) pb}, \quad (10.21)$$

where the systematic uncertainty includes the uncertainty in luminosity. Using the same method, the ATLAS collaboration has also performed the measurement in the same flavor channel with a dataset of 85 pb^{-1} [161]. The results of this measurement, shown below, are also in agreement with the ones obtained in this work.

$$\sigma_{tt,ee}^{\text{ATLAS}}(85 \text{ pb}^{-1}) = 824 \pm 88 \text{ (stat.)} \pm 91 \text{ (syst.)} \pm 82 \text{ (lumi.) pb}, \quad (10.22)$$

$$\sigma_{tt,\mu\mu}^{\text{ATLAS}}(85 \text{ pb}^{-1}) = 683 \pm 74 \text{ (stat.)} \pm 76 \text{ (syst.)} \pm 68 \text{ (lumi.) pb}. \quad (10.23)$$

The comparison of the obtained results in the $e^{\pm}\mu^{\mp}$ channel with the theory prediction and the experimental results of ATLAS and CMS is given in Figure 10.11.

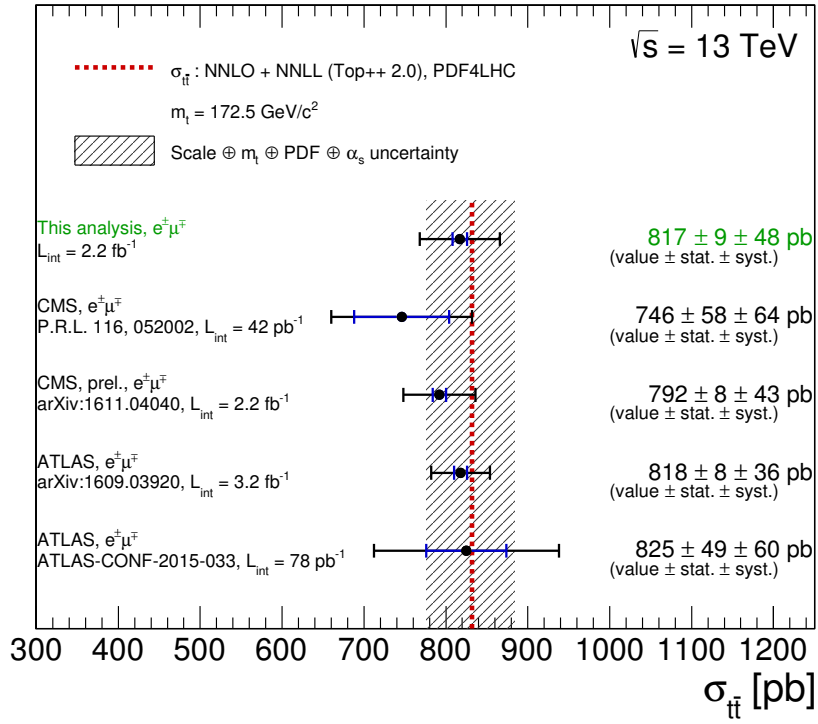


Figure 10.11 Comparison of the inclusive $t\bar{t}$ cross section results in the $e^{\pm}\mu^{\mp}$ channel of the presented analysis with all published measurements by the CMS and ATLAS collaborations in the same decay channel. The experimental results are shown with the statistical and systematic (including luminosity uncertainty) uncertainties. The outer error bars correspond to the total uncertainties while the inner error bars indicate the statistical uncertainty. The vertical line and band represent the central value of the predicted cross section and the total uncertainty, respectively.

Chapter 11

Summary and Outlook

The work conducted in this thesis is divided into two topics. The first topic is dedicated to detector development for the CMS Phase-II outer tracking system upgrade. The second topic is focused on the measurements of the $t\bar{t}$ production cross section at a center-of-mass energy of 13 TeV.

The first part of this thesis is devoted to studies for the Phase-II upgrade of the CMS outer tracking detector. In its Phase-II, the HL-LHC will achieve an instantaneous luminosity of about $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, corresponding to about 3000 fb^{-1} of integrated luminosity to be recorded by CMS in around 10 years of operation. To cope with the harsh radiation conditions and the increased collision rates, the CMS collaboration decided to replace the current tracking detector with an entirely new system. The new system will not only be able to resolve up to 200 collisions per bunch crossing, but will also provide information to the first level trigger. It is foreseen that the future outer tracker p_T -modules will provide trigger information by means of an on-board p_T -discrimination logic. This logic is implemented in the CBC read-out chip, which is under development in 130 nm CMOS technology.

In this thesis, two fully functional p_T -module prototypes equipped with CBC2 chips for read-out have been tested for the first time in a test beam. The performance is found to be well in agreement with the expectations. Clusters study revealed that the cluster width is in good agreement with geometrical predictions, and the cluster efficiency is found to be uniform across all tested sensors and above 99%. For the first time, the trigger logic of such modules has been tested by emulating the track bending in the magnetic field via a rotation of the module. The trigger efficiency shows the desired behavior and proves the p_T -discrimination capability of the CBC2. The efficiency to identify high- p_T tracks is found to be around 99%. With the used setup particles with momentum below 1.70 GeV could be rejected with a resolution of about 0.07 GeV.

Following the first test beam, and in the light of its results, the CBC2 has been further tested with irradiated mini-2S module [162] and with full 2S module. These measurements aim to investigate the performance of the CBC2 after irradiation as well as with full 2S module. Preliminary results show that the chip still performs well within expectations. Developments of the chip towards an improved version, the CBC3, are also taking place and further test beam measurements are planned.

The second part of this thesis is dedicated to the measurement of the top quark pair production cross section. Data corresponding to 2.2 fb^{-1} collected at a center-of-mass energy of 13 TeV by the CMS detector are analyzed. The top quark decays predominantly to a bottom quark and a W boson. The presented measurement is performed in the di-lepton channel ee , $e\mu$ and $\mu\mu$, where for the first time at such energy the cross section is measured in the same flavor channels using CMS data.

The measurement in this thesis is performed using an event counting method. The baseline event selection requires two well isolated leptons from prompt W boson decay in the final state, and at least two jets where at least one of the jets is identified as a b-jet. The Experimental uncertainties arising from detector and particle reconstruction effects, and theoretical uncertainties arising due to signal modeling and other theoretical assumptions, are included in the measurement. In this work a special b-jets reweighting technique is developed and implemented for the treatment of the $t\bar{t}$ signal modeling uncertainties. This technique is used to disentangles the b-tagging effects from the signal modeling effects, which lead into significant improvement of the overall precision of the cross section measurement. The obtained results, using the baseline event selection and the b-jets reweighting, in the three di-lepton channels are found to be in good agreement with the SM predictions.

For the evaluation of the event selection, variations to the baseline scenario are performed. These variations include different electron identification requirement, different number of required b-jets, and different b-jets identification criteria. The analysis is repeated independently for each of these variations and the results are compared to the ones from the baseline event selection. As a result of this study it is found that the use of the electron MVA-based identification, and the selection of at least one b-jet tagged using the medium b-tagging working point reduces the total uncertainty of the measurement.

By the end of 2016 around 38 fb^{-1} [163] of proton-proton collision data at $\sqrt{s} = 13\text{ TeV}$ had been recorded by the CMS detector. This increase in integrated luminosity will further enhance the precision of the $t\bar{t}$ production cross section measurement by reducing the statistical and systematic uncertainties. The improved precision of the measurement will be beneficial to many analysis programs probing the SM and the physics beyond.

Appendix A

Scale Factors Used in the $t\bar{t}$ Cross section Measurement

A.1 Di-lepton Trigger Scale Factors

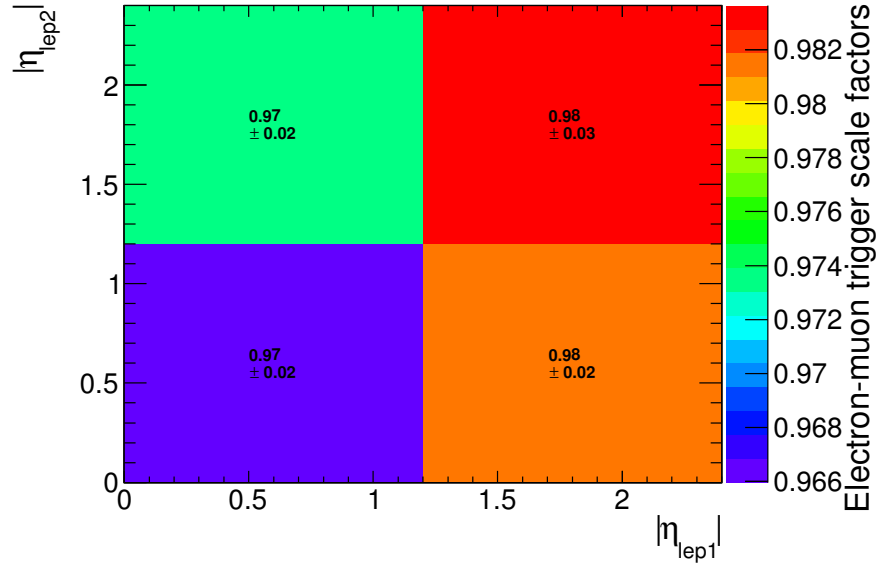


Figure A.1 Two dimensional distribution of the data-to-simulation trigger efficiency ratio ($SF_{trigger}$), for the $e\mu$ HLT trigger paths [164]. Presented as a function of the pseudo-rapidity of the two triggering leptons ($|\eta_{lep1}|$, $|\eta_{lep2}|$) including the total uncertainty on the efficiency derivation method.

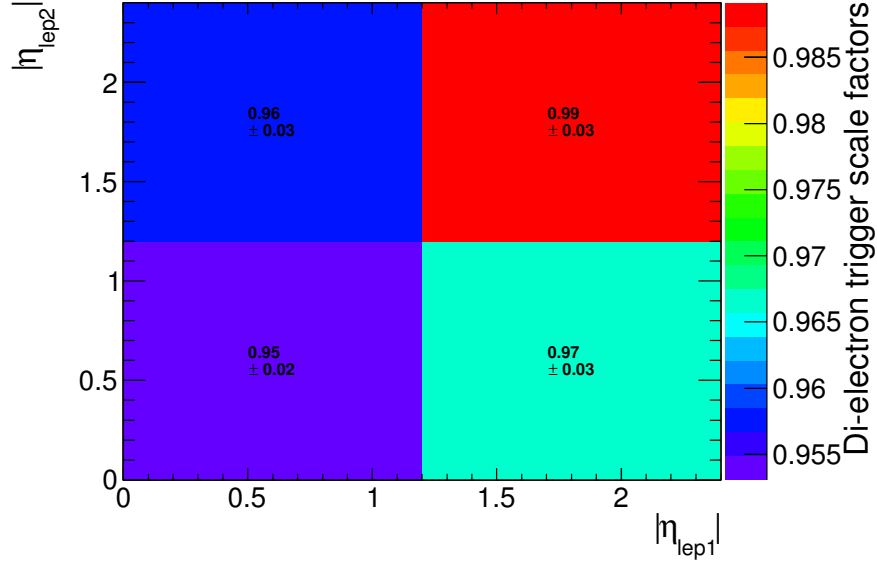


Figure A.3 Two dimensional distribution of the data-to-simulation trigger efficiency ratio ($SF_{trigger}$), for the ee HLT trigger paths [164]. Presented as a function of the pseudo-rapidity of the two triggering leptons ($|\eta_{lep1}|$, $|\eta_{lep2}|$) including the total uncertainty on the efficiency derivation method.

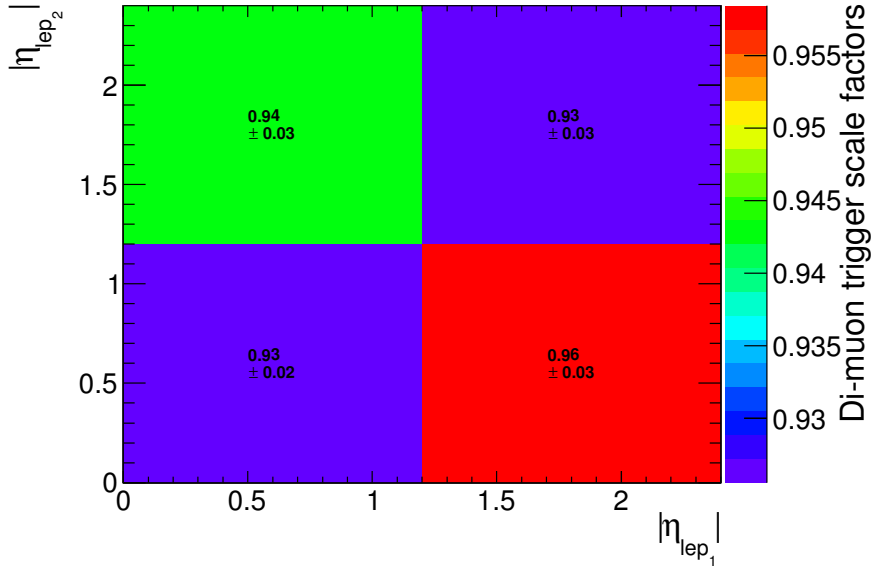


Figure A.2 Two dimensional distribution of the data-to-simulation trigger efficiency ratio ($SF_{trigger}$), for the $\mu\mu$ HLT trigger paths [164]. Presented as a function of the pseudo-rapidity of the two triggering leptons ($|\eta_{lep1}|$, $|\eta_{lep2}|$) including the total uncertainty on the efficiency derivation method.

A.2 Leptons Scale Factors

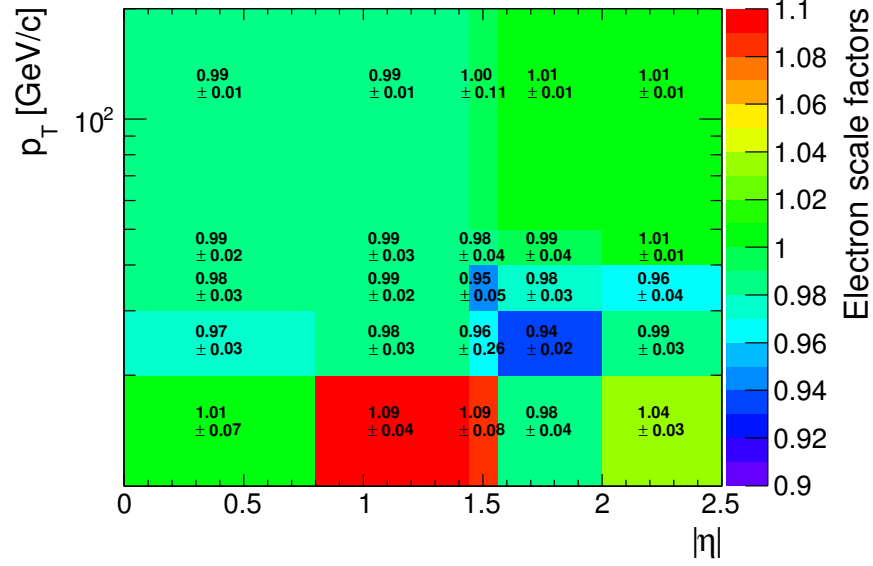


Figure A.4 Two dimensional distribution of the data-to-simulation lepton Identification and isolation efficiency ratio ($SF_{lep.}$) for electrons as a function of the leptons ($|\eta|, p_T$) including the total uncertainty on the efficiency derivation method. Provided by the CMS EGamma physics objects group.

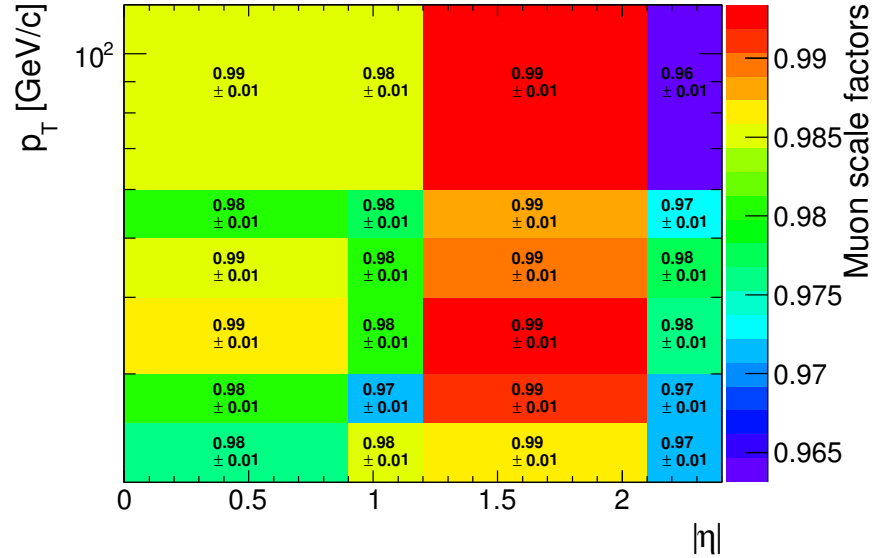


Figure A.5 Two dimensional distribution of the data-to-simulation lepton Identification and isolation efficiency ratio ($SF_{lep.}$) for muons as a function of leptons ($|\eta|, p_T$) including the total uncertainty on the efficiency derivation method. Provided by the CMS Muon physics objects group.

Appendix B

Impact of b-jets reweighting

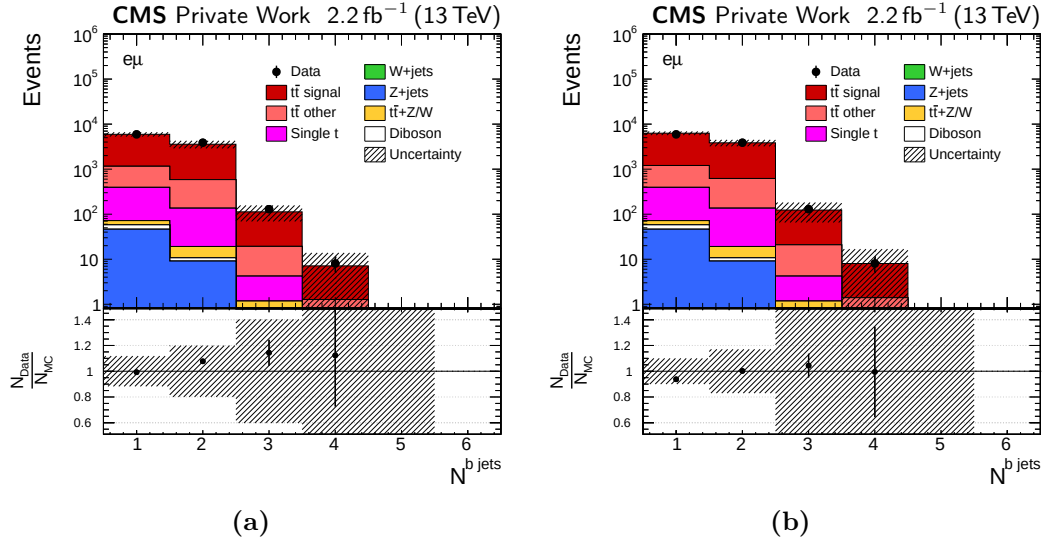


Figure B.1 Distributions of the b-jet multiplicity in the $e^\pm\mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the Q^2 scale down variation. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

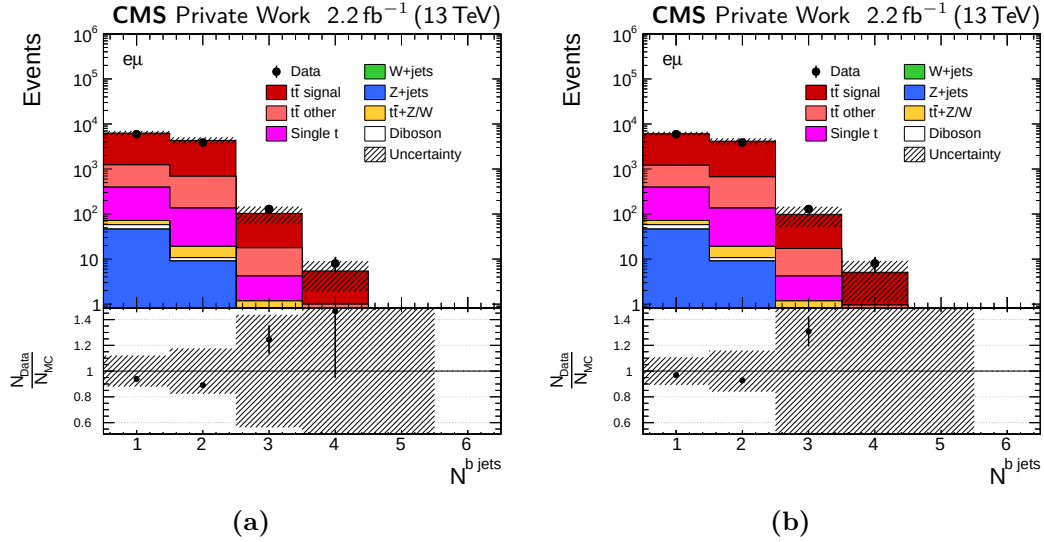


Figure B.2 Distributions of the b-jet multiplicity in the $e^\pm\mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the Q^2 scale up variation. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

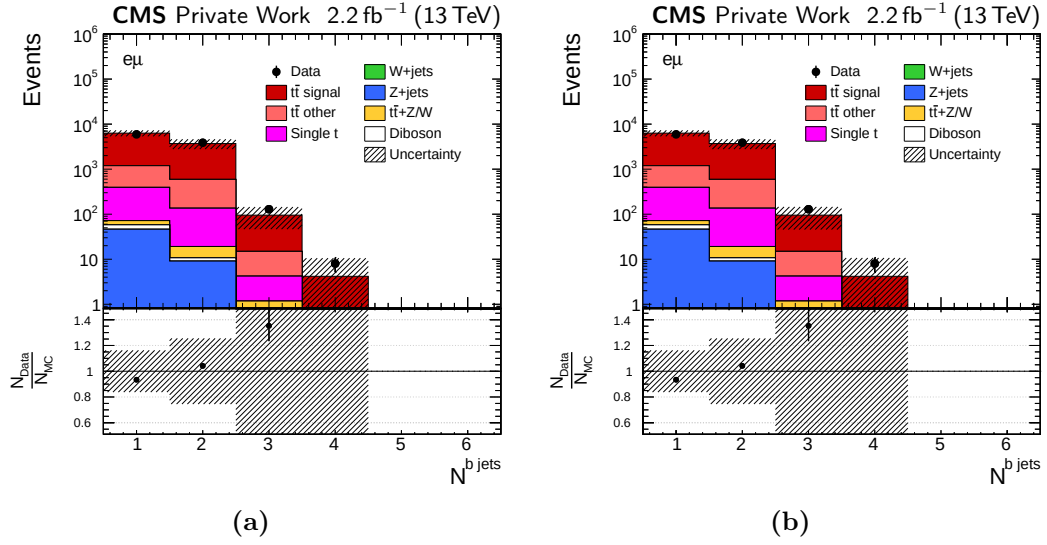


Figure B.3 Distributions of the b-jet multiplicity in the $e^\pm\mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the parton showering and hadronization variation. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

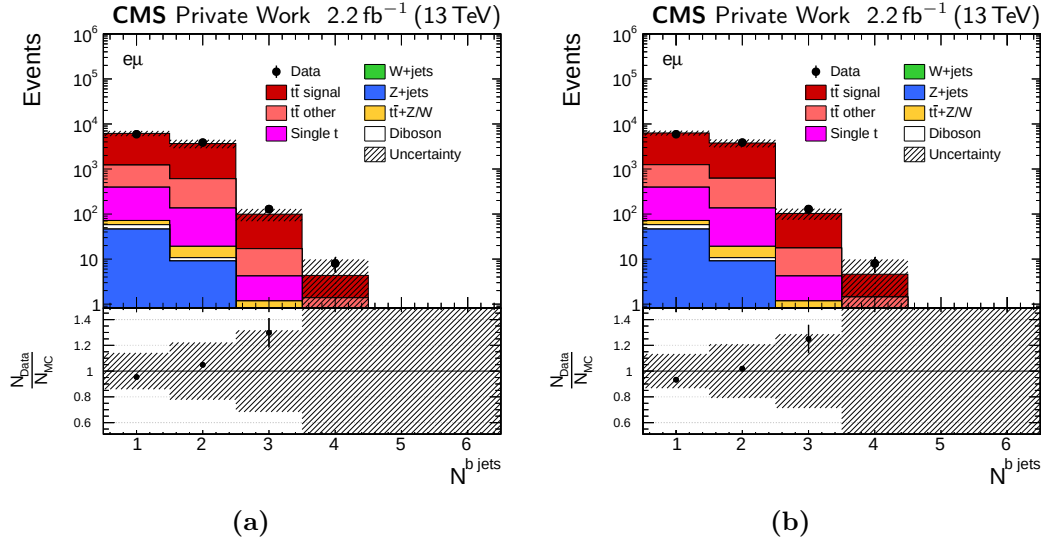


Figure B.4 Distributions of the b-jet multiplicity in the $e^\pm\mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the matrix element generator variation. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

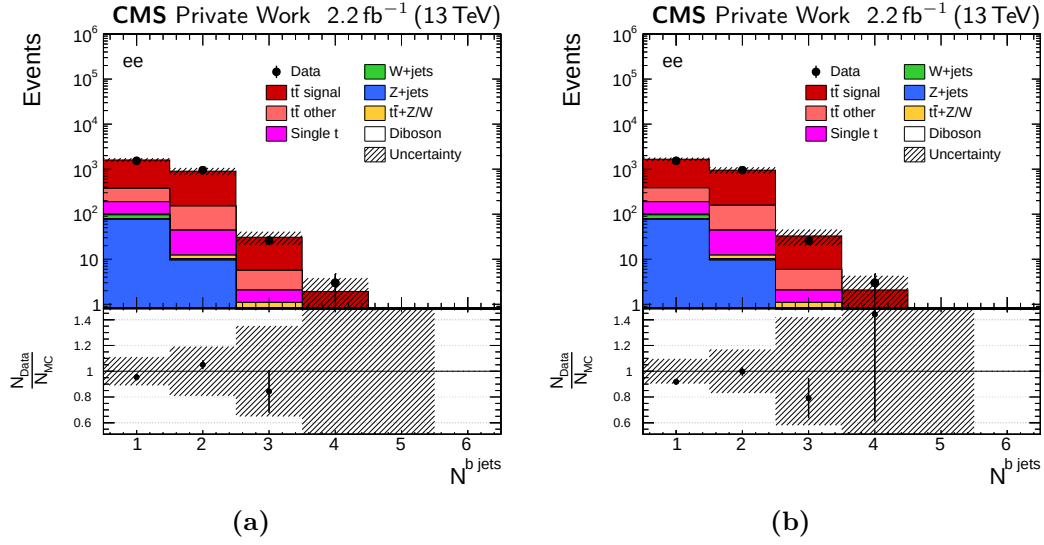


Figure B.5 Distributions of the b-jet multiplicity in the $e^\pm e^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the Q^2 scale down variation. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the tt signal/background simulation events (see Chapter 10).

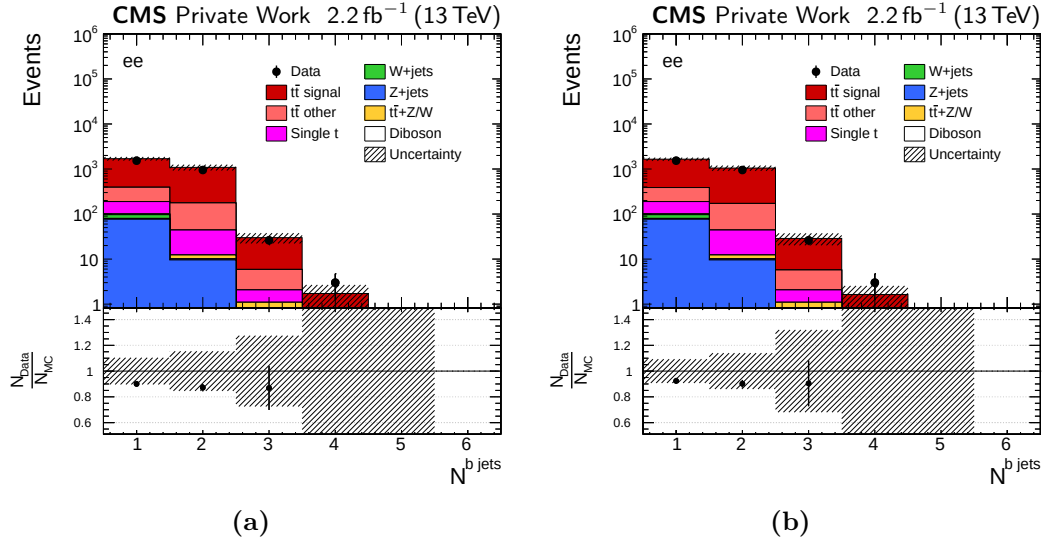


Figure B.6 Distributions of the b-jet multiplicity in the $e^\pm e^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the Q^2 scale up variation. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the tt signal/background simulation events (see Chapter 10).

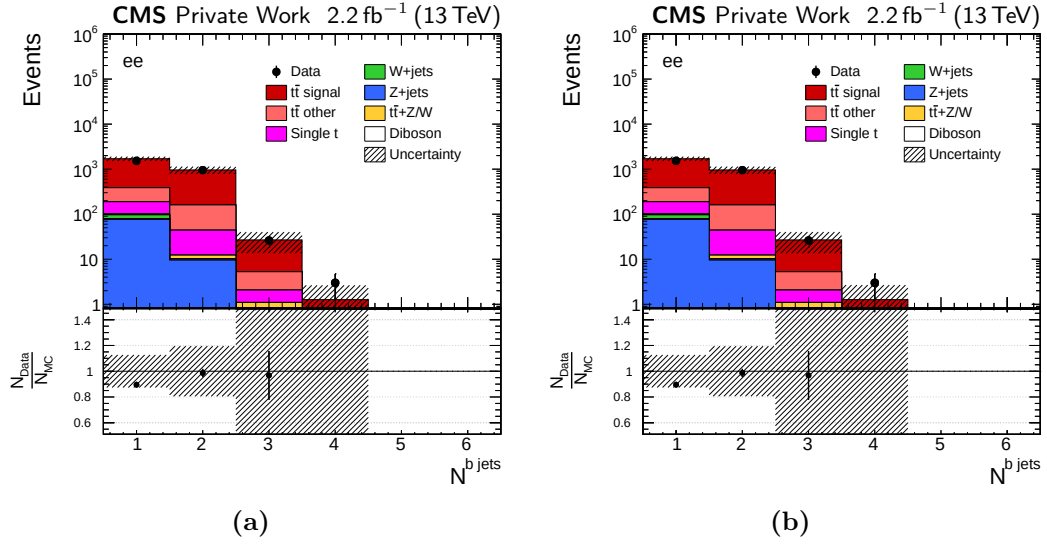


Figure B.7 Distributions of the b-jet multiplicity in the $e^\pm e^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the parton showering and hadronization variation. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

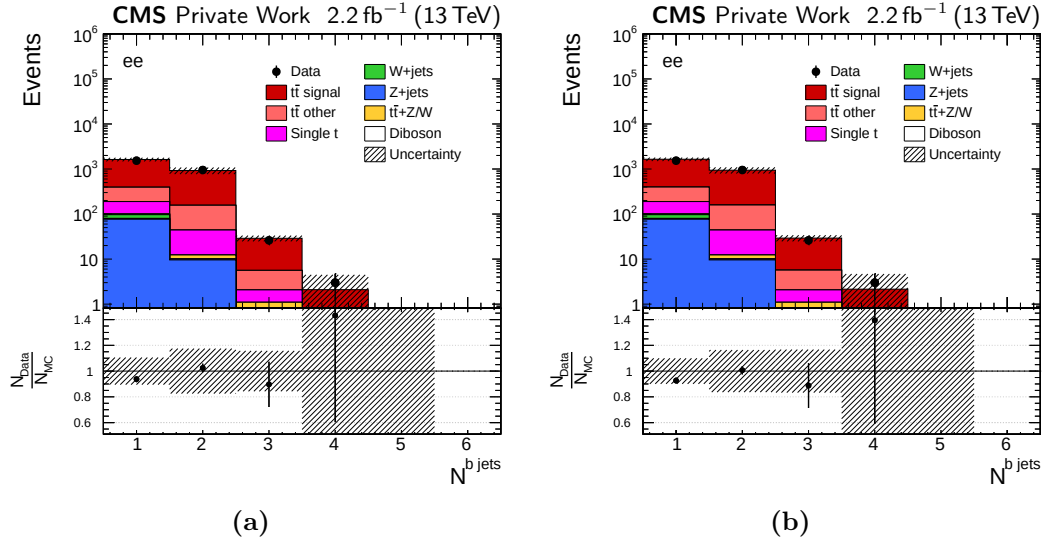


Figure B.8 Distributions of the b-jet multiplicity in the $e^\pm e^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the matrix element generator variation. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

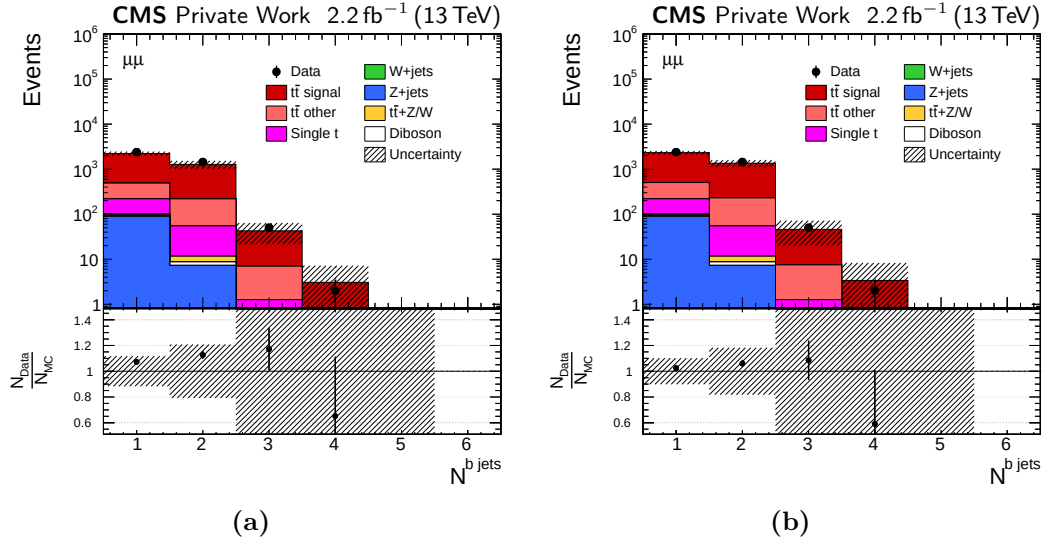


Figure B.9 Distributions of the b-jet multiplicity in the $\mu^+\mu^-$ channel before applying the b-jets reweighting (a) and after (b) for the Q^2 scale down variation. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

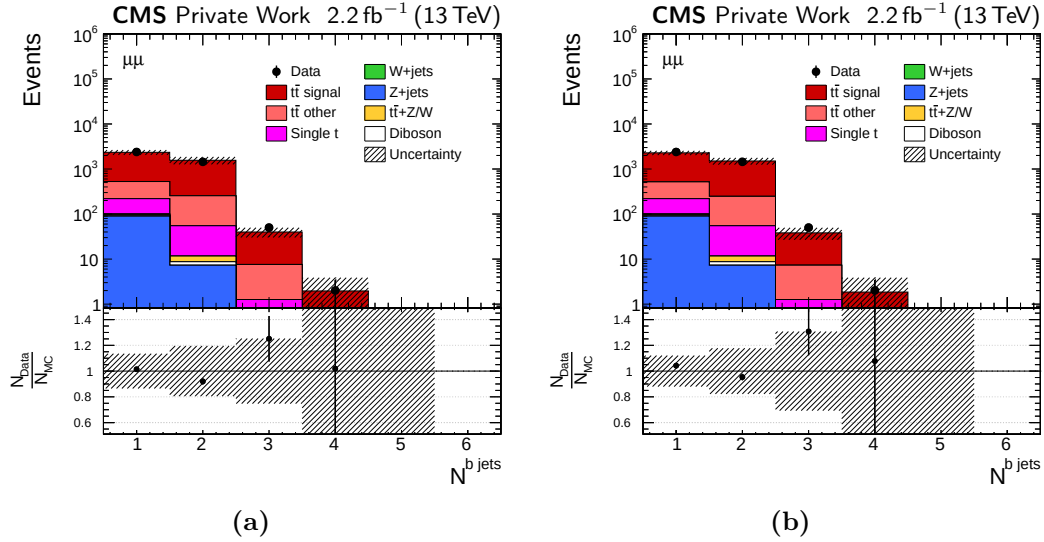


Figure B.10 Distributions of the b-jet multiplicity in the $\mu^+\mu^-$ channel before applying the b-jets reweighting (a) and after (b) for the Q^2 scale up variation. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

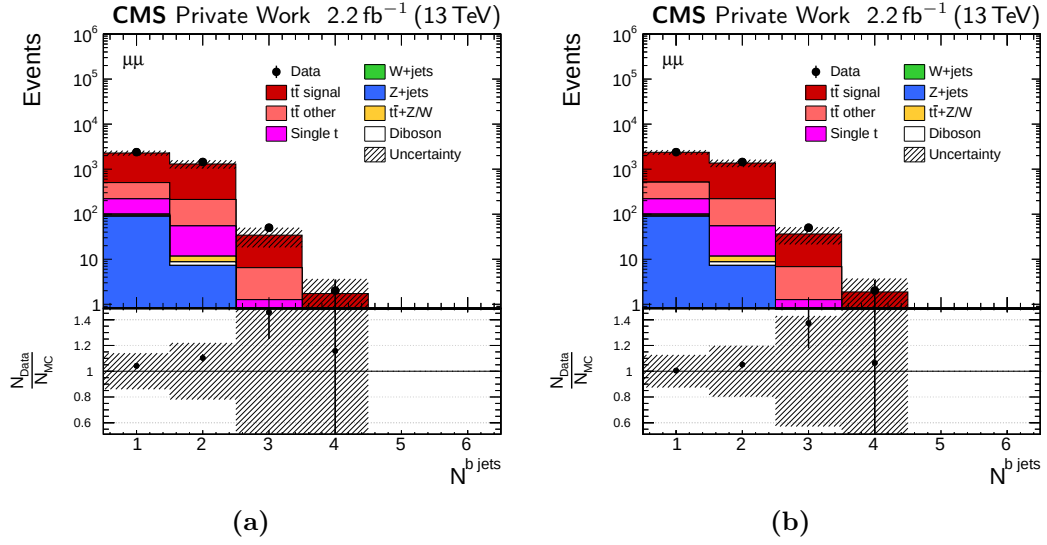


Figure B.11 Distributions of the b-jet multiplicity in the $\mu^\pm\mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the parton showering and hadronization variation. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

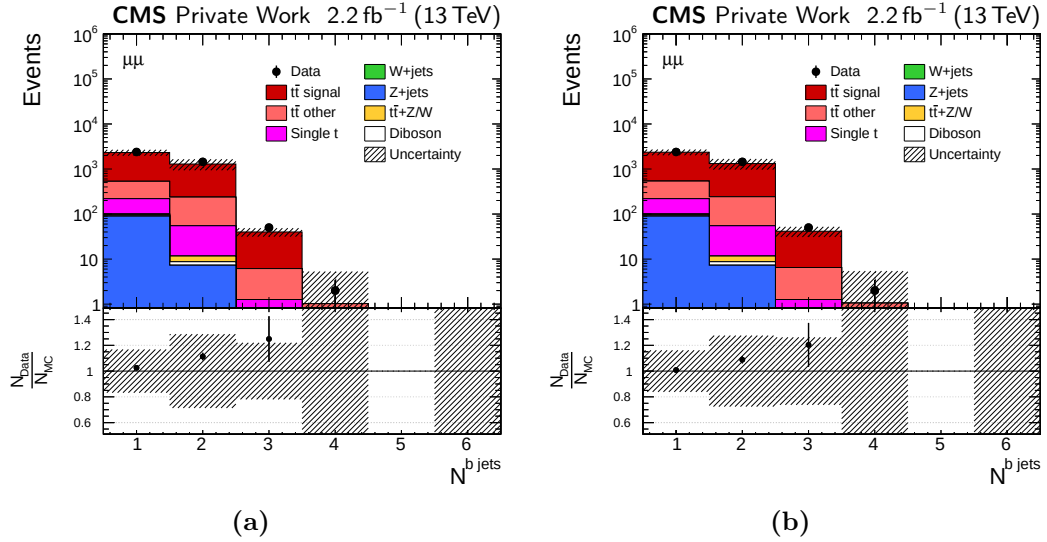
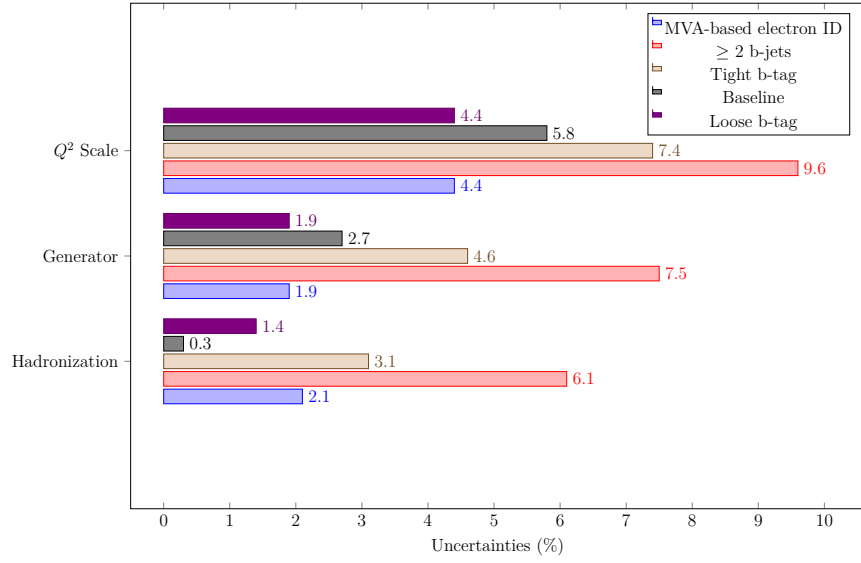
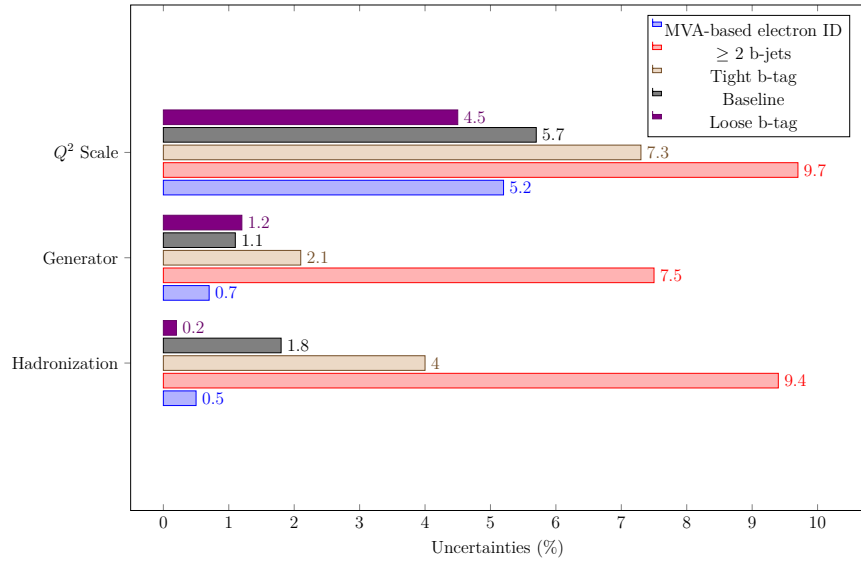
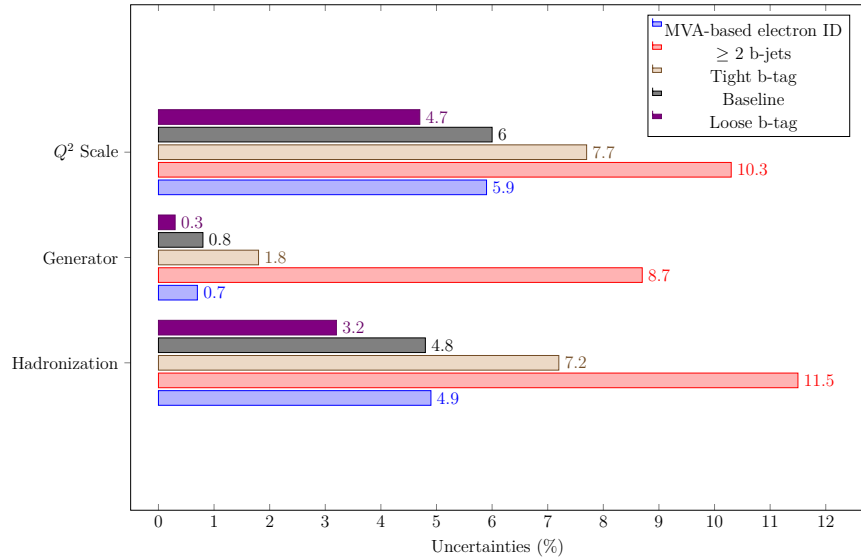


Figure B.12 Distributions of the b-jet multiplicity in the $\mu^\pm\mu^\mp$ channel before applying the b-jets reweighting (a) and after (b) for the matrix element generator variation. The distributions are obtained for data and simulation after the full event selection. The data-to-simulation ratio is shown. The hatched bands represent the total shape uncertainties on the $t\bar{t}$ signal/background simulation events (see Chapter 10).

(a) $e^\pm e^\mp$ channel(b) $e^\pm \mu^\mp$ channel(c) $\mu^\pm \mu^\mp$ channel**Figure B.13** Signal modeling uncertainties values if no b-jets reweighting is applied.

Appendix C

Electron Efficiencies

C.1 Electron Efficiency Calculation Using Tag&Probe

The Tag&Probe method is exploited in many high energy physics analyses, and typically used to calculate efficiencies for physics objects reconstruction quantities. In this thesis, and as a contribution to two analyses independent from the one presented in Chapter 10, the Tag&Probe is used to calculate electron identification and isolation efficiencies.

For electron identification and isolation efficiencies events are selected with two oppositely charged, same flavor, leptons having their invariant mass m^{ll} within the region of the Z -boson peak ($60 < m^{ll} < 120$ Gev). One of the leptons, referred to as *tag*, is selected with a tight criteria, while the second, referred to as *probe*, is usually selected with a looser criteria consistent with the analysis requirements.

The same selection of tag and probe electrons are applied independently on data and simulated $Z \rightarrow e^+e^-$ events in order to obtain the electron efficiencies. After the selection of the tag and probe pairs, a fit is applied on their invariant mass in order to subtract the background. Different fitting functions can be used to fit simultaneously the signal and the background of passing and failing probes in both data and simulation. The simulation sample is background free, but this practice is performed mainly to remove the non-signal probes from data, which can bias the efficiencies. After background subtraction the efficiency of a desired quantity can be calculated using

$$\epsilon = \frac{P_{pass}}{P_{pass} + P_{fail}} \quad (C.1)$$

where P_{pass} is the number of *passing probes* satisfying the quantity under study, in addition to the analysis selection criteria, divided by all probes $P_{pass} + P_{fail}$. Usually

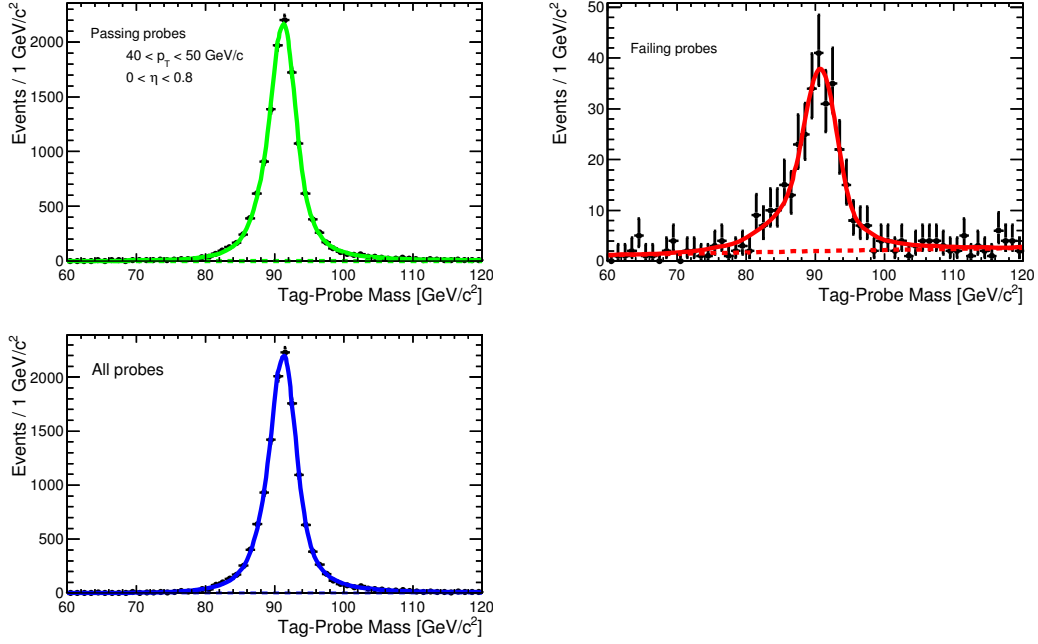


Figure C.1 An example fit of the tag and probe pair mass for the passing, failing, and all probes. The fit is performed on data for signal and background in the pseudo-rapidity region of $0 \leq \eta \leq 0.8$ and $40 \leq p_T \leq 50$ GeV/c.

a Breit-Wigner or Crystal-Ball functions are used for signal fit and an exponential function for background. The fits are performed in bins of η and p_T of the electron pairs. An example fit of passing, failing, and all probes is shown in Figure C.1 for simulation events in the central region ($0 < \eta < 0.8$) and for $40 < p_T < 50$ GeV.

C.1.1 Electron identification and isolation efficiencies for $t\bar{t}$ early analysis

As part of this thesis, the electron identification and isolation efficiencies are calculated for the first $t\bar{t}$ inclusive and differential cross section measurements at $\sqrt{s} = 13$ TeV using data corresponding to 42 fb^{-1} [144, 165]. For this measurement medium cut-based electron identification is used, and therefore the calculation of the efficiency of this requirement is performed. For this study, the used Drell-Yan events are generated with aMC@NLO. The following criteria is used for the selection of the tag and probe electrons.

- Tag:
 - Tight cut-based electron identification including isolation
 - $p_T > 30$ GeV, $|\eta| < 2.1$
 - Reject: $1.4442 < |\eta| < 1.5660$
 - Matched to single electron HLT trigger path

- Probe:
 - $p_T > 20 \text{ GeV}$, $|\eta| < 2.4$
- Passing Probe:
 - Medium cut-based electron definition and isolation

Fits for the passing and failing probes are given for different η and p_T bins in Figure C.2 and Figure C.3. For signal a convolution of Breit-Wigner (or Voigtian) and Crystal-Ball functions is used. For background an exponential function (or Chebyshev) is used. The resulting efficiencies and scale factors are given in Figure C.4. The two dimensional distribution of the obtained scale factors as function of η and p_T is also given in Figure C.5. The systematic uncertainties are obtained by varying the fit parameters, the tag electron selection requirements, the Z-peak window ($\pm 15 \text{ GeV}$).

C.1.2 Electron isolation efficiency for $t\bar{t}H$ analysis

The tag and probe method is also used as part of this thesis for the calculation of the electron isolation efficiency for the analysis searching for $t\bar{t}H$ production at $\sqrt{s} = 13 \text{ TeV}$ [166]. For this analysis an mva-based identification is used and therefore the isolation efficiencies are derived independently. For this calculation, a dataset corresponding to 2.7 fb^{-1} is used with a Drell-Yan sample generated using MadGraph LO event generator. The following criteria are used for the selection of the tag and probe pairs:

- Tag:
 - Tight cut-based electron identification including isolation
 - $p_T > 30 \text{ GeV}$, $|\eta| < 2.1$
 - Matched to single electron trigger path
- Probe:
 - $p_T > 15 \text{ GeV}$, $|\eta| < 2.5$
- Passing Probe:
 - Medium mva-based electron identification
 - $I_{rel.} < 0.15$

The obtained scale factors and the uncertainties due to different variations are shown in the two dimensional distributions in Figure C.6 as a function of $|\eta|$ and p_T of the electron.

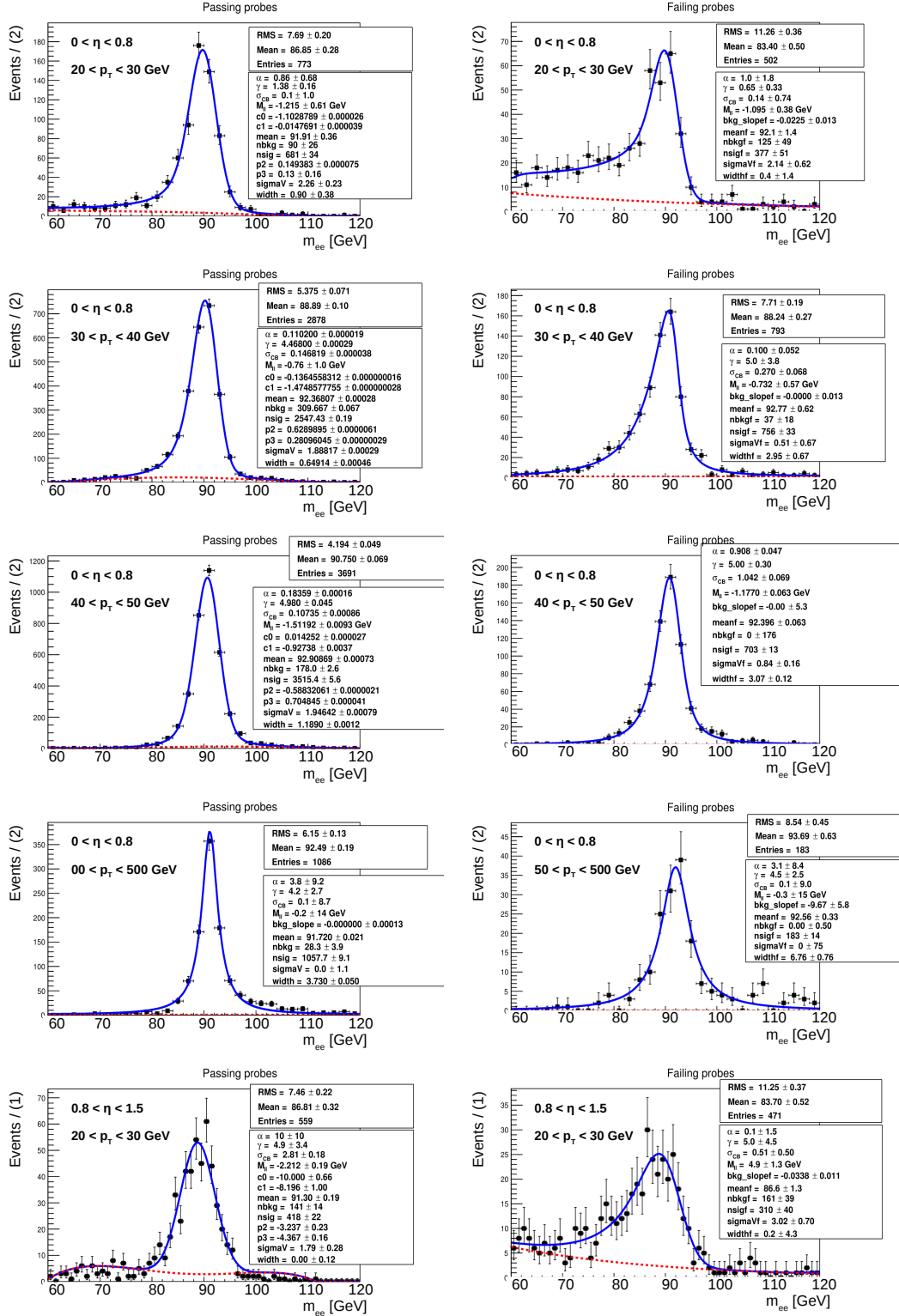


Figure C.2 Passing and failing probes fits performed on data and simulated events in different kinematic regions.

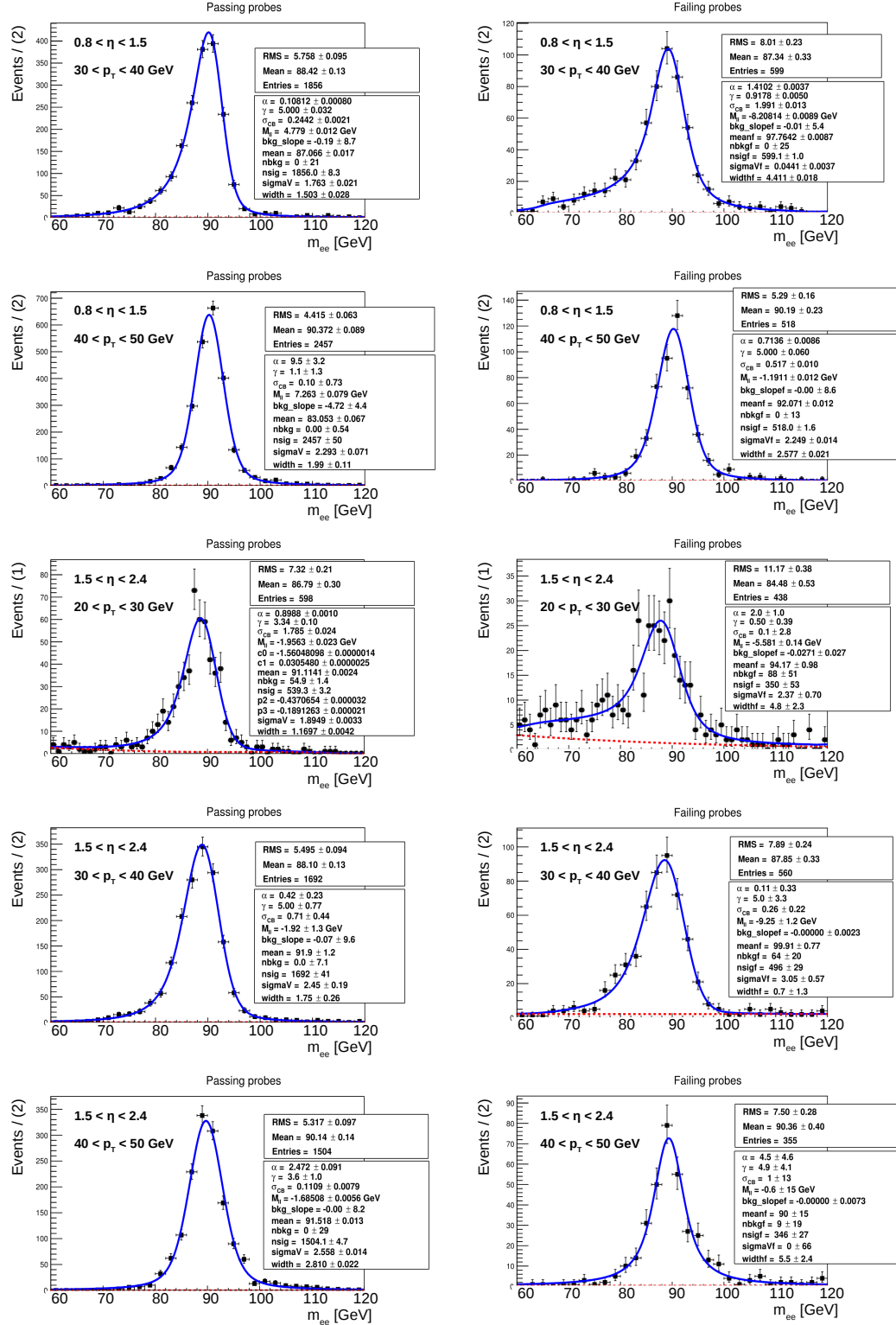


Figure C.3 Passing and failing probes fits performed on data and simulated events in different kinematic regions.

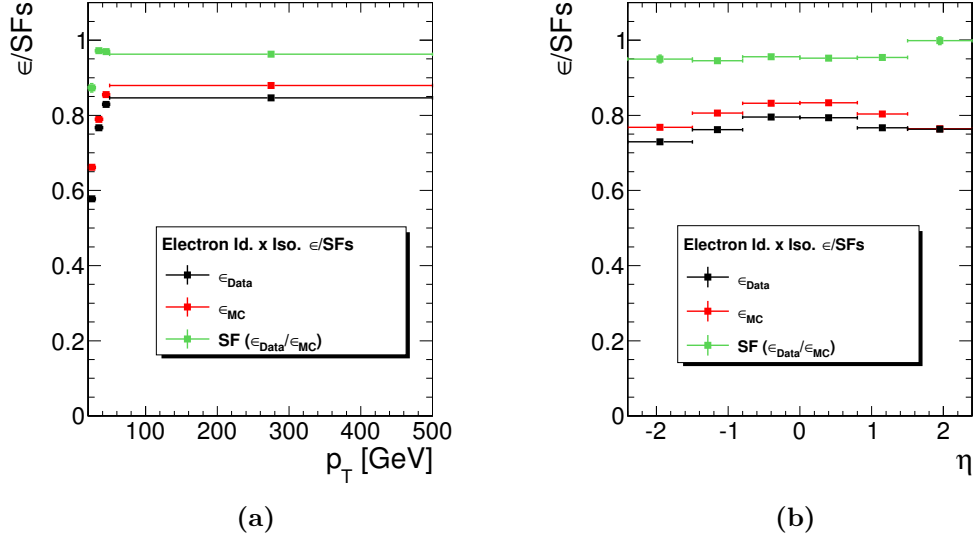


Figure C.4 Distribution of the electron identification and isolation efficiencies as a function of p_T (a) and $|\eta|$ (b) of the electron. The errors shown correspond to the statistical and the systematic uncertainties.

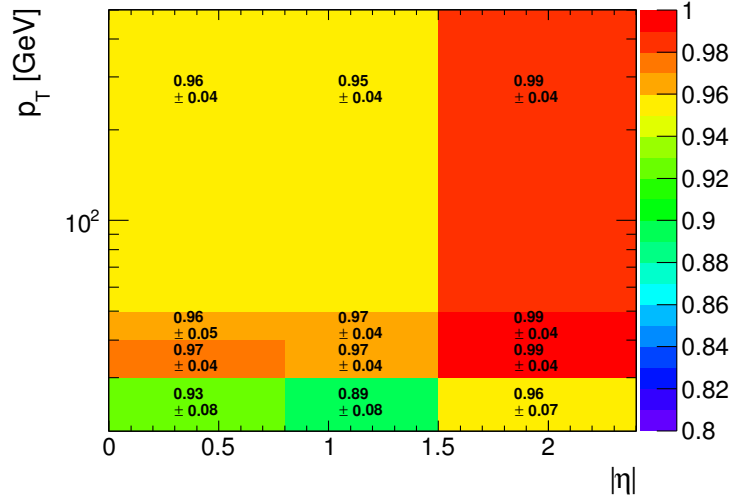
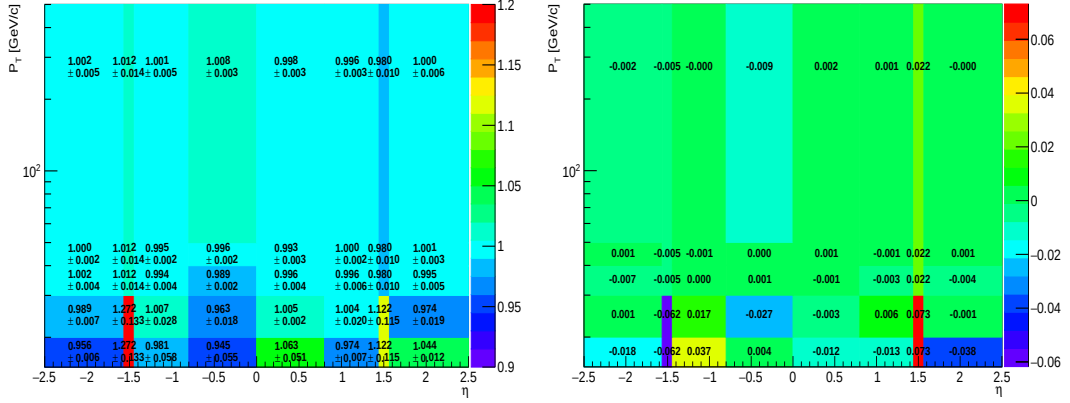
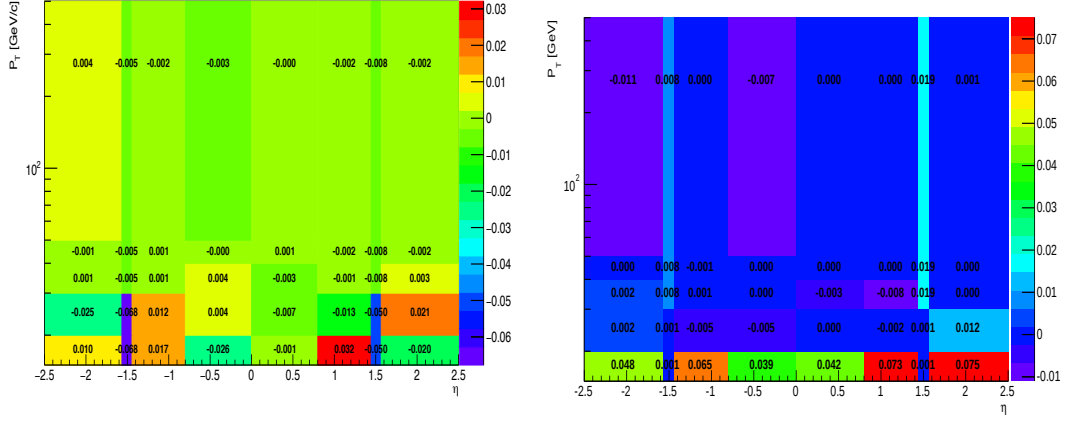


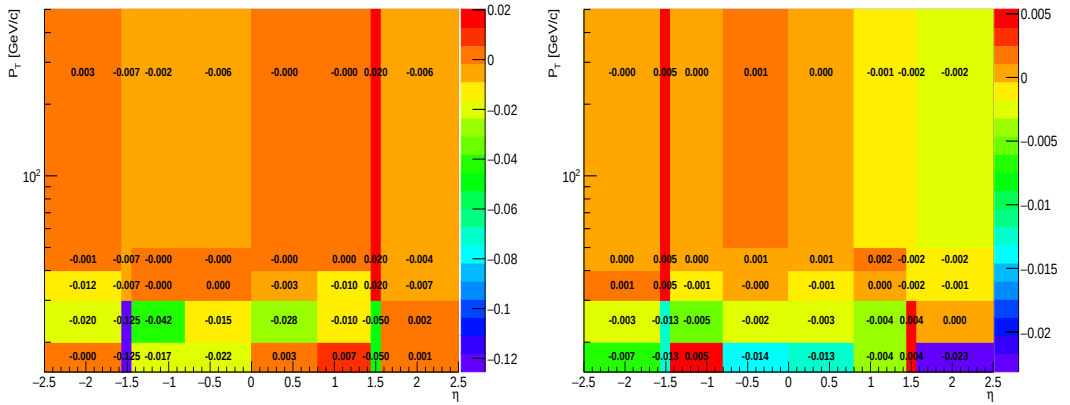
Figure C.5 Two dimensional distribution of the electron identification and isolation efficiencies as a function of $|\eta|$ and p_T of the electron. The errors shown correspond to the statistical and the systematic uncertainties. The scale factors range from 0.85 to 0.99.



(a) Electron isolation scale factors including statistical and systematic uncertainties. (b) Uncertainties obtained by varying the tag electron kinematic requirements.



(c) Uncertainties obtained by using medium identification requirement for the tag electron. (d) Uncertainties obtained by varying the signal fit parameters.



(e) Uncertainties obtained by varying the back-ground fit parameters. (f) Uncertainties obtained by using NLO simulated Drell-Yan sample.

Figure C.6 Distribution of the electron isolation scale factors (a) and uncertainties (b, c, d, e, and f) as a function of p_T and $|\eta|$ of the electron.

Appendix D

Tables

The simulation signal and background samples with their corresponding estimated cross sections are given in Table [D.1](#). The datasets used for the measurement of the $t\bar{t}$ inclusive cross section are given in Table [D.2](#) together with the certified runs.

In Table [D.3](#), the high level trigger (HLT) trigger paths used in the event pre-selection for dileptonic $t\bar{t}$ decays are presented. All paths are di-lepton triggers with minimal kinematics requirements for each lepton. The same selection rules are applied for the simulated Monte Carlo (MC) samples.

The electron variables used in the electron cut-based identification and isolation criteria are summarized in Table [D.4](#) with the corresponding cut values. These values represent a medium working point with around 70% of identification and isolation efficiency. This table is provided by the CMS EGamma physics object group.

In Table [D.5](#), the event yields after the application of each of the selection criterion in the three di-lepton channels, in addition to their combination, are given. The numbers are given for data, and for the simulation of $t\bar{t}$ signal, $t\bar{t}$ background, and each of the other non- $t\bar{t}$ backgrounds.

Sample	$\sigma [pb]$
/TT_TuneCUETP8M1_13TeV-powheg-pythia8/ RunIIFall15MiniAODv1-PU25nsData2015v1_76X_mcRun2_asymptotic_v12_ext3-v1	831.76
/ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	35.85
/ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	35.85
/DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1+_ext1-v1	22635.1
/DYJetsToLL_M-50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/ RunIIFall15MiniAODv2-PU25nsData2015v1_HCALDebug_76X_mcRun2_asymptotic_v12-v1	6025.2
/WJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	61526.7
/WW_TuneCUETP8M1_13TeV-pythia8/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	118.7
/WZ_TuneCUETP8M1_13TeV-pythia8/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	44.9
/ZZ_TuneCUETP8M1_13TeV-pythia8/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	15.4
/TTZToQQ_TuneCUETP8M1_13TeV-amcatnlo-pythia8/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	0.611
/TTWJetsToQQ_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	0.435
/TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	0.210
/TTJets_TuneCUETP8M1_13TeV-madgraphMLM-pythia8/ RunIIFall15MiniAODv1-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	831.76
/TTJets_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/ RunIIFall15MiniAODv1-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	831.76
/TT_TuneEE5C_13TeV-powheg-herwigpp/ RunIIFall15MiniAODv1-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	831.76
/TT_TuneCUETP8M1_mtop1695_13TeV-powheg-pythia8/ RunIIFall15MiniAODv1-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	831.76
/TT_TuneCUETP8M1_mtop1755_13TeV-powheg-pythia8/ RunIIFall15MiniAODv1-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	831.76
/TT_TuneCUETP8M1_13TeV-powheg-scaleup-pythia8/ RunIIFall15MiniAODv1-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1+_ext3-v2	831.76
/TT_TuneCUETP8M1_13TeV-powheg-scaledown-pythia8/ RunIIFall15MiniAODv1-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1+_ext3-v1	831.76
/ST_tW_top_5f_mtop1695_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	35.85
/ST_tW_top_5f_mtop1755_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v2	35.85
/ST_tW_antitop_5f_mtop1695_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	35.85
/ST_tW_antitop_5f_mtop1755_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1/ RunIIFall15MiniAODv2-PU25nsData2015v1_76X_mcRun2_asymptotic_v12-v1	35.85

Table D.1 Summary of simulated signal and background samples. The theory cross section used for the normalization of each sample is also given.

Sample	Run range
/MuonEG/Run2015C_25ns-16Dec2015-v1	254227 - 254914
/MuonEG/Run2015D_25ns-16Dec2015-v1	256630 - 260627
/DoubleMuonEG/Run2015C_25ns-16Dec2015-v1	254227 - 254914
/DoubleMuonEG/Run2015D_25ns-16Dec2015-v1	256630 - 260627
/DoubleEG/Run2015C_25ns-16Dec2015-v1	254227 - 254914
/DoubleEG/Run2015D_25ns-16Dec2015-v1	256630 - 260627

Table D.2 Data samples used in the measurement of the $t\bar{t}$ production cross section.

Di-lepton	HLT path name
$\mu^\pm\mu^\mp$	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v*
$\mu^\pm\mu^\mp$	HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v*
$e^\pm e^\mp$	HLT_Ele17_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*
$\mu^\pm e^\mp$	HLT_Mu17_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*
$\mu^\pm e^\mp$	HLT_Mu8_TrkIsoVVL_Ele17_CaloIdL_TrackIdL_IsoVL_v*

Table D.3 Summary of the di-lepton HLT paths used in data for the three dilepton channels (ee , $e\mu$, $\mu\mu$).

Variable	Barrel	End-cap
$ \Delta\eta <$	0.0103	0.00733
$ \Delta\phi <$	0.0336	0.114
$\frac{H}{E} <$	0.0876	0.0678
full $5 \times 5 \sigma_{I_\eta I_\eta} <$	0.0101	0.0283
$ d_0 <$	0.0118	0.0039
$ d_z <$	0.3730	0.602
$\frac{1}{E} - \frac{1}{p} <$	0.0174	0.0898
$I_{rel.} <$	0.0766	0.0678
Expected missing inner hits $\leq$	2	1
pass photon conversion veto	yes	yes

Table D.4 Summary of the variables used to define the identification and isolation criteria of electrons.

$\mu^\pm\mu^\mp$	2 leptons	2 jets	E_T^{miss}	b-tagging
$t\bar{t}$ signal	6548.16	4704.81	3683.92	3028.4
$t\bar{t}$ other	1044.62	752.513	602.911	487.288
$t\bar{t}+Z/W$	15.0305	14.1477	12.0045	9.4909
tW	754.399	287.587	223.152	163.263
di-boson	1016.1	108.887	56.2616	5.99292
W+jets	57.0348	18.5142	18.5142	0
Z+jets	121570	6225.22	830.396	95.013
Sum MC	131005	12111.7	5427.16	3789.44
Data	129161	11916	5472	3872

$\mu^\pm e^\mp$	2 leptons	2 jets	E_T^{miss}	b-tagging
$t\bar{t}$ signal	14155.8	10222.4	10222.4	8441.13
$t\bar{t}$ other	2284.73	1642.05	1642.05	1326.87
$t\bar{t}+Z/W$	32.5519	30.7535	30.7535	23.7026
tW	1596.72	602.515	602.515	442.311
di-boson	1924.08	140.073	140.073	13.2925
W+jets	594.35	26.8687	26.8687	0
Z+jets	5686.45	363.231	363.231	55.244
Sum MC	26274.7	13027.8	13027.8	10302.6
Data	25378	12579	12579	9889

$e^\pm e^\mp$	2 leptons	2 jets	E_T^{miss}	b-tagging
$t\bar{t}$ signal	4594.24	3315.1	2606.12	2132.65
$t\bar{t}$ other	693.6	499.482	399.346	326.241
$t\bar{t}+Z/W$	10.765	10.0314	8.54881	6.6248
tW	530.029	207.998	164.76	121.6
di-boson	670.564	77.253	38.8822	3.60878
W+jets	292.498	30.9035	35.7991	16.8589
Z+jets	72880.8	3724.4	534.11	85.3634
Sum MC	79672.5	7865.16	3787.56	2692.95
Data	77656	7762	3639	2504

<i>Combined</i>	2 leptons	2 jets	E_T^{miss}	b-tagging
$t\bar{t}$ signal	25298.2	18242.3	16512.4	13602.2
$t\bar{t}$ other	4022.95	2894.04	2644.3	2140.4
$t\bar{t}+Z/W$	58.3474	54.9326	51.3068	39.8183
tW	2881.15	1098.1	990.427	727.173
di-boson	3610.75	326.213	235.217	22.8942
W+jets	943.883	76.2864	81.1821	16.8589
Z+jets	200137	10288	1724.82	235.539
Sum MC	236952	32979.8	22239.7	16784.9
Data	232195	32257	21690	16265

Table D.5 Number of expected signal and background events, compared to the event yields in the data, after each selection step.

Eidesstattliche Erklärung/Declaration

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

I hereby declare, on oath, that I have written the present dissertation by my own and have not used other than the acknowledged resources and aids.

Hamburg, February 2017

Ali Harb

Some of the results presented in this thesis are shown or used in the following publications:

[73] CMS Tracker Collaboration, “Test beam demonstration of silicon microstrip modules with transverse momentum discrimination for the future CMS tracking detector,” (2017). [To be published].

[144] CMS Collaboration, “Measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV,” *Phys. Rev. Lett.* **116** no. 5, (2016) 052002, arXiv:1510.05302.

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