

VRIJE  
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<sup>1</sup> A search for flavour changing neutral currents  
<sup>2</sup> involving a top quark and a Z boson, using the  
<sup>3</sup> data collected by the CMS collaboration at a  
<sup>4</sup> centre-of-mass energy of 13 TeV

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# 1

71

## Theoretical basis

72 The Standard Model (SM) [1] is a name given in 1970s to a theory describing the fundamental  
73 particles and their interactions. This quantum field theory describes the particles and their  
74 interactions as fields and has successfully incorporated three of the four fundamental forces in  
75 the universe. In [Section 1.1](#), the particle content of the SM is summarised, while [Section 1.2](#)  
76 describes the SM Lagrangian and its symmetries. In [Section 1.3](#), the flavour content of the SM  
77 is highlighted, while [Section 1.4](#) focusses on the SM top quark. The latest experimental results  
78 of the top quark are given in [Section 1.5](#).

79 The successful theory of the SM has some shortcomings which are discussed in [Section 1.6](#)  
80 and lead to searches for a more general theory. One of such a search is using effective field  
81 theory (EFT) [2] to search for new physics in a model independent way. In [Section 1.7](#) an EFT  
82 model focussing on flavour changing neutral currents (FCNC) involving a top quark is presented.  
83 Its current experimental constraints are given in [Section 1.8](#).

### 84 1.1 Getting to the nature of things

85 The interactions in nature can be described by four forces, the strong force, the electromagnetic  
86 (EM) force, the weak force and the gravitational force. These interactions happen via particles  
87 with an integer spin known as bosons. The strong interaction is mediated by eight gluons  $g$ ,  
88 while the electromagnetic force is mediated by photons  $\gamma$ , and the weak force by  $Z$  and  $W^\pm$   
89 bosons. In [Table 1.1](#), the forces and their characteristics are shown. The gravitational force is  
90 the only force not included in the SM and can be neglected for energies lower than the Planck  
scale ( $1.22 \cdot 10^{19}$  GeV).

Table 1.1: The four forces of nature and their characteristics.

	Range	Mediator
Strong force	$10^{\text{-}e} - 15$ m	8 gluons
Electromagnetic force	$\infty$	photon
Weak force	$10^{\text{-}18}$ m	$W^\pm$ , Z bosons
Gravitational force	$\infty$	unknown

91

The fermions are the particles that make up the visible matter in the universe. They carry half integer spin and can be subdivided into leptons and quarks, where leptons don't interact strongly. Each fermion has a corresponding anti-fermion which has the same mass and is oppositely charged. The electron  $e^-$  is the first elementary particle discovered [3] and belongs to the first generation of leptons together with the electron neutrino  $\nu_e$ . The second generation compromises the muon  $\mu^-$  and muon neutrino  $\nu_\mu$ , whereas the third generation consists of the tau  $\tau$  and tau neutrino  $\nu_\tau$ . The neutrino's are neutral particles, while the other leptons have charge  $\pm q_e$  where  $q_e$  represents the elementary charge of  $1.602 \cdot 10^{-19}$  C. The masses of charged leptons differ by four orders of magnitude between the first and third generations. In the SM the neutrino's are assumed to be massless, nonetheless it is experimentally established that neutrino do have a tiny non-zero mass. In Table 1.2, the leptons and their properties in the SM are summarised.

**Table 1.2:** The properties of the leptons in the three generations of the SM [4], where  $q_e$  represents the elementary charge.

Generation	Particle	Mass	Charge
First	$e^-$	0.511 MeV	$-q_e$
	$\nu_e$	$\approx 0$	0
Second	$\mu^-$	106 MeV	$-q_e$
	$\nu_\mu$	$\approx 0$	0
Third	$\tau$	1 777 MeV	$-q_e$
	$\nu_\tau$	$\approx 0$	0

103

The quarks can also be divided into three generations. Unlike the leptons, they carry colour charge and can interact via the strong interaction. The top quark, discovered in 1995 at the Tevatron [observationtopD0, observationtopCDF], is the heaviest SM particle with a mass close to  $173.1 \pm 0.6$  GeV<sup>1</sup> [4]. The quarks and their properties are summarized in Table 1.3. In nature, only colour neutral objects can exist. This has as consequence that quarks are bound through gluons into mesons (quark+anti-quark) and baryons (three quarks). These mesons and baryons are mostly short-lived and unstable particle that rapidly decay through  $W^\pm$  and  $Z$  bosons, associated with a fermion. The only known stable baryon is the proton, made up of two up quarks and one down quark.

The scalar boson, commonly known as the Higgs boson, is the last piece of the SM and is discovered in 2012 [5, 6]. It is responsible for the masses of the  $W^\pm$  and  $Z$  boson, and that of the fermions.

## 1.2 Standard Model Lagrangian, connecting fields with particles

The SM is a quantum field theory and thus describes the dynamics and kinematics of particles and forces by a Lagrangian  $\mathcal{L}$ . The theory is based on the  $SU_C(3) \times SU_L(2) \times U_Y(1)$  gauge

---

<sup>1</sup>In this thesis all masses and energies are expressed in natural units, where the speed of light and  $\hbar$  are taken to be equal to one.

**Table 1.3:** The properties of the quarks in the three generations of the SM [4], where  $q_e$  represents the elementary charge.

	Generation	Particle	Mass	Charge
First	up u	$2.2^{+0.6}_{-0.4}$ MeV	$\frac{2}{3} q_e$	
	down d	$4.7^{+0.5}_{-0.4}$ MeV	$\frac{-1}{3} q_e$	
Second	charm c	$1.28 \pm 0.03$ GeV	$\frac{2}{3} q_e$	
	strange s	$96^{+8}_{-4}$ MeV	$\frac{-1}{3} q_e$	
Third	top t	$173.1 \pm 0.6$ GeV	$\frac{2}{3} q_e$	
	bottom b	$4.18^{+0.04}_{-0.03}$ GeV	$\frac{-1}{3} q_e$	

symmetry, where  $SU_L(2) \times U_Y(1)$  describes the electroweak interaction and  $SU_C(3)$  the strong coupling. The indices refer to colour C, the left chiral nature of the  $SU_L(2)$  coupling L, and the weak hypercharge Y. Its Lagrangian is constructed such that contains symmetries representing physics conservation laws such as conservation of energy, momentum and angular momentum. The symmetries under local group transformations are sustained by demanding gauge invariance .

The  $U_Y(1)$  group has one generator Y with an associated gauge field  $B_\mu$ . The three gauge fields  $W_\mu^1$ ,  $W_\mu^2$ , and  $W_\mu^3$ , are associated to  $SU_L(2)$  with three generators that can be written as half of the Pauli matrices:

$$T_1 = \frac{1}{2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad T_2 = \frac{1}{2} \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \text{and} \quad T_3 = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad (1.1)$$

The generators  $T^a$  satisfy the Lie algebra:

$$[T^a, T^b] = i\epsilon^{abc} T_c \text{ and } [T^a, Y] = 0, \quad (1.2)$$

where  $\epsilon^{abc}$  is an antisymmetric tensor. The gauge fields of  $SU_L(2)$  only couple to left-handed fermions as required by the observed parity violating nature of the weak force. The  $SU_C(3)$  group represents quantum chromodynamics (QCD). It has eight generators corresponding to eight gluon fields  $G_\mu^{1\dots 8}$ . Unlike  $SU_L(2) \times U_Y(1)$ ,  $SU_C(3)$  is not chiral.

Under  $SU_C(3)$  quarks are colour triplets while leptons are colour singlets. This implies that the quarks carry a colour index ranging between one and three, whereas leptons do not take part in strong interactions. Based on the chirality, the quarks and leptons are organized in doublets or singlets. Each generation  $i$  of fermions consists of left-handed doublets and right-handed singlets:

$$l_{L,i} = \begin{pmatrix} e^-_{L,i} \\ \nu_{L,i} \end{pmatrix}, \quad e^-_{R,i}, \quad q_{L,i} = \begin{pmatrix} u_{L,i} \\ d_{L,i} \end{pmatrix}, \quad u_{R,i}, \quad \text{and} \quad d_{R,i} \quad (1.3)$$

The SM Lagrangian can be decomposed as a sum of four terms

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_f + \mathcal{L}_{Yuk} + \mathcal{L}_\phi, \quad (1.4)$$

**NOTE:**  
should I explain gauge invariance or is a reference enough?

that are related to the gauge, fermion, Yukawa and scalar sectors. The gauge Lagrangian regroups the gauge fields of all three symmetry groups, and the fermionic part consists of kinetic energy terms for quarks and leptons. The interaction between fermions and the scalar doublet  $\phi$  gives rise to fermion masses and is described by the Yukawa Lagrangian. The scalar part of the Lagrangian is composed of a kinematic and potential component related to the scalar boson.

For the electroweak theory, two coupling constants are introduced, namely  $g'$  for  $U_Y(1)$  and  $g$  for  $SU_L(2)$ . The physically observable gauge bosons of this theory are the photon field  $A_\mu$ , the Z boson field  $Z_\mu^0$ , and the W field  $W_\mu^\pm$ . These are a superposition of the four gauge fields of  $SU_L(2) \times U_Y(1)$ :

$$A_\mu = \sin\theta_W W_\mu^1 + \cos\theta_W B_\mu, \quad Z_\mu^0 = \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu, \quad \text{and} \quad W_\mu^\pm = \sqrt{\frac{1}{2}} (W_\mu^1 \mp W_\mu^2), \quad (1.5)$$

where  $\theta_W$  represents the weak mixing angle defined as  $\tan\theta_W = \frac{g'}{g}$ .

The coupling constant representing the strength of the QCD interactions is denoted as  $g_s$ . In QCD there is asymptotic freedom whereby the strong coupling constant becomes weaker as the energy with which the interaction between strongly interacting particles is probed increases, and stronger as the distance between the particles increases. A consequence of this is known as colour confinement. The quarks and gluons can not exist on their own and are not observed individually. They are bound in colour neutral states called hadrons, this process is known as hadronisation.

## 142 Electroweak symmetry breaking

In  $\mathcal{L}_{\text{gauge}}$  and  $\mathcal{L}_f$  are no mass terms for fermions present because only singlets under  $SU_C(3) \times SU_L(2) \times U_Y(1)$  can acquire a mass with an interaction of the type  $m^2 \phi^\dagger \phi$  without breaking the gauge invariance. In order to accommodate mass terms for fermions and gauge fields, electroweak symmetry breaking, leading to  $\mathcal{L}_\phi$  is introduced.

The scalar doublet is introduced in the SM as

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \varphi_1 + i\varphi_2 \\ \varphi_3 + i\varphi_4 \end{pmatrix}. \quad (1.6)$$

**NOTE:**  
check if I  
need to add  
constants  
here

Its field potential is of the form

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad (1.7)$$

with  $\mu^2 < 0$  and  $\lambda$  a positive integer. This choice of parameters gives the potential a "Mexican hat" shape. It has an infinite set of minima (ground states) and by expanding the field around an arbitrary choice of ground state, the electroweak symmetry is broken (EW):

$$\phi = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} + \hat{\phi}, \quad (1.8)$$

where  $v$  is the vacuum expectation value (vev), measured to be around 245 GeV and corresponds to  $\sqrt{\frac{-\mu}{\lambda}}$ . The scalar doublet's four degrees of freedom is reduced to three degrees of freedom

that couple to the gauge fields and mix with the  $W^+$ ,  $W^-$  and  $Z$  bosons. The remaining fourth degree of freedom has given rise to a physically observable particle , called the Brout-Englert-Higgs (BEH) boson. This spontaneous symmetry breaking leaves the gauge invariance intact and gives masses to the  $W^\pm$  and  $Z$  bosons as:

$$m_W = \frac{1}{2}v|g| \quad \text{and} \quad m_Z = \frac{1}{2}v\sqrt{g'^2 + g^2}. \quad (1.9)$$

- 147 The Brout-Englert-Higgs field couples universally fermions with a strength proportional to their  
148 masses, and to gauge bosons with a strength proportional to the square of their masses.

### 149 1.3 Flavours in the SM

Flavour changing charged currents are introduced in 1963 by Nicola Cabibbo [7]. Via interaction with a  $W$  boson the flavour of the quarks is changed. At the time of the postulation only up, down, and strange quarks were known and the charged weak current was described as a coupling between the up quark and  $d_{\text{weak}}$ , where  $d_{\text{weak}}$  is a linear combination of the down and strange quarks,  $d_{\text{weak}} = \cos\theta_c d + \sin\theta_c s$ . This linear combination is a direct consequence of the chosen rotation

$$\begin{pmatrix} d_{\text{weak}} \\ s_{\text{weak}} \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix} = \mathcal{R} \begin{pmatrix} d \\ s \end{pmatrix}, \quad (1.10)$$

where the rotation angle  $\theta_c$  is known as the Cabibbo angle. This provides a definition for the charged weak current between u and d quarks,

$$J_\mu = \bar{u} \gamma_\mu (1 + \gamma_5) d_{\text{weak}}. \quad (1.11)$$

A consequence of Cabibbo's approach is that the  $s_{\text{weak}}$  is left uncoupled, leading to Glashow, Iliopoulos and Maiani (GIM) [8–10] to require the existence of a fourth quark with charge  $\frac{2}{3}q_e$ . This quark, known as the charm quark, couples to  $s_{\text{weak}}$  and a new definition of the charged weak current is modified to

$$J_\mu = (u \ c) \gamma_\mu (1 + \gamma_5) \mathcal{R} \begin{pmatrix} d \\ s \end{pmatrix} = \bar{U} \gamma_\mu (1 + \gamma_5) \mathcal{R} D. \quad (1.12)$$

The neutral weak current is defined as

$$J_3 = \bar{U} \gamma_\mu (1 + \gamma_5) [\mathcal{R}, \mathcal{R}^\dagger] D, \quad (1.13)$$

- 150 and is diagonal in flavour space. This has as consequence that no flavour changing neutral  
151 currents occur at tree-level Feynmann diagrams<sup>2</sup>.

Kobayashi and Maskawa generalised the Cabibbo rotation matrix to accommodate for a third generation of quarks. The result is a  $3 \times 3$  unitary matrix known as the CKM matrix, responsible

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<sup>2</sup>Feynmann diagrams are physical representation of interaction between particles. They are based on Feynmann rules [1].

**NOTE:**  
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explain  
feynmann  
diagrams?

for the mixing of weak interaction states of down-type quarks:

$$\begin{pmatrix} d_{\text{weak}} \\ s_{\text{weak}} \\ b_{\text{weak}} \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \mathcal{V}_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (1.14)$$

The unitarity of the matrix ( $\mathcal{V}_{\text{CKM}}^\dagger \mathcal{V}_{\text{CKM}} = \mathbb{1}$ ). A general  $3 \times 3$  unitary matrix depends on three real angles and six phases. For the CKM matrix, the freedom to redefine the phases of the quark eigenstates can remove five of the phases, leaving a single physical phase known as the Kobayashi-Maskawa phase. This phase is responsible for the charge parity violation in the SM [11]. Each element  $V_{ij}$  of  $\mathcal{V}_{\text{CKM}}$  represents the transition probability of a quark  $i$  going to a quark  $j$ , and is experimentally determined to be [4]

$$\mathcal{V}_{\text{CKM}} = \begin{pmatrix} 0.97425 \pm 0.00022 & 0.2253 \pm 0.0008 & (4.13 \pm 0.49) 10^{-3} \\ 0.225 \pm 0.008 & 0.986 \pm 0.016 & (41.1 \pm 1.3) 10^{-3} \\ (8.4 \pm 0.6) 10^{-3} & (40.0 \pm 2.7) 10^{-3} & 1.021 \pm 0.032 \end{pmatrix}. \quad (1.15)$$

152 From Equation 1.15 follows that top quarks predominantly decay via charged weak currents to  
 153 bottom quarks, with a probability consist with unity. In the SM, FCNC can only occur via higher  
 154 loop Feynmann diagrams which are highly suppressed. The expected transition probabilities for  
 155 a top quark decaying via a FCNC interaction in the SM are given in Table 1.4, where it is clear  
 156 that the FCNC sector of the SM is still beyond the reach of the sensitivity of current experiments.

**Table 1.4:** The predicted branching ratios  $\mathcal{B}$  for FCNC interactions involving the top quark in the SM [12]

Process	$\mathcal{B}$ in the SM	Process	$\mathcal{B}$ in the SM
$t \rightarrow uZ$	$8 \cdot 10^{-17}$	$t \rightarrow cZ$	$1 \cdot 10^{-14}$
$t \rightarrow u\gamma$	$4 \cdot 10^{-16}$	$t \rightarrow c\gamma$	$5 \cdot 10^{-14}$
$t \rightarrow ug$	$4 \cdot 10^{-14}$	$t \rightarrow cg$	$5 \cdot 10^{-12}$
$t \rightarrow uH$	$2 \cdot 10^{-17}$	$t \rightarrow cH$	$3 \cdot 10^{-15}$

157

## 158 1.4 The top of the SM

Discovered in 1995 by the CDF and D0 collaborations at Tevatron with proton-antiproton data [13, 14], the top quark plays an important role in studying high energy physics. Its Yukawa interaction is given by

$$\mathcal{L}_{\text{top-Yukawa}} = -\frac{\lambda_t \nu}{\sqrt{2}} \bar{t}_L t_R - \frac{\lambda_t}{\sqrt{2}} H \bar{t}_L t_R + \text{h.c.}, \quad (1.16)$$

yielding a Yukawa coupling of

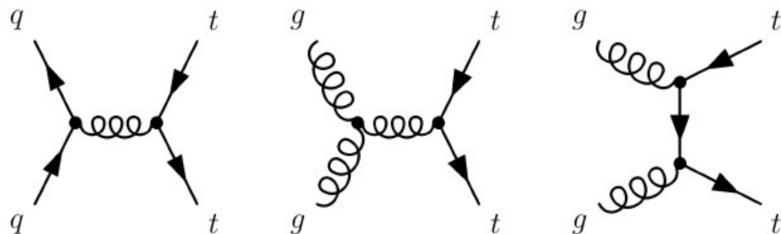
$$\lambda_t = \frac{\sqrt{2} m_t}{\nu} = 0.991 \pm 0.003, \quad (1.17)$$

with the top mass  $m_t$  equal to  $172.44 \pm 0.49$  GeV [4]. This Yukawa coupling is very large compared to the other Yukawa couplings in the SM ( $\mathcal{O}(10^{-2})$ ), leading to the belief that the top quark may have an important role in understanding the mechanism of electroweak symmetry breaking. On top of this, the very short lifetime of the top quark makes it an excellent candidate for property studies. Its high mass, almost 40 times higher than the mass of the closest particle in mass, leads to a large coupling with the Higgs boson and makes the top quark an interesting candidate for the understanding of how particles acquire mass.

The CKM matrix element  $V_{tb}$ , given in Equation 1.15, is experimentally found to be much larger than  $V_{ts}$ ,  $V_{td}$ , and close to unity. The top quark decays through electroweak interactions since the W boson mass is smaller than the top mass and the W boson can be on shell. A consequence of this is that the top quark has a very short lifetime of only  $1/\Gamma_t \approx 5 \cdot 10^{-25}$  s [4] leading to the fact that the formation of bound states involving top quarks are not allowed. This lifetime is even shorter than the typical hadronisation timescale of  $1/\Lambda_{\text{QCD}} \approx 10^{-23}$  s, prohibiting gluons to radiate from the top quark and keeping its spin coherent. Since the electroweak interactions have a V-A coupling structure, the top quark spin orientation can be derived from the angular distributions of its decay products. This makes it possible to study the polarisation of top quarks from the angular distributions in various processes.

**NOTE:** Ex-plain V-A

The massiveness of the top quark leads to the fact that a large amount of energy is needed to create one. This is only the case for high energy collisions such as those in the Earth's upper atmosphere as cosmic rays collide with particles in air, or by particle accelerators. The production of top quarks happens in two ways: single via the electroweak interaction or in pairs via the strong interaction. At hadron colliders, the dominant production mechanism is top quark production via gluon ( $gg \rightarrow t\bar{t}$ ) or quark fusion ( $q\bar{q} \rightarrow t\bar{t}$ ). In Figure 1.1, the different top pair production mechanisms are shown. The production channel of gluon fusion is the main contributor to the top pair cross section at the LHC compared to quark fusion at Tevatron. The  $gg \rightarrow t\bar{t}$  process contributes 80-90% to the total top pair cross section in the LHC centre-of-mass energy regime of 7-14 TeV [4]. In Table 1.5 the predicted top pair production cross sections are given for the LHC and Tevatron.



**Figure 1.1:** Leading order diagrams of the top pair production. Gluon fusion (right and middle) are the dominant processes at the LHC, while quark fusion (left) is the dominant one at Tevatron.

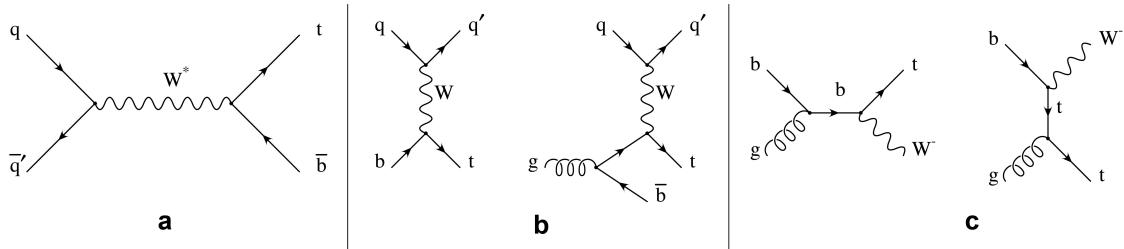
186

The singly produced top quarks are produced via the electroweak interaction. These production mechanisms are subdivided at leading order into three main channels based on the virtuality ( $Q^2 = -p_\mu p^\mu$ ) of the exchanged W boson. In Figure 1.2, the corresponding Feynman diagrams are shown. The single top quark production cross section, given in Table 1.6, are smaller than

**Table 1.5:** Predictions on the top quark pair production cross sections at next-to-next-to-leading order with next-to-next-to-leading log soft gluon resummation per centre-of-mass energy [4]. The first uncertainty is from scale dependence, while the second uncertainty originates from parton density functions.

Experiment	Top mass	Centre-of-mass energy	Cross section (pb)
Tevatron	$m_t = 173.3$ GeV	$\sqrt{s} = 1.96$ TeV	$\sigma_{t\bar{t}} = 7.16^{+0.11+0.17}_{-0.20-0.12}$
LHC	$m_t = 173.2$ GeV	$\sqrt{s} = 7$ TeV	$\sigma_{t\bar{t}} = 173.6^{+4.5+8.9}_{-5.9-8.9}$
LHC	$m_t = 173.2$ GeV	$\sqrt{s} = 8$ TeV	$\sigma_{t\bar{t}} = 247.7^{+6.3+11.5}_{-8.5-11.5}$
LHC	$m_t = 173.2$ GeV	$\sqrt{s} = 13$ TeV	$\sigma_{t\bar{t}} = 816.0^{+19.4+34.4}_{-28.6-34.4}$

191 the top pair production cross sections since the electroweak coupling strength is smaller than  
 192 the strong coupling strength. In addition, for the single top production, there is the need of sea  
 193 quarks ( $b, \bar{q}$ ) in the initial states for which the parton density functions increase less steeply at  
 low momentum fractions compared to the gluon parton density functions.



**Figure 1.2:** Leading order Feynman diagrams of the electroweak production of single top quarks in the  $s$ -channel (left),  $t$ -channel (middle), and for the  $tW$  associated production. Figure taken from [15].

194

195 The production via the  $t$ -channel has a virtuality of the  $W$  boson  $Q^2 > 0$ , making it space-like.  
 196 It is produced via the scattering of the  $W$  boson of a bottom quark coming from a proton or  
 197 from gluon splitting ( $g \rightarrow b\bar{b}$ ). This process is also known as  $W$ -gluon fusion production. It has  
 198 the highest single top quark cross section in proton collisions and the top quark production is  
 199 roughly twice more than the antitop quarks. This is a consequence of the up-down valence  
 200 quark composition of the proton. This feature makes the  $t$ -channel sensitive to the parton  
 201 density functions of the proton. The  $s$ -channel is the production mechanism with the smallest  
 202 cross section. Here the  $W$  boson is time-like ( $Q^2 < 0$ ) which requires the  $W$  boson to have a  
 203 large virtuality to produce the heavier top quark. It is produced from two quarks belonging  
 204 to the same isodoublet (e.g.  $u\bar{d}$ ) and subsequently decays to  $t\bar{b}$ . This process get enhanced  
 205 by many beyond the Standard Model scenarios via the addition of new heavy particles such  
 206 as  $W'$ . The  $tW$ -channel has a top quark produced in association with a  $W$  boson produced on  
 207 shell  $Q^2 = -m_W^2$ . This mode is negligible at Tevatron, but of relevant size at the LHC. The  
 208  $tW$ -channel is sensitive to new physics affecting the  $Wtb$  vertex.

**Table 1.6:** Predictions on the single top quark production cross sections at next-to-leading order per centre-of-mass energy [4]. The uncertainties from scale dependence and from parton density functions are combined in quadrature or given separately (scale + PDF). For the  $t$ -channel the relative proportions to  $t$  and  $\bar{t}$  are 65% and 35%. For the  $s$ -channel this respectively 69% and 31%. The  $tW$ -channel has an equal proportion of top and antitop quarks. For Tevatron, the top mass is assumed to be 173.3 GeV, while for the LHC predictions  $m_t = 172.5$  GeV [4, 16].

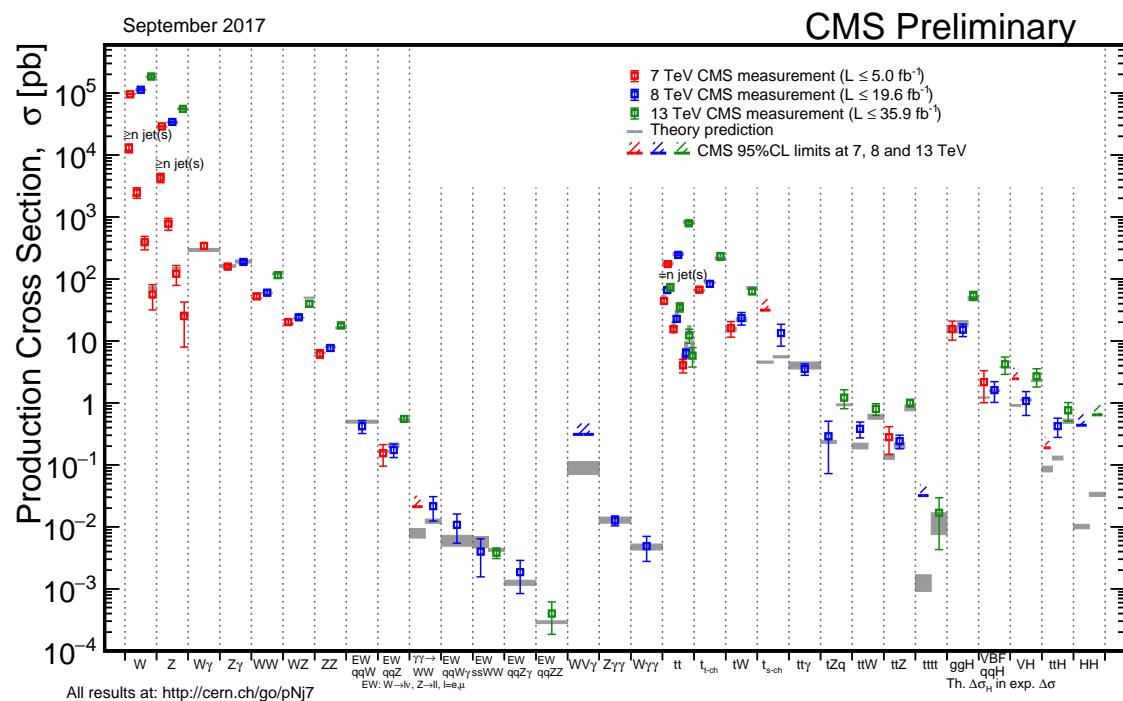
Experiment	Centre-of-mass energy	Cross section $\sigma_{t+\bar{t}}$ (pb)		
		$t$ -channel	$s$ -channel	$tW$ -channel
Tevatron	$\sqrt{s} = 1.96$ TeV	$2.06^{+0.13}_{-0.13}$	$1.03^{+0.05}_{-0.05}$	-
LHC	$\sqrt{s} = 7$ TeV	$63.89^{+2.91}_{-2.52}$	$4.29^{+0.19}_{-0.17}$	$15.74^{+0.40+1.10}_{-0.40-1.14}$
LHC	$\sqrt{s} = 8$ TeV	$84.69^{+3.76}_{-3.23}$	$5.24^{+0.22}_{-0.20}$	$22.37^{+0.60+1.40}_{-0.60-1.40}$
LHC	$\sqrt{s} = 13$ TeV	$216.99^{+9.04}_{-7.71}$	$10.32^{+0.40}_{-0.36}$	$71.7^{+1.80+3.40}_{-1.80-3.40}$

## 209 1.5 Hunting down the SM top quark

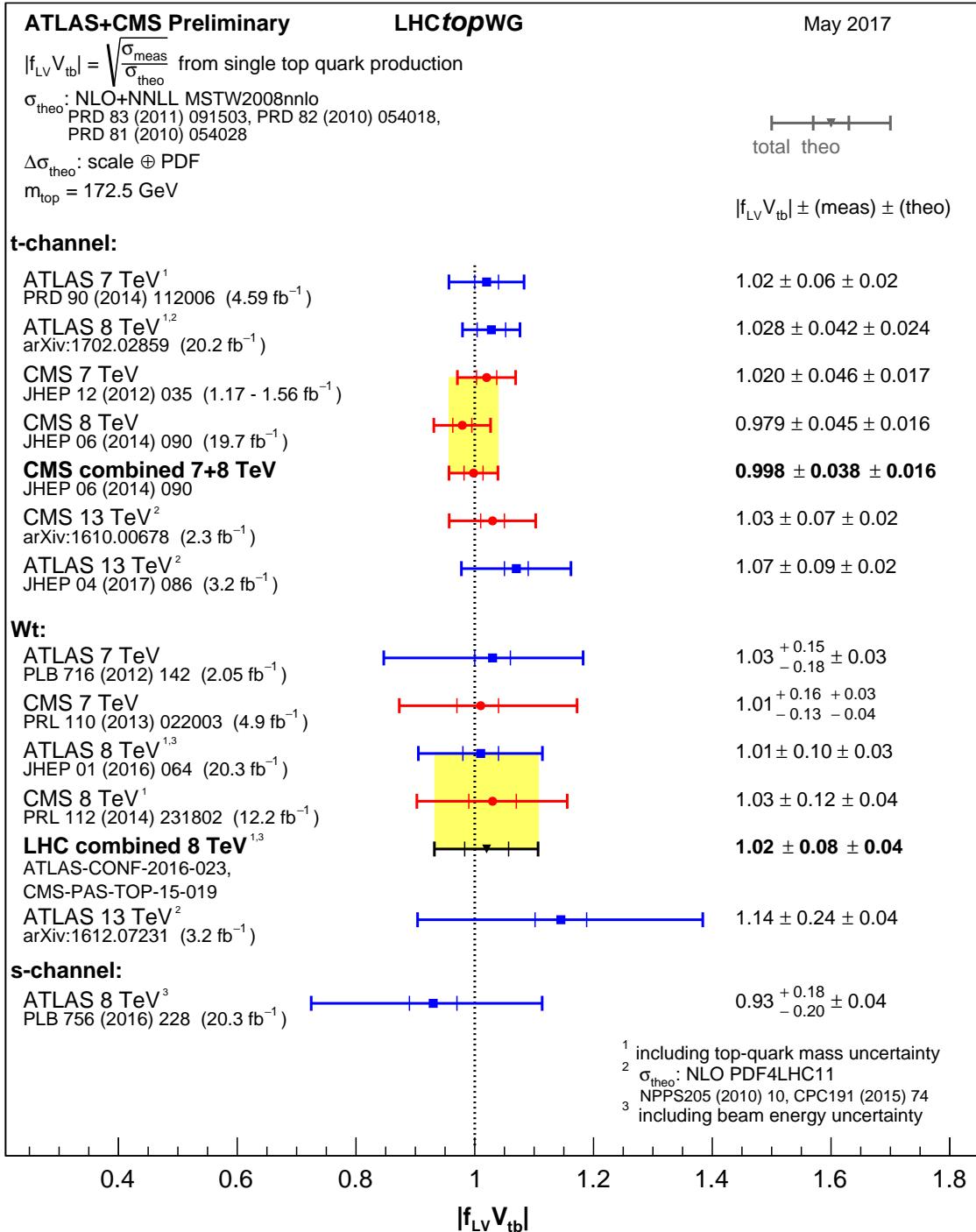
210 In this section a selection of experimental results of measurements on the SM are presented.  
 211 In Figure 1.3, a summary plot of the CMS cross section measurements can be found. The  
 212 estimations by the CMS and ATLAS collaborations of the CKM matrix element  $V_{tb}$  from single  
 213 top quark measurement is given in Figure 1.4. The most precise estimation of  $V_{tb}$  originates  
 214 from a combination of  $t$ -channel cross section measurements at 7 and 8 TeV by the CMS  
 215 collaboration resulting in  $|f_L V_{tb}| = 0.998 \pm 0.038$  (exp.)  $\pm 0.016$  (theo.). Assuming the  $f_L = 1$   
 216 and  $|V_{tb}| < 1$ , this result yields a limit of  $|V_{tb}| > 0.92$  at 95% confidence level. The most recent  
 217 top mass measurements are given in Figure 1.5. The CMS combined top mass measurement is  
 218  $m_t = 172.44 \pm 0.48$  GeV from 7+8 TeV data.

219 In general the various measurements show a good agreement with the SM predictions and by  
 220 lack of deviations of the SM, limits on the anomalous couplings can be derived. The estimated  
 221 coupling strengths per operator contributing to single top quark production obtained from  
 222 various measurements at the LHC and Tevatron are shown in Figure 1.6. These results are  
 223 consistent with the SM expectation for which those operators vanish.

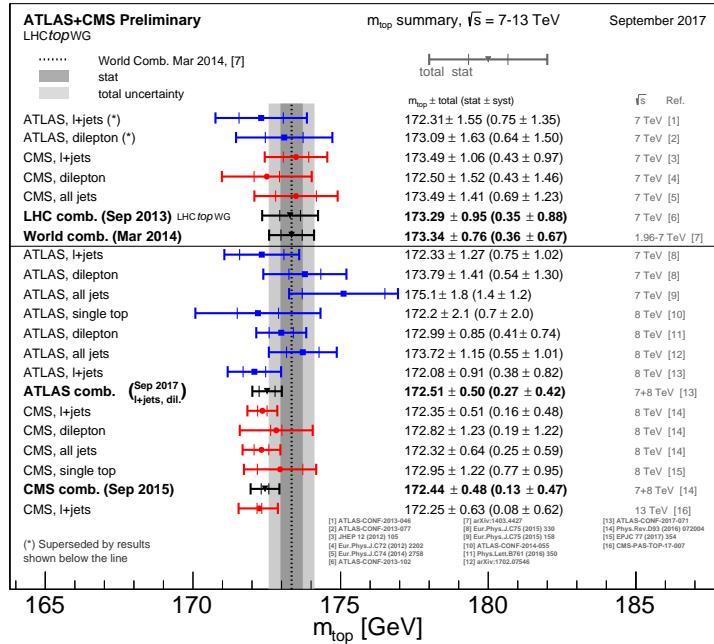
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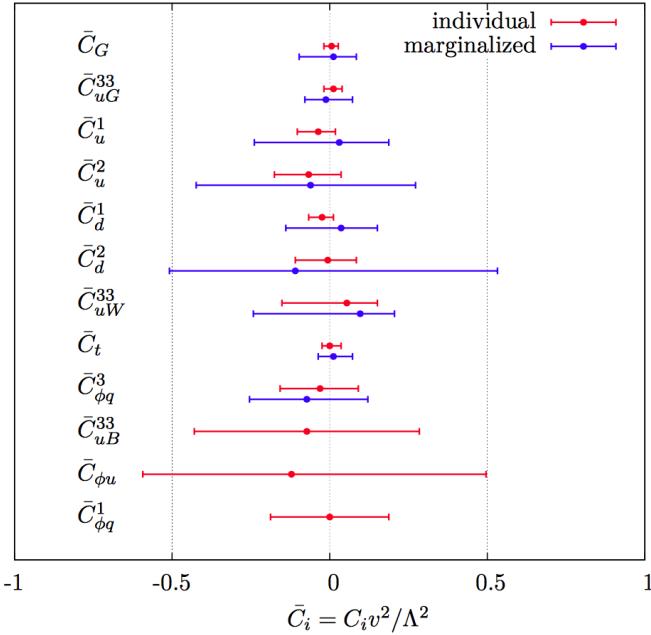
**Figure 1.3:** Summary of the SM cross section measurements performed by the CMS collaboration. Figure taken from [17]



**Figure 1.4:** Estimations of the SM  $V_{tb}$  CKM element from single top cross section measurements. Figure taken from [18].



**Figure 1.5:** Summary of the top mass direct measurements performed by CMS and ATLAS, and compared with the LHC and LHC+Tevatron combinations. The results below the line are produced after the LHC and LHC+Tevatron combinations. Figure taken from [18].



**Figure 1.6:** Global fit results of top quark effective field theory to experimental data including all constrained operators at dimension six. For the operators, the Warsaw basis of [19] is used. The bounds are set on the Wilson coefficients of various operators contributing to top quark production and decay in two cases (red) all other coefficients set to zero, or (blue) all other coefficient are marginalised over. Figure taken from [20].

## 224 1.6 Why to look beyond the SM

225 Many high energy experiments confirm the success of the SM. In particular the scalar boson,  
 226 the cornerstone of the SM, has consecrated the theory. Unfortunately there are also strong  
 227 indications that the SM ought to be a lower energy expression of a more global theory. The  
 228 existence of physics beyond the SM (BSM) [BSMWiley] is strongly motivated. These motivations  
 229 are based on direct evidence from observation such as the existence of neutrino masses, the  
 230 existence of dark matter and dark energy, or the matter-antimatter asymmetry, and also from  
 231 theoretical problems such as the hierarchy problem, the coupling unification or the large numbers  
 232 of free parameters in the SM.

233 In the SM, the neutrino is assumed to be massless, whilst experiments with solar, atmospheric,  
 234 reactor and accelerator neutrinos have established that neutrinos can oscillate and change  
 235 flavour during flight [21, 22]. These oscillations are only possible when neutrino's have masses.  
 236 The flavour neutrinos ( $\nu_e$ ,  $\nu_\mu$ ,  $\nu_\tau$ ) are then linear expressions of the fields of at least three mass  
 237 eigenstate neutrinos  $\nu_1$ ,  $\nu_2$ , and  $\nu_3$ .

238 The ordinary or baryonic matter described by the SM describes only 5% of the mass (energy)  
 239 content of the universe. Astrophysical evidence indicated that dark matter is contributing  
 240 to approximately 27%, and dark energy to 68% of the content of the universe. From the  
 241 measurements of the temperature and polarizations anisotropies of the cosmic microwave  
 242 background by the Planck experiment [23], the density of cold non baryonic matter is determined.  
 243 Cold dark matter is assumed to be only sensitive to the weak and gravitational force, leading  
 244 to only one possible SM candidate: the neutrino. However, these are too light to account for  
 245 the vast amount of dark matter and other models are needed. Dark energy is assumed to be  
 246 responsible for the acceleration in the expansion of the universe [24].

247 At the Big Bang matter and antimatter is assumed to be produced in equal quantities. However,  
 248 it is clear that we are surrounded by matter. So where did all the antimatter go? In 1967,  
 249 Sakharov identified three mechanisms that are necessary to obtain a global matter antimatter  
 250 asymmetry [25]. These mechanisms are those of baryon and lepton number violation, that at a  
 251 given moment in time there was a thermal imbalance for the interactions in the universe, and  
 252 there is charge C and charge parity CP violation<sup>3</sup>.

253 The large numbers of free parameters in the SM are taken as nine fermion masses, three CKM  
 254 mixing angles and one CP violating phase, one EM coupling constant  $g'$ , one weak coupling  
 255 constant  $g$ , one strong coupling constant  $g_s$ , one QCD vacuum angle, one vacuum expectation  
 256 value, and one mass of the scalar boson. This large number of free parameters lead to the  
 257 expectation of a more elegant, general theory beyond the SM.

258 The hierarchy problem [26] is related to the huge difference in energy between the weak  
 259 scale and the Planck scale. The vev of the Brout-Englert-Higgs field determines the weak scale  
 260 that is approximately 246 GeV. The radiative corrections to the scalar boson squared mass  $m_H^2$ ,  
 261 coming from its self couplings and couplings to fermions and gauge bosons, are quadratically

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<sup>3</sup>The rate of a process  $i \rightarrow f$  can be different from the CP-conjugate process:  $\tilde{i} \rightarrow \tilde{f}$ . The SM includes sources of CP-violation through the residual phase of the CKM matrix. However, these could not account for the magnitude of the asymmetry observed.

262 proportional to the ultraviolet momentum cut-off  $\Lambda_{\text{UV}}$ . This cut-off is at least equal to the energy  
 263 to which the SM is valid without the need of new physics. The SM is valid up to the Planck mass  
 264 making the correction to  $m_H^2$  about thirty orders of magnitude larger than  $m_H^2$ . This implies that  
 265 an extraordinary cancellation of terms should happen. This is also known as the naturalness  
 266 problem of the H boson mass.

The correction to the squared mass of the scalar boson coming from a fermion  $f$ , coupling to the scalar field  $\phi$  with a coupling  $\lambda_f$  is given by

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{\text{UV}}^2, \quad (1.18)$$

while the correction to the mass from a scalar particle  $S$  with a mass  $m_S$ , coupling to the scalar field with a Lagrangian term  $-\lambda_{\text{mathrm}{S}} |\phi|^2 |S|^2$  is

$$\Delta m_H^2 = -\frac{|\lambda_S|^2}{16\pi^2} \left( \Lambda_{\text{UV}}^2 - 2m_S^2 \ln\left(\frac{\Lambda_{\text{UV}}}{m_S}\right) + \dots \right). \quad (1.19)$$

267 As one can see the correction term to  $m_H^2$  is much larger than  $m_H^2$  itself. By introducing BSM  
 268 physic models that introduce new scalar particles at TeV scale that couple to the scalar boson  
 269 can cancel the  $\Lambda_{\text{UV}}^2$  divergence and avoid this fine-tuning.

270 The choice of the  $SU_C(3) \times SU_L(2) \times U_Y(1)$  symmetry group itself as well as the separate  
 271 treatment of the three forces included in the SM raises concern. The intensity of the forces  
 272 show a large disparity around the electroweak scale, but have comparable strengths at higher  
 273 energies. The electromagnetic and weak forces are unified in a electroweak interaction, but the  
 274 strong coupling constant does not encounter the other coupling constants at high energies. In  
 275 order to reach a grand unification, the running of couplings can be modified by the addition of  
 276 new particles in BSM models.

## 277 1.7 An effective approach beyond the SM: FCNC involving a top 278 quark

279 The closeness of the top mass to the electroweak scale led physicist to believe that it is a sensitive  
 280 probe for new physics. Its property study is therefore an important topic of the experimental  
 281 program at the LHC. Several extensions of the SM enhance the FCNC branching ratios and can  
 282 be probed at the LHC [12], from which some of them are shown in Table 1.7. Previous searches  
 283 have been performed at the Fermilab Tevatron by the CDF [27] and D0 [28] collaborations,  
 284 and at the LHC by the ATLAS [29–32] and CMS [33–37] collaborations.

285 The impact of BSM models can written in a model independent way by means of an effective  
 286 field theory valid up to an energy scale  $\Lambda$ . The leading effects are parametrized by a set of  
 287 fully gauge symmetric dimension-6 operators that are added to the SM Lagrangian and can be  
 288 reduced to a minimal set of operators as discussed in [38, 39]. The full Lagrangian, neglecting  
 289 neutrino physics, in the fully gauge symmetric case is given by

$$\mathcal{L}_{\text{SM+EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{\bar{c}_i}{\Lambda^2} \mathcal{O}_i + \mathcal{O}\left(\frac{1}{\Lambda^3}\right), \quad (1.20)$$

**Table 1.7:** The predicted branching ratios  $\mathcal{B}$  for FCNC interactions involving the top quark in some BSM models [12]: quark singlet (QS), generic two Higgs doublet model (2HDM) and the minimal supersymmetric extensions to the SM (MSSM);

Process	QS	2HDM	MSSM	Process	QS	2HDM	MSSM
$t \rightarrow uZ$	$\leq 1.1 \cdot 10^{-4}$	—	$\leq 2 \cdot 10^{-6}$	$t \rightarrow cZ$	$\leq 1.1 \cdot 10^{-4}$	$\leq 10^{-7}$	$\leq 2 \cdot 10^{-6}$
$t \rightarrow u\gamma$	$\leq 7.5 \cdot 10^{-9}$	—	$\leq 2 \cdot 10^{-6}$	$t \rightarrow c\gamma$	$\leq 7.5 \cdot 10^{-9}$	$\leq 10^{-6}$	$\leq 2 \cdot 10^{-6}$
$t \rightarrow ug$	$\leq 1.5 \cdot 10^{-7}$	—	$\leq 8 \cdot 10^{-5}$	$t \rightarrow cg$	$\leq 1.5 \cdot 10^{-7}$	$\leq 10^{-4}$	$\leq 8 \cdot 10^{-5}$
$t \rightarrow uH$	$\leq 4.1 \cdot 10^{-5}$	$\leq 5.5 \cdot 10^{-6}$	$\leq 10^{-5}$	$t \rightarrow cH$	$\leq 4.1 \cdot 10^{-5}$	$\leq 10^{-3}$	$\leq 10^{-5}$

where the Wilson coefficients  $\bar{c}_i$  depend on the considered theory and on the way that new physics couples to the SM particles. Considering that  $\Lambda$  is large, contributions suppressed by powers of  $\Lambda$  greater than two are neglected. Moreover, all four fermion operators are omitted for the rest of this thesis. After electroweak symmetry breaking the operators induce [12, 40] both corrections to the SM couplings and new interactions at tree level such as FCNC interactions. The FCNC interactions of the top quark that are not present in the SM are given by

$$\mathcal{L}_{\text{EFT}}^t = \frac{\sqrt{2}}{2} \sum_{q=u,c} \left[ g' \frac{\kappa_{t\gamma q}}{\Lambda} A_{\mu\nu} \bar{t} \sigma^{\mu\nu} (f_{\gamma q}^L P_L + f_{\gamma q}^R P_R) q \right. \quad (1.21)$$

$$+ \frac{g}{2\cos\theta_W} \frac{\kappa_{tZq}}{\Lambda} Z_{\mu\nu} \bar{t} \sigma^{\mu\nu} (f_{Zq}^L P_L + f_{Zq}^R P_R) q \quad (1.22)$$

$$+ \frac{\sqrt{2}g}{4\cos\theta_W} \zeta_{tZq} \bar{t} \gamma^\mu (\tilde{f}_q^L P_L + \tilde{f}_q^R P_R) q Z_\mu \quad (1.23)$$

$$+ g_S \frac{\kappa_{gqt}}{\Lambda} Z_{\mu\nu} \bar{t} \sigma^{\mu\nu} (f_{gq}^L P_L + f_{gq}^R P_R) q G_{\mu\nu}^a \quad (1.24)$$

$$+ \eta_{Hqt} \bar{t} (\hat{f}_q^L P_L + \hat{f}_q^R P_R) q H + \text{h.c.} \Big], \quad (1.25)$$

**NOTE:** At something about Warsaw basis

where the value of the FCNC couplings at scale  $\Lambda$  are represented by  $\kappa_{tZq}, \kappa_{gqt}, \kappa_{t\gamma q}, \zeta_{tZq}$ , and  $\eta_{Hqt}$ . These are assumed to be real and positive, with the unit of  $\text{GeV}^{-1}$  for  $\kappa_{tXq}/\Lambda$  and no unit for  $\zeta_{xqt}$  and  $\eta_{xqt}$ . In the equation  $\sigma^{\mu\nu}$  equals to  $\frac{i}{2} [\gamma^\mu, \gamma^\nu]$ , and the left- and right-handed chirality projector operators are denoted by  $P_L$  and  $P_R$ . The electromagnetic coupling constant is denoted by  $g'$ , the strong interaction coupling is denoted as  $g_S$ , while the electroweak interaction is parametrised by the coupling constant  $g$  and the electroweak mixing angle  $\theta_W$ . The complex chiral parameters are normalized according to  $|f_{xq}^L|^2 + |f_{xq}^R|^2 = 1$ ,  $|\tilde{f}_q^L|^2 + |\tilde{f}_q^R|^2 = 1$ , and  $|\hat{f}_q^L|^2 + |\hat{f}_q^R|^2 = 1$ . In the expression for  $\mathcal{L}_{\text{EFT}}^t$ , the unitary gauge is adopted and the scalar field is expanded around its vacuum expectation value with  $H$  being the SM scalar boson, and the field strength tensors of the photon  $A_\mu$ , the gluon field  $G_\mu^{1\dots 8}$ , and the Z boson  $Z_\mu^0$  are defined as

$$A_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu, \text{ and } G_{\mu\nu} = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_S f_{bc}^a G_\mu^b G_\nu^c. \quad (1.26)$$

290 Denoting the structure constant of the  $SU_C(3)$  group as  $f_{bc}^a$ . Note that there are two coupling  
 291 constants arising in  $\mathcal{L}_{\text{EFT}}^t$ , which is a residue of electroweak symmetry breaking. The massive Z  
 292 boson will appear in both the  $Z_\mu^0$  field as well as the covariant derivative , leading to an extra  
 293 Z-vertex.

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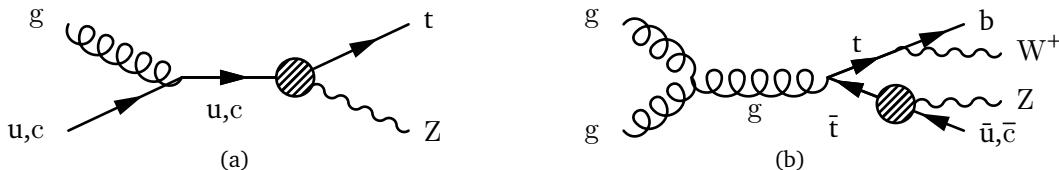
294 **1.8 The top-FCNC constrained**

Experiments commonly put limits on the branching ratio's which allow an easier interpretation across different EFT models by use of the branching ratio  $\mathcal{B}$

$$\mathcal{B}(t \rightarrow qX) = \frac{\delta_{txq}^2 \Gamma_{t \rightarrow qX}}{\Gamma_t}, \quad (1.27)$$

295 where  $\Gamma_{t \rightarrow qX}$  represents the FCNC decay width<sup>4</sup> for a coupling strength  $\delta_{txq}^2 = 1$ , and  $\Gamma_t$  the full  
296 decay width of the top quark. In the SM, supposing a top quark mass of 172.5 GeV, the full  
297 width becomes  $\Gamma_t^{\text{SM}} = 1.32$  GeV [41].

298 Searches for top-FCNC usually adopt a search strategy depending on the experimental set-up  
299 and the FCNC interaction of interest, looking either for FCNC interactions in the production of  
300 a single top quark or in its decay for top pair interactions. In Figure 1.7, these two cases are  
301 shown for the tZq vertex.



**Figure 1.7:** Feynman diagrams for the tZq FCNC interaction, where the FCNC interaction is indicated with the shaded dot. (a) Single top production through an FCNC interaction. (b) Top pair production with an FCNC induced decay.

302

303 The observation of top-FCNC interactions has yet to come and experiments have so far only  
304 been able to put upper bounds on the branching ratios. An overview of the best current limits is  
305 given in Table 1.8. In Figure 1.8 a comparison is shown between the current best limits set by  
306 ATLAS and CMS with respect to several BSM model benchmark predictions. From there one can  
307 see that FCNC searches involving a Z or H boson are close to excluding or confirming several  
308 BSM theories.

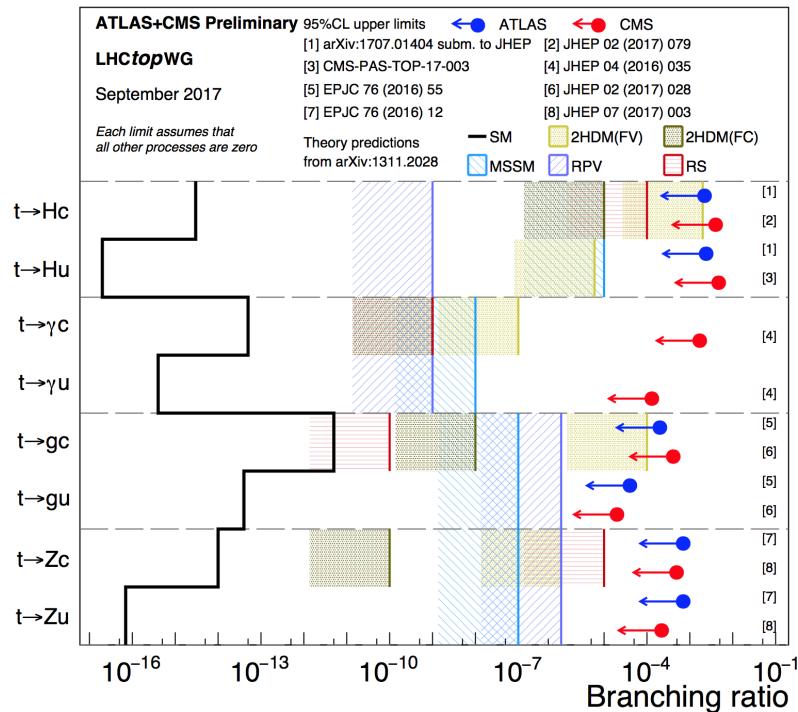
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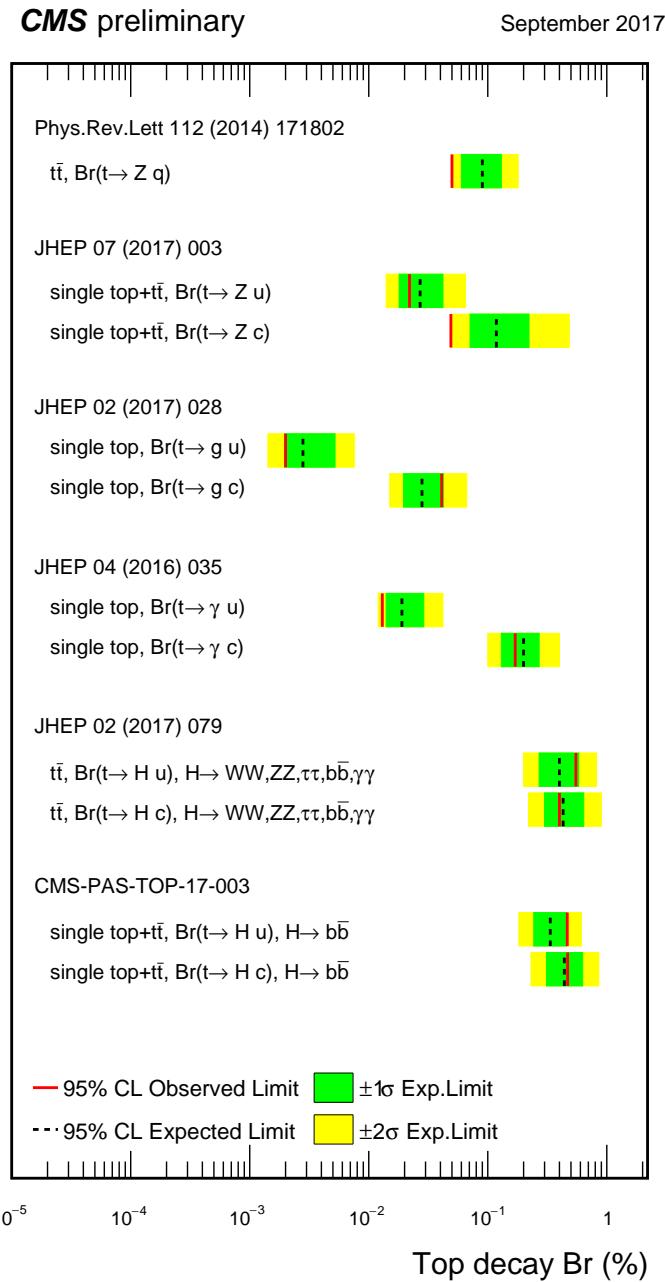
<sup>4</sup>The decay width of a certain process represents the probability per unit time that a particle will decay. The total decay width, defined as all possible decay widths of a particle, is inversely proportional to its lifetime.

**Table 1.8:** Overview of the most stringent observed and expected experimental limits on top-FCNC branching ratios  $\mathcal{B}$  at 95% confidence level.

Process	Search mode	Observed $\mathcal{B}$	Expected $\mathcal{B}$	Experiment	Reference
$t \rightarrow uZ$	top pair decay and single top production	$2.2 \cdot 10^{-4}$	$2.7 \cdot 10^{-4}$	CMS	[33]
$t \rightarrow u\gamma$	single top production	$1.3 \cdot 10^{-4}$	$1.9 \cdot 10^{-4}$	CMS	[35]
$t \rightarrow ug$	single top production	$4.0 \cdot 10^{-5}$	$3.5 \cdot 10^{-5}$	ATLAS	[30]
$t \rightarrow uH$	top pair decay	$2.4 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	ATLAS	[32]
$t \rightarrow cZ$	top pair decay and single top production	$4.9 \cdot 10^{-4}$	$12 \cdot 10^{-4}$	CMS	[33]
$t \rightarrow c\gamma$	single top production	$2.0 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$	CMS	[35]
$t \rightarrow cg$	single top production	$2.0 \cdot 10^{-4}$	$1.8 \cdot 10^{-4}$	ATLAS	[30]
$t \rightarrow cH$	top pair decay	$2.2 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	CMS	[32]



**Figure 1.8:** Current best limits set by CMS and ATLAS for top-FCNC interactions. Figure taken from [17].



**Figure 1.9:** Summary of the FCNC branching ratios from CMS searches at 8 TeV. Figure taken from [17].

# Experimental set-up

# 2

310 The main objective of the Large Hadron Collider (LHC) was the search for the Brout-Englert-  
 311 Higgs boson. The Large Electron Positron (LEP) [42] and Tevatron [43] experiments had  
 312 established that the mass of the scalar boson has to be larger than 114 GeV [44, 45], and smaller  
 313 than approximate 1 TeV due to unitarity and perturbativity constraints [46]. On top of this,  
 314 the search for new physics such as supersymmetry or the understanding of dark matter were  
 315 part of the motivation for building the LHC. Since the start of its operation, the LHC is pushing  
 316 the boundaries of the Standard Model, putting the most stringent limits on physics beyond the  
 317 Standard Model as well as precision measurements of the parameters of the Standard Model. A  
 318 milestone of the LHC is the discovery the scalar boson in 2012 by the two largest experiments  
 319 at the LHC [5, 6].

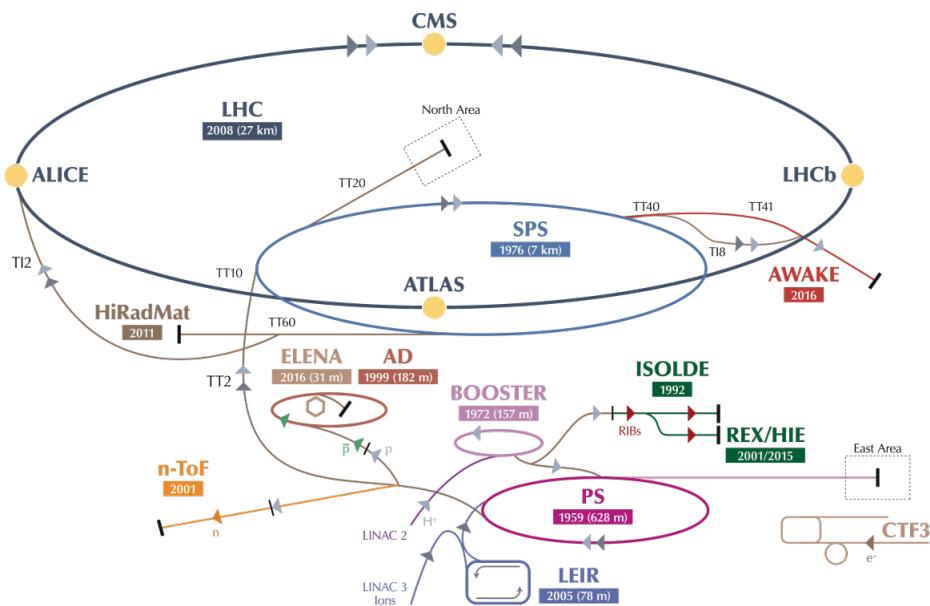
320 This chapter is dedicated to the experimental set up of the LHC and the Compact Muon  
 321 Solenoid (CMS) experiment. [Section 2.1](#) describes the LHC and its acceleration process for  
 322 protons to reach their design energies. The CMS experiment and its components are presented  
 323 in [Section 2.2](#). The upgrades performed during the long shutdown in 2013 are discussed  
 324 in [Section 2.2.4](#). The data acquisition of CMS is presented in [Section 2.2.3](#), while the CMS  
 325 computing model is shown in [Section 2.2.5](#).

## 326 2.1 The Large Hadron Collider

327 The LHC has started its era of cutting edge science on 10 September 2008 [47] after approval by  
 328 the European Organisation of Nuclear Research (CERN) in 1995 [48]. Installed in the previous  
 329 LEP tunnels, the LHC consists of a 26.7 km ring, that is installed between 45 and 170 m under  
 330 the French-Swiss border amidst Cessy (France) and Meyrin (Switzerland). Built to study rare  
 331 physics phenomena at high energies, the LHC can accelerate two type of particles, protons or  
 332 ions  $Pb^{45+}$ , and provides collisions at four interaction points, where the particle bunches are  
 333 crossing. Experiments for studying the collisions are installed on each interaction point.

334 As can be seen in [Figure 2.1](#), the LHC is last element in a chain that creates, injects and  
 335 accelerates protons. The starting point is the ionisation of hydrogen, creating protons that are  
 336 injected in a linear accelerator (LINAC 2). Here, the protons obtain an energy of 50 MeV. They  
 337 continue to the proton synchrotron booster (PSB or Booster), where the packs of protons are

338 accelerated to 1.4 GeV and each pack is split up in twelve bunches with 25 ns spacing for Run 2  
 339 (50 ns for Run 1). The proton synchrotron (PS) then increases their energy to 25 GeV before the  
 340 super proton synchrotron (SPS) increases the proton energy up to 450 GeV. Each accelerator  
 341 ring expands in radius in order to reduce the energy loss of the protons by synchrotron radiation<sup>1</sup>  
 342 Furthermore, the magnets responsible for the bending of the proton trajectories have to be  
 343 strong enough to sustain to higher proton energy. Ultimately, the protons are injected into  
 344 opposite directions into the LHC, where they are accelerated to 3.5 TeV (in 2010 and 2011),  
 345 4 TeV (in 2012 and 2013) or 6.5 TeV (in 2015 and 2016) [49]. Before the start of the LHC  
 346 in 2010, the previous energy record was held by the Tevatron collider at Fermilab, colliding  
 347 proton with antiprotons at  $\sqrt{s} = 1.96$  TeV. When completely filled, the LHC nominally contains  
 2220 bunches in Run 2, compared to 1380 in Run 1 (design: 2200).



**Figure 2.1:** Schematic representation of the accelerator complex at CERN [50]. The LHC (dark blue) is the last element in chain of accelerators. Protons are successively accelerated by LINAC 2, the Booster, the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) before entering the LHC.

348

Inside the LHC ring [51], the protons are accelerated by the means of radio frequency cavities, while 1232 dipole magnets of approximately 15 m long, each weighing 35 t ensure the deflection of the beams. The two proton beams circulate in opposite direction in separate pipes inside of the magnet. Through the use of a strong electric current in the coils around the beam pipe, magnetic fields are generated and cause the protons to bend in the required orbits. In order to get the coil to become superconducting and able to produce - with the aid of an iron return yoke - a strong magnetic field of 8.3 T, the magnet structure is surrounded by a vessel. This vessel is filled with liquid Helium making it possible to cool down the magnet to 1.9 K. In order to get

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<sup>1</sup>This energy loss is proportional to the fourth power of the proton energy and inversely proportional to the bending radius.

more focussed and stabilised proton beams, additional higher-order multipole and corrector magnets are placed along the LHC beam line.

The LHC is home to seven experiments, each located on an interaction point:

- A Toroidal LHC ApparatuS (ATLAS) [52] and the Compact Muon Solenoid (CMS) [53] experiments are the two general purpose detectors at the LHC. They both have a hermetic, cylindrical structure and were designed to search for new physics phenomena along with precision measurements of the Standard Model. The existence of two distinct experiments allows cross-confirmation of any discovery.
- A Large Ion Collider Experiment (ALICE) [54] and the LHC Beauty (LHCb) [55] experiments are focusing on specific phenomena. ALICE studies strongly interacting matter at extreme energy densities where a quark-gluon plasma forms in heavy ion collisions (Pb-Pb or p-Pb). LHCb searches for differences between matter and antimatter with the focus on b physics..
- The forward LHC (LHCf) [56] and the TOTal cross section, Elastic scattering and diffraction dissociation Measurement (TOTEM) [57] experiments are two smaller experiments that focus on head on collisions. LHCf consists of two parts placed before and after ATLAS and studies particles created at very small angles. TOTEM is placed in the same cavern as CMS and measures the total proton-proton cross section and studies elastic and diffractive scattering.
- The Monopoles and Exotics Detector At the LHC (MoEDAL) [58] experiment is situated near LHCb and tries to find magnetic monopoles.

For the enhancement of the exploration of rare events and thus enhancing the number of collisions, high beam energies as well as high beam intensities are required. The luminosity [59] is a measurement of the number of collisions that can be produced in a detector per square meter and per second and is the key role player in this enhancement. The LHC collisions create a number of events per second given by

$$N_{\text{event}} = L \sigma_{\text{event}}, \quad (2.1)$$

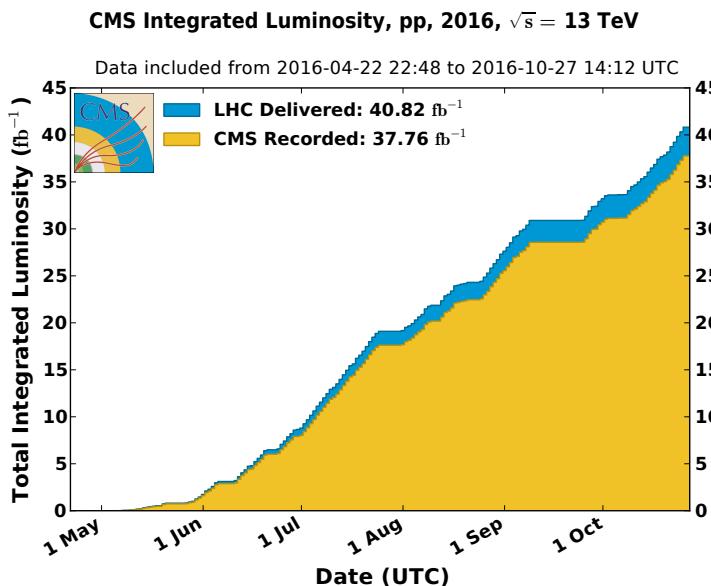
where  $\sigma_{\text{event}}$  is the cross section of the event of interest and  $L$  the machine luminosity. This luminosity depends only on the beam parameters and is for a Gaussian beam expressed as

$$L = \frac{1}{4\pi} N_b n_b f_{\text{rev}} \frac{N_b}{\epsilon_n} \left( 1 + \left( \frac{\theta_c \sigma_z}{2\sigma^*} \right)^2 \right)^{-\frac{1}{2}} \frac{\gamma_r}{\beta^*}. \quad (2.2)$$

The number of particles per bunch is expressed by  $N_b$ , while  $n_b$  is the number of bunches per beam,  $f_{\text{rev}}$  the revolution frequency,  $\gamma_r$  the relativistic gamma factor,  $\epsilon_n$  the normalized transverse beam emittance - a quality for the confinement of the beam ,  $\beta^*$  the beta function at the collision point - a measurement for the width of the beam,  $\theta_c$  the angle between two beams at the interaction point,  $\sigma_z$  the mean length of one bunch, and  $\sigma^*$  the mean height of one bunch.

383 In Equation 2.2, the blue part represents the stream of particles, the red part the brilliance, and  
 384 the green part the geometric reduction factor due to the crossing angle at the interaction point.

385 The peak design luminosity for the LHC reached in 2016 is  $10^{34} \text{ m}^{-2}\text{s}^{-1}$ , which leads to about  
 386 1 billion proton interactions per second. In 2016, the LHC was around 10% above this design  
 387 luminosity [60]. The luminosity is not a constant in time since it diminishes due to collisions  
 388 between the beams, and the interaction of the protons and the particle gas that is trapped in  
 389 the centre of the vacuum tubes due to the magnetic field. The diffusion of the beam degrades  
 390 the emittance and therefore also the luminosity. For this reason, the mean lifetime of a beam  
 391 inside the LHC is around 15 h. The integrated luminosity - the luminosity provided in a certain  
 392 time range - recorded by CMS and ATLAS over the year 2016 is given in Figure 2.2. In Run 2,  
 the peak luminosity is  $13\text{-}17 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  compared to  $7.7 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  in Run 1.



**Figure 2.2:** Cumulative offline luminosity measured versus day delivered to (blue), and recorded by CMS (orange) during stable beams and for proton collisions at 13 TeV centre-of-mass energy in 2016. The delivered luminosity accounts for the luminosity delivered from the start of stable beams until the LHC requests CMS to turn off the sensitive detectors to allow a beam dump or beam studies [61].

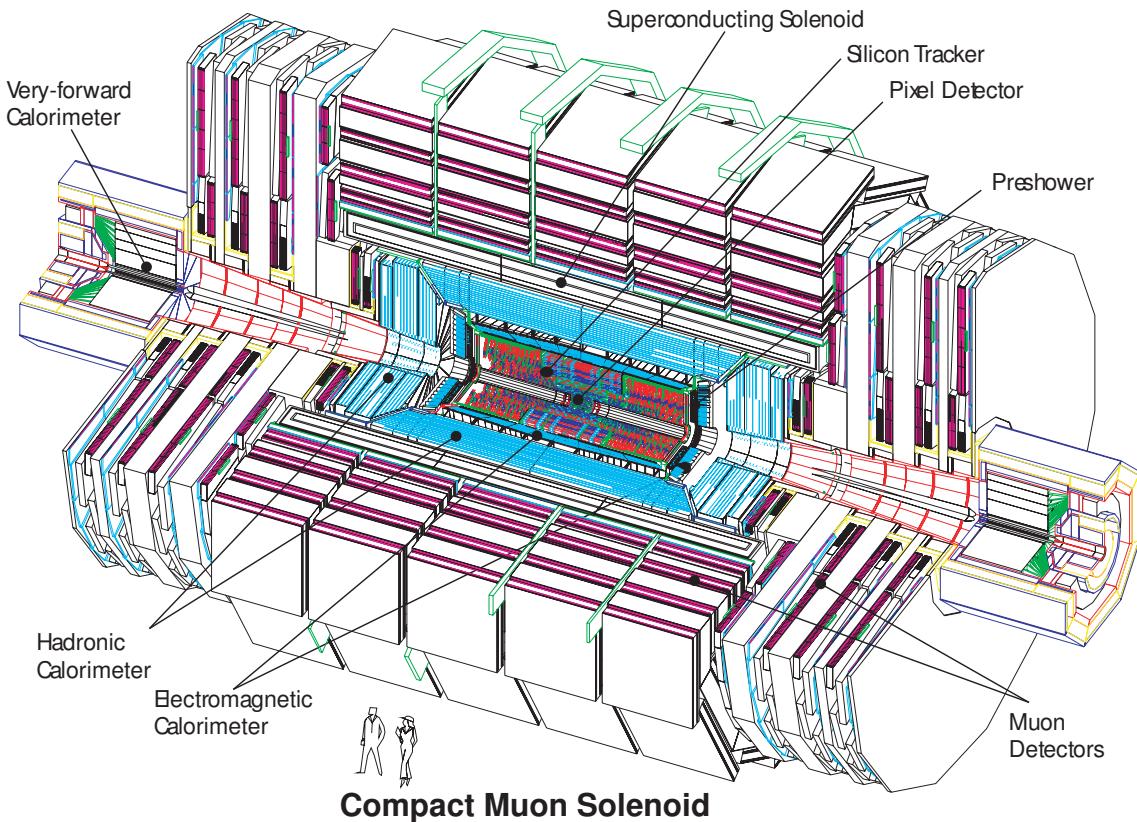
393

394 Multiple proton-proton interactions can occur during one bunch crossing, referred to as  
 395 pileup. On average, the number of pileup events is proportional to the luminosity times the total  
 396 inelastic proton-proton cross section. In 2016, an average of about 27 of pileup interactions  
 397 has been observed in 13 TeV proton collisions at the interaction point of CMS. For 2012, this  
 398 number was about 21 pileup interactions for 8 TeV collisions.

## 399 2.2 The Compact Muon Solenoid

400 At one of the collision points of the LHC, the CMS detector[62–64] is placed. Weighing 14 000 t,  
 401 this cylindrical detector is about 28.7 m long and 15 m in diameter. It has an onion like structure

of several specialised detectors and contains a superconducting solenoid with a magnetic field of 3.8 T. Living in a hadronic environment, multi-jet processes produced by the strong interaction are a main source of background for rare physics processes. Therefore, good identification, momentum resolution, and charge determination of muons, electrons and photons are one of the main goals of the CMS detector. Additionally, a good charged particle momentum resolution and reconstruction efficiency in the inner tracker provides identification for jets coming from b quarks or tau particles can be identified. Also the electromagnetic resolution for an efficient photon and lepton isolation as well as a good hadronic calorimeter for the missing transverse energy<sup>2</sup> were kept into account while designing CMS. In Figure 2.3, an overview of the CMS detector is shown.



**Figure 2.3:** Mechanical layout of the CMS detector. Figure taken from [65].

411

#### 412 2.2.1 CMS coordinate system

The coordinate system used by CMS can be found in Figure 2.4. The origin of the right handed orthogonal coordinate system is chosen to be the point of collisions. The x-axis points towards the centre of the LHC ring such that the y-axis points towards the sky, and the z-axis lies tangent to the beam axis. Since the experiment has a cylindrical shape, customary coordinates are used

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<sup>2</sup>The missing transverse energy comes from an imbalance in the transverse plane. This will be discussed in Chapter 4.

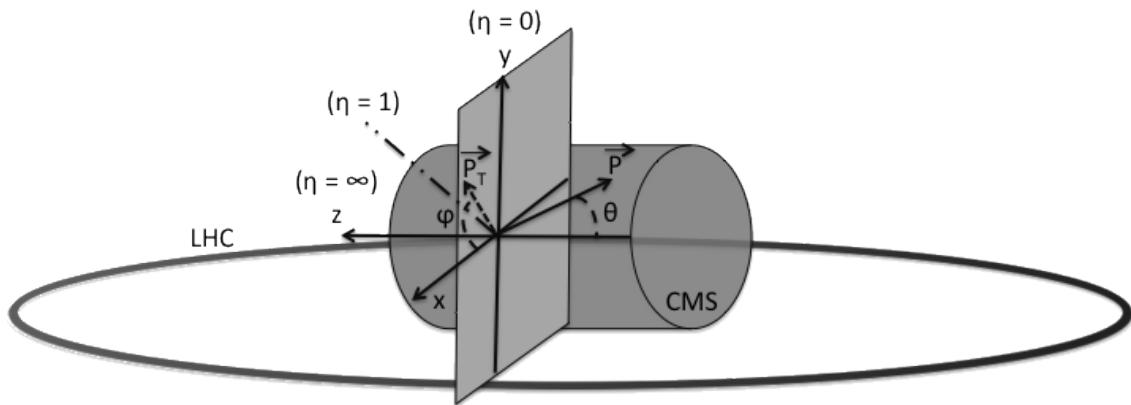
to describe the momentum  $\vec{p}$  : the distance  $p = |\vec{p}|$ , the azimuthal angle<sup>3</sup>  $\phi \in [-\pi, \pi]$ , the pseudo-rapidity<sup>4</sup>  $\eta$  :

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right). \quad (2.3)$$

For the energies considered at the LHC, where  $E \gg m$ , the pseudo-rapidity is a good approximation of the rapidity  $y$

$$y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right), \quad (2.4)$$

- 413 where the difference of rapidities of two particles is invariant under a Lorentz boost in the z-direction.



**Figure 2.4:** Representation of the coordinate system used by CMS. The point of origin is put at the collision point. The x-axis points towards the centre of the LHC ring such that the z-axis lies tangent to the beam axis.

- 414

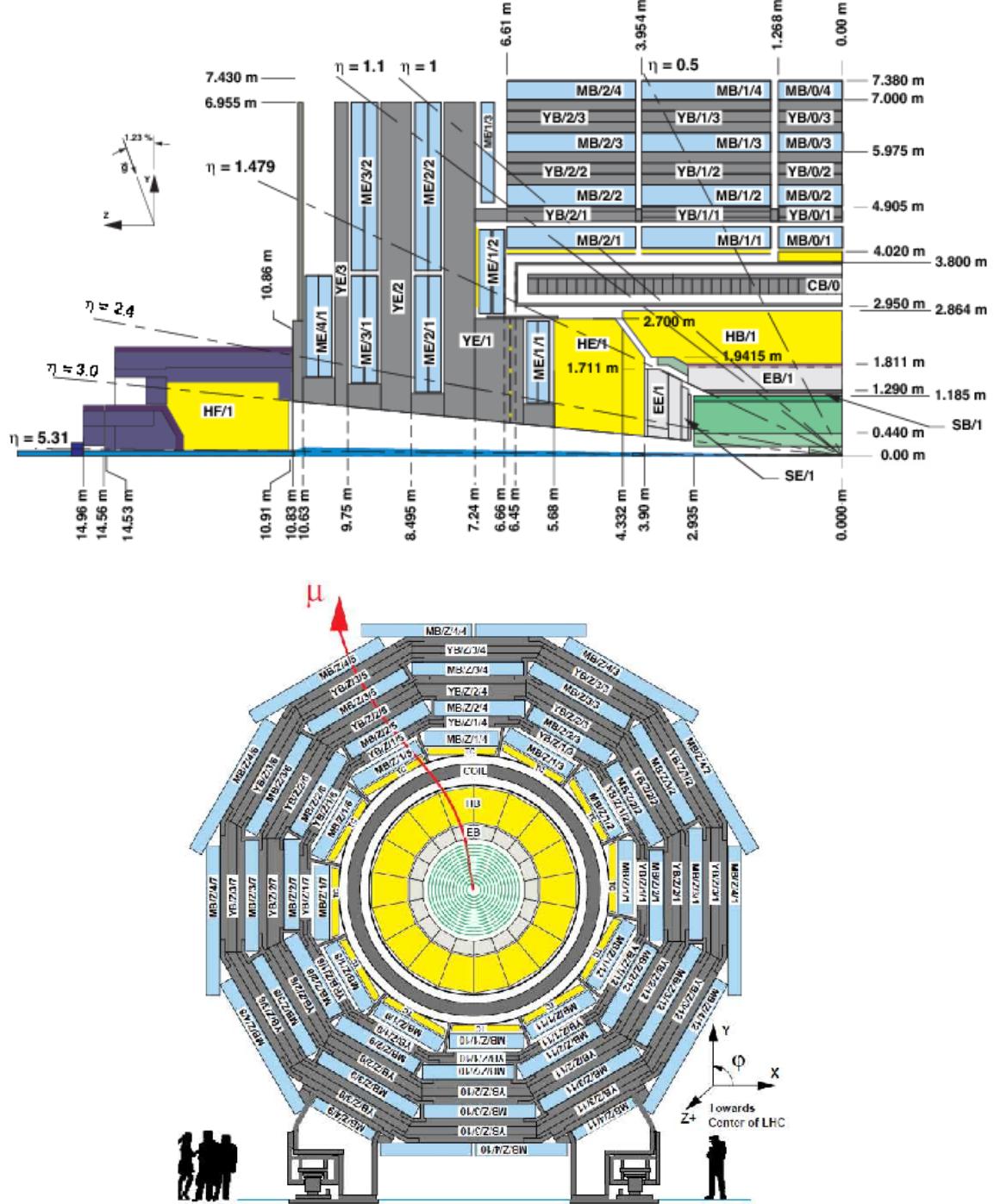
### 415 2.2.2 Towards the heart of CMS

- 416 The CMS detector can be divided into two parts. A central barrel is placed around the beam  
 417 pipe ( $|\eta| < 1.4$ ), and two plugs (end caps) ensure the hermeticity of the detector. In [Figure 2.3](#)  
 418 and [Figure 2.5](#) the onion like structure of the CMS detector is visible. The choice of a solenoid of  
 419 12.9 m long and 5.9 m diameter gives the advantage of bending the particle trajectories in the  
 420 transverse plane. The hadronic calorimeter ([Section 2.2.2.3](#)), the electromagnetic calorimeter  
 421 ([Section 2.2.2.4](#)) and the tracker ([Section 2.2.2.5](#)) are within the solenoid ([Section 2.2.2.2](#)),  
 422 while the muon chambers ([Section 2.2.2.1](#)) are placed outside the solenoid. The data used for  
 423 the search presented in this thesis is collected after the long shutdown 1. After discussing each  
 424 part of CMS in their Run 1 configuration, [Section 2.2.4](#) elaborates on their different upgrades  
 425 for the data collected in Run 2.

---

<sup>3</sup>The azimuthal angle is the angle between the x-axis and the projection in the transverse plane of the momentum  $\vec{p}$ , denoted as  $\vec{p}_T$ .

<sup>4</sup>The pseudo rapidity is expressed by the polar angle  $\theta$  between the direction of  $\vec{p}$  and the beam.

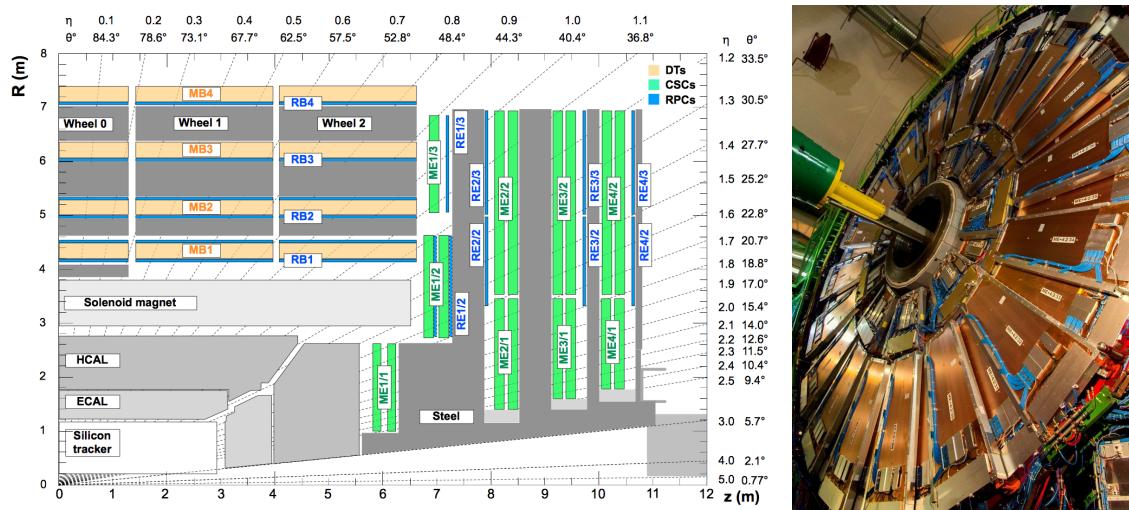


**Figure 2.5:** Schematic view of the CMS detector in the Run 1 configuration. The longitudinal view of one quarter of the detector is given on top, while the transversal view is shown on the bottom. The muon system barrel elements are denoted as  $MBZ/N/S$ , where  $z = -2 \dots +2$  is the barrel wheel number,  $n = 1 \dots 4$  the station number and  $S = 1 \dots 12$  the sector number. Similarly, the steel return yokes are denoted as  $YBZ/N/S$ . The solenoid is denoted as  $CB0$ , while the hadronic calorimeter is denoted as  $HE$  (end cap)/  $HB$  (barrel)/  $HF$  (forward) and the electromagnetic calorimeter as  $EE$  (end cap)/  $EB$  (barrel). The green part represents the tracking system (tracker + pixel). Figure taken from [66].

426 **2.2.2.1 Muon system**

427 The outermost part of CMS consists of the muon system. The magnet return yoke is interleaved  
 428 with gaseous detector chambers for muon identification and momentum measurement. The  
 429 barrel contains muon stations arranged in five separate iron wheels, while in the end cap four  
 430 muon stations are mounted onto three independent iron discs on each side. Each barrel wheel  
 431 has 12 sectors in the azimuthal angle.

432 The muon system is divided into three parts, shown in Figure 2.6. The muon rate and neutron  
 433 induced backgrounds are small and the magnetic field is very low for the barrel, thus CMS can  
 434 use drift tube (DT) chambers. For the end caps however, the muon and background flux is much  
 435 higher and there is a need to use cathode strip chambers (CSC) which are able to provide a  
 436 faster response, higher granularity and have a better resistance against radiation. In order to  
 437 form a redundant trigger system, resistive plate chambers (RPC) are added. This makes a total  
 of 250 DT, 540 CSC and 610 RPC chambers. In Figure 2.5 the arrangement is shown.



**Figure 2.6:** (Left) Schematic view of one quarter of the CMS muon system in the Run 1 configuration. The cathode strip chambers (CSC) are shown in green, the drift tubes (DT) are shown in yellow, while the resistive plate chambers (RPC) are shown in blue. Figure taken from [66]. (Right) Cathode strip chambers (ME+4/2 chambers on YE+3). Photo taken from [67].

438

439 Providing a measurement for  $|\eta| < 1.2$ , the DT chambers in the barrel are on average  
 440  $2 \times 2.5 \text{ m}^2$  in size and consist of 12 layers of DT cells<sup>5</sup> arranged in three groups of four. The  
 441  $r\phi$  coordinate is provided by the two outside groups, while the middle group measures the  
 442  $z$  coordinate. For the outer muon station, the DT chambers contain only 8 layers of DT cells,  
 443 providing a muon position in the  $r\phi$  plane. There are four CSC stations in each end cap, providing  
 444 muon measurements for  $0.9 < |\eta| < 2.4$  (Run 1 configuration). These CSCs are multi-wired  
 445 proportional chambers that consist of 6 anode wire planes crossed by 7 copper strips cathode  
 446 panels in a gas volume. The  $r$  coordinate is provided by the copper strips, while the  $\phi$  coordinate  
 447 comes from the anode wires, giving a two dimensional position measurement. There are six

<sup>5</sup>The DT cells are 4 cm wide gas tubes with positively charged stretched wires inside.

448 layers of RPCs in the barrel muon system and one layer into each of the first three stations  
 449 of the end cap. They are made from two high resistive plastic plates with an applied voltage  
 450 and separated by a gas volume. Read out strips mounted on top of the plastic plates detect the  
 451 signal generated by a muon passing through the gas volume. The RPCs provide a fast response  
 452 with a time resolution of 1 ns and cover a range of  $|\eta| < 1.8$  for the Run 1 configuration.

453 The muon system provides triggering on muons, identifying muons and improves the momen-  
 454 tum measurement and charge determination of high  $p_T$  muons. On top of the muon system,  
 455 the muon energy is deposited in the electromagnetic calorimeter, the hadronic calorimeter, and  
 456 outer calorimeter. The high magnetic field enables an efficient first level trigger and allows a  
 457 good momentum resolution of  $\Delta p/p \approx 1\%$  for a  $p_T$  of 100 GeV and  $\approx 10\%$  for a  $p_T$  of 1 TeV.  
 458 There is an efficient muon measurement up to  $|\eta| < 2.4$ .

**NOTE:**  
check numbers for run  
2

#### 459 2.2.2.2 Solenoid

460 Making use of the knowledge of previous experiments like ALEPH and DELPHI at LEP and H1  
 461 at HERA, CMS choose for a large super conducting solenoid with a length of 12.9 m and a  
 462 inner bore of 5.9 m [64]. With 2 168 turns, a current of 19.5 kA and a total energy of 2.7 GJ, a  
 463 large bending power can be obtained for a modestly-sized solenoid. In order to ensure a good  
 464 momentum resolution in the forward regions, a favourable length/radius was necessary. In  
 465 [Figure 2.7](#), a photo of the CMS solenoid is shown.

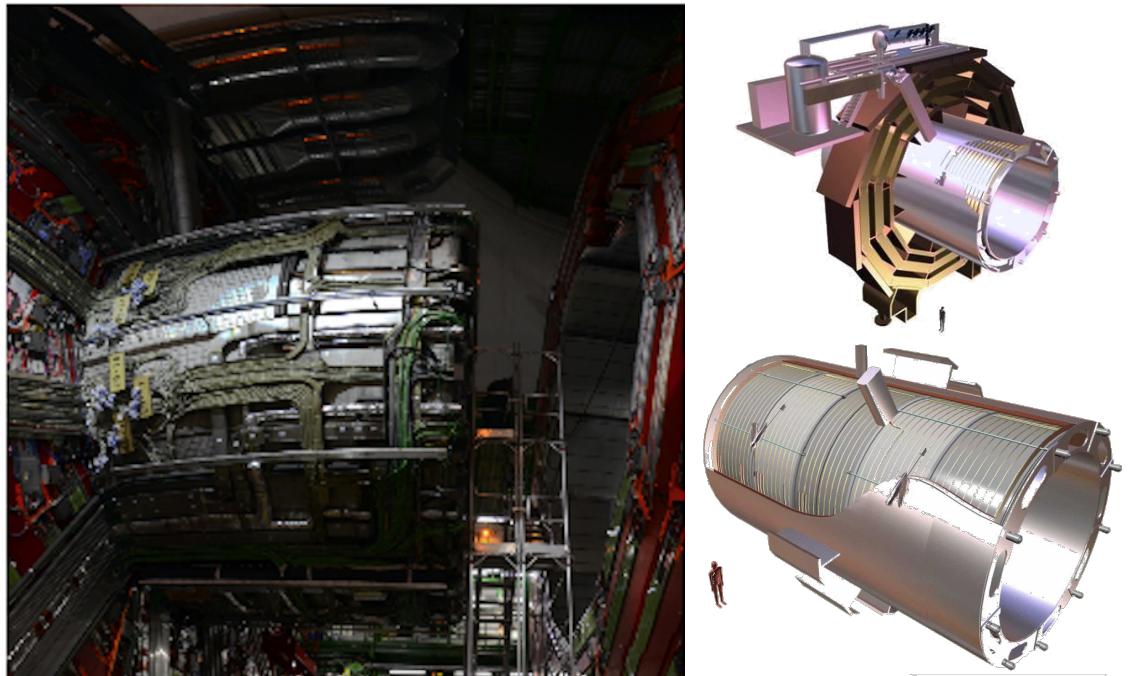
466 The solenoid uses a high-purity aluminium stabilised conductor with indirect cooling from  
 467 liquid helium, together with fully epoxy impregnation. A four-layer winding is implemented that  
 468 can withstand an outward pressure of 64 atm. The NbTi cable is co-extruded by pure aluminium  
 469 that acts as a thermal stabilizer and has an aluminium alloy for mechanical reinforcement. The  
 470 return of the magnetic field is done by fives wheels, noted by YB in [Figure 2.5](#).

#### 471 2.2.2.3 Hadronic calorimeter

472 The hadronic calorimeter (HCAL) is dedicated to precisely measure the energy of charged and  
 473 neutral hadrons via a succession of absorbers and scintillators. This makes it crucial for physics  
 474 analyses with hadronic jets or missing transverse energy. The HCAL barrel extends between  
 475  $1.77 < r < 2.95$  m, where  $r$  is the radius in the transverse plane with respect to the beam. Due  
 476 to space limitations, the HCAL needs to be as small as possible and is made from materials  
 477 with short interaction lengths<sup>6</sup>. On top of this, the HCAL should be as hermetic as possible and  
 478 extend to large absolute pseudo rapidities such that it can proved a good measurement of the  
 479 missing transverse energy.

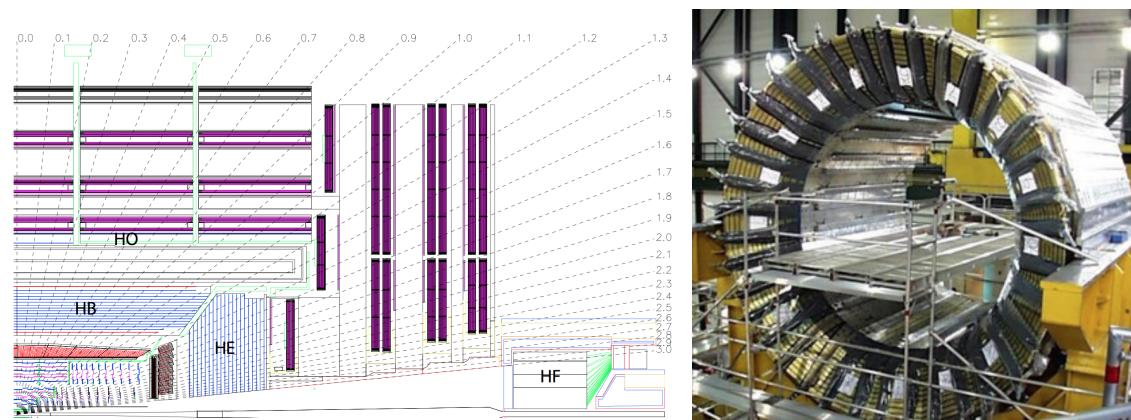
480 The quality of the energy measurements is dependent on the fraction of the hadronic shower  
 481 that can be detected. Therefore, the HCAL barrel (HB) inside the solenoid is reinforced by an  
 482 outer hadronic calorimeter between the solenoid and muon detectors (HO, see [Figure 2.8](#)),  
 483 using the solenoid as extra absorber. This increases the thickness to 12 interaction lengths.

<sup>6</sup>Here the interaction length is the nuclear interaction length and this is the length needed for absorbing 36.7% of the relativistic charged particles. For the electromagnetic calorimeter this is defined in radiation length  $X_0$ . The radiation length is the mean distance over which a high energy electron loses all but  $1/e$  of its energy by bremsstrahlung.



**Figure 2.7:** (Left) CMS solenoid during the long shutdown in 2013. (Right) An impression of the solenoid magnet taken from [68].

484 The HB and HO provide measurements for  $|\eta| < 1.3$ , while an end cap on each side (HE,  
 485  $1.3 < |\eta| < 3$ ) and a forward calorimeter (HF,  $3.0 < |\eta| < 5.2$ ) extend the pseudo rapidity  
 486 range.



**Figure 2.8:** (Left) Longitudinal view of the CMS detector showing the locations of the HB, HE, HO, and HF calorimeters. Figure taken from [53]. (Right) CMS barrel calorimeter. Photo taken from [69].

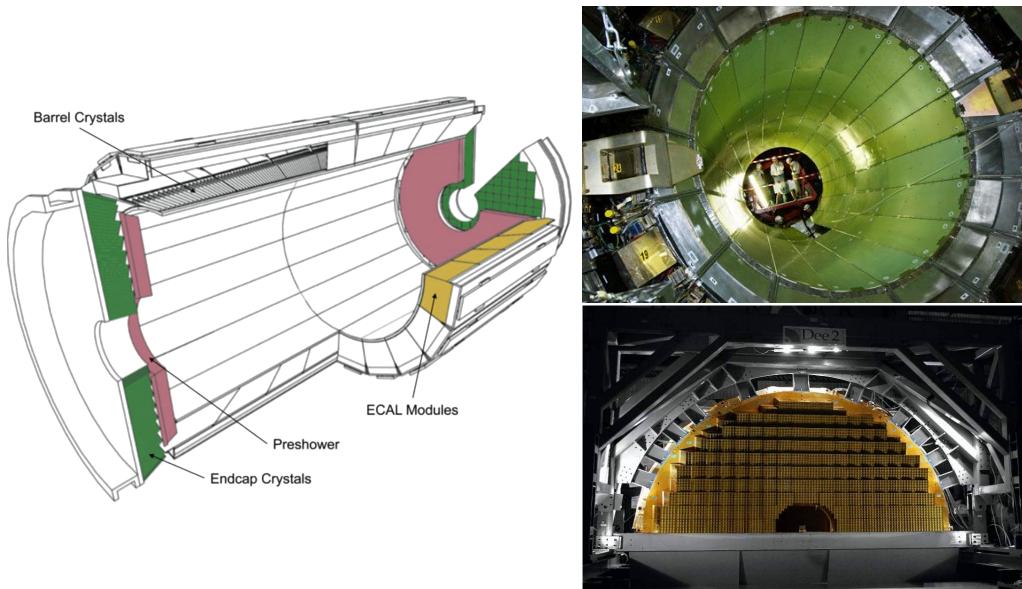
487 The HB is made of 16 absorber plates where most of them are built from brass and others are  
 488 made from stainless steel and is about five to ten interaction lengths thick. It is divided in  $\eta \times \phi$   
 489 towers and contains 2592 read out channels. The HO complements the HB and extends the  
 490 reach up to twelve interaction lengths. This subsystem contains 2160 read out channels. The HE

is also composed of brass absorber plates and has a thickness corresponding to approximately ten interaction lengths, with 2592 read out channels.. The HF experiences intense particle fluxes with an expected energy of 760 GeV deposited on average in a proton interaction at a centre-of-mass of 14 TeV, compared to 100 GeV in the rest of the detector. Therefore, these are Cherenkov light detectors made of radiation hard quartz fibers. The main causes of such large energy events are high energy muons, cosmic particles and charged particles from late showering hadrons. During Run 1, it became clear that the glass windows of the photon multiplier tubes (PMTs) had to be replaced which was done during LS1 [70]. The HF represents 1728 read out channels.

The HCAL and electromagnetic calorimeter combined can measure the hadron energy with a resolution  $\Delta E/E \approx 100\% \sqrt{E[\text{GeV}]} + 5\%$ .

#### 2.2.2.4 Electromagnetic calorimeter

The electromagnetic calorimeter (ECAL) is designed to measure the energy of photons and electrons and covers  $|\eta| < 3$ . It is an hermetic, homogeneous detector and consists of 75 848 lead tungstate ( $\text{PbWO}_4$ ) crystals. These crystals have a fast response time - 80% of the light is emitted within 25 ns - and are radiation hard. The electromagnetic showers produced by passing electrons or photons ionize the crystal atoms which emit a blue-green scintillation light, that is collected by silicon avalanche photodiodes (APDs) in the barrel and vacuum phototriodes (VPTs) in the end caps. The crystals and the APD response is sensitive to temperature changes and require a stable temperature.



**Figure 2.9:** (Left) Schematic cross section of the electromagnetic calorimeter taken from [53]. (Right top) The ECAL barrel during construction [71]. (Right bottom) One half of an EE [72].

There are three regions: a central barrel (EB), an endcap region (EE) and a preshower (ES) (Figure 2.9). The EB has an inner radius of 129 cm and corresponds to a pseudo rapidity of  $0 < |\eta| < 1.479$ . At a distance of 314 cm from the vertex and covering a pseudo rapidity of  $1.479 <$

514  $|\eta| < 3.0$ , are the EE. They consist of semi-circular aluminium plates from which structural  
 515 units of  $5 \times 5$  crystals (super crystals) are supported. The ES is placed in front of the crystal  
 516 calorimeter over the end cap pseudo rapidity range with two planes of silicon strip detectors as  
 517 active elements.

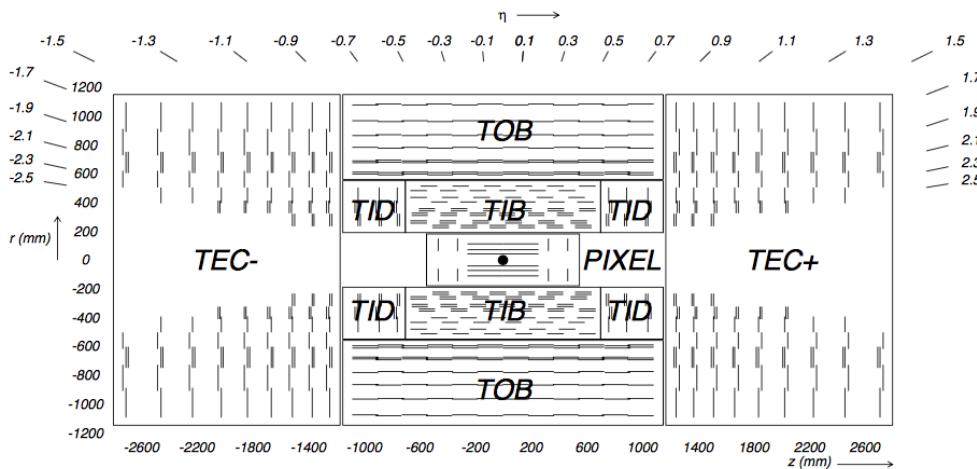
The electromagnetic shower will typically involve more than one channel. More than 90% of the energy of a 35 GeV electron or photon is contained in a  $5 \times 5$  matrix of crystals. Therefore, a clustering algorithm is performed in order to associate the energy deposits to the particles impinging the calorimeter. The achieved precision [73] for the barrel is  $2.10^{-3}$  rad in  $\phi$  and  $10^{-3}$  in  $\eta$ . For the end caps this is  $5.10^{-3}$  rad in  $\phi$  and  $2.10^{-3}$  in  $\eta$ . The energy is reconstructed by a supercluster algorithm, taking into account energy radiated via bremsstrahlung or conversion [53]. The energy resolution is given by

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E(GeV)} \oplus 0.3\%, \quad (2.5)$$

518 in the absence of a magnetic field, where the contributions come from the stochastic, noise and  
 519 constant terms respectively. The dominating term is the constant term ( $E_{shower} \approx 100$  GeV)  
 520 and thus the performance is highly dependent on the quality of calibration and monitoring .

### 521 2.2.2.5 Inner tracking system and operations

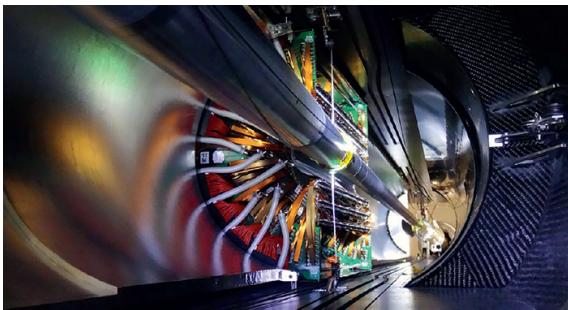
522 The tracking system (tracker) [74] is the detecting unit closest to the point of interaction.  
 523 Responsible for the reconstruction of trajectories from charged particles with  $|\eta| < 2.5$  that are  
 524 bent by the magnetic field, it provides a measurement of the momentum. The tracker is also  
 525 responsible for the determination of the interaction point or vertex. It should be able to provide  
 526 high granularity as well as fast read out, and be able to endure high radiation. For this reason,  
 527 the CMS collaboration choose silicon detector technology.



**Figure 2.10:** Schematic cross section through the CMS tracker. Each line represents a detector module. Double lines indicate back-to-back modules that deliver stereo hits. Figure taken from [53].

528 The tracking system consists of a cylinder of 5.8 m long and 2.5 m in diameter. It is immersed  
 529 in a co-axial magnetic field of 3.8 T provided by the solenoid. As shown in Figure 2.10, the

530 tracker is built up from a large silicon strip tracker with a small silicon pixel tracker inside. The  
 531 inner pixel region ( $4.4 < r < 10.2$  cm), gets the highest flux of particles. Therefore, pixel silicon  
 532 sensors of  $100 \times 150 \mu\text{m}^2$  are used. It consists of three cylindrical barrels that are complemented  
 533 by two discs of pixel modules at each side. The silicon strip tracker ( $20 < r < 116$  cm) has three  
 534 subdivisions. The Tracker Inner Barrel and Discs (TIB, TID, see Figure 2.12) are composed  
 535 of four barrel layers accompanied by three discs at each end. The outer part of the tracker -  
 536 Tracker Outer Barrel (TOB) - consists of 6 barrel layers. In the outer discs, there are nine discs  
 537 of silicon sensors, referred to as Tracker End Caps (TEC).



**Figure 2.11:** The pixel barrel being re-installed after the Long Shutdown in 2015, around the beam pipe at CMS [75].



**Figure 2.12:** First half of the inner tracker barrel, consisting of three layers of silicon modules [76].

538 The pixel, shown in Figure 2.11, has 1440 modules that cover an area of about  $1 \text{ m}^2$  and have  
 539 66 million pixels. It provides a three-dimensional position measurement of the hits arising from  
 540 the interaction from charged particles with the sensors. In transverse coordinate ( $r\phi$ ), the hit  
 541 position resolution is about  $10 \mu\text{m}$ , while  $20\text{-}40 \mu\text{m}$  is obtained in the longitudinal coordinate  
 542 ( $z$ ). The sensor plane position provides the third coordinate. The TIB/TID, shown in Figure  
 543 2.12, delivers up to four  $r\phi$ -measurements using a  $320 \mu\text{m}$  thick silicon micro-strip sensors.  
 544 These sensors are placed with their strips parallel to the beam axis in the barrel and radial  
 545 in the discs. In the TIB, the first two layers have a strip pitch of  $80 \mu\text{m}$ , while the remaining  
 546 to have a strip pitch of  $120 \mu\text{m}$ . This leads to a respective single point resolution of  $23 \mu\text{m}$   
 547 and  $35 \mu\text{m}$ . For the TID, the pitch varies between  $100 \mu\text{m}$  and  $141 \mu\text{m}$ . The TOB provides six  
 548  $r\phi$ -measurements with a single point resolutions of  $53 \mu\text{m}$  in the first four layers, and  $35 \mu\text{m}$  in  
 549 the last two layers. It consists of  $500 \mu\text{m}$  thick micor strip sensors with strip pitches of  $183 \mu\text{m}$   
 550 (first 4 layers) or  $122 \mu\text{m}$  (last two layers). The TEC provides up to 9  $\phi$ -measurements via 9  
 551 discs consisting of up to 7 rings of silicon microstrip sensor of  $97 \mu\text{m}$  to  $184 \mu\text{m}$  average pitch.

552 A second co-ordinate measurement ( $z$  in the barrel,  $r$  on the discs) is provided through the  
 553 use of a second micro strip detector module mounted back-to-back with a stereo angle of 100  
 554 mrad. This is done on the modules in the first two layers and rigns of the TIB, TID, and TOB, as  
 555 wel as rigns 1,2, and 5 of the TECs (blue line in Figure 2.10). The resolution in the  $z$  direction is  
 556 approximately  $230 \mu\text{m}$  in the TIB and  $530 \mu\text{m}$  in the TOB, and is varying with pitch in the TID  
 557 and TEC. To allow overlay and avoid gaps in acceptance, each module is shifted slightly in  $r$  or  
 558  $z$  with respect to its neighbouring modules within a layer. With this detector lay out, at least  
 559 nine points per charged particle trajectory can be measured in an  $|\eta|$  range up to 2.4, where at  
 560 least four of them being two dimensional. The CMS silicon tracker provides 9.3 million readout

561 channels and covers an active area of about  $198\text{ m}^2$ .

### 562 2.2.3 Data acquisition

563 At a design luminosity of  $10^{34}\text{ m}^{-2}\text{s}^{-1}$ , the proton interaction rate exceeds 1 GHz. Given the  
 564 large size of an event (about 1 MB), the high crossing rate, and that typically tens of collisions  
 565 happen at the same time, it is impossible for the CMS experiment to store all the data generated.  
 566 In order to deal with the large amount of data, a two level trigger system has been put in place.  
 567 The first level (Level-1) is a custom hardware system, while a second high level trigger (HLT) is  
 568 software based running on a large farm of computers.

### 569 CMS Level-1 Trigger

570 The Level-1 Trigger has to be a flexible, maintainable system, capable of adapting to the  
 571 evolving physics programme of CMS [77]. Its output rate is restricted to 100 kHz imposed  
 572 by the CMS readout electronics. It is implemented by custom hardware and selects events  
 573 containing candidate objects - e.g. ionization deposits consistent with a muon, or energy clusters  
 574 corresponding to an electron / photon / tau lepton / missing transverse energy / jet. Collisions  
 575 with large momenta can be selected by using scalar sum of the transverse momenta of the jets.

576 By buffering the raw data from the CMS subdetectors in front-end drivers, the Level-1 Trigger  
 577 has a pipeline memory of 3.2  $\mu\text{s}$  to decide whether to keep an event or reject it. The trigger  
 578 primitives (TP) from the calorimeters and muon detectors are processed in several steps and  
 579 combined into a global trigger. This information is then combined with the input from the other  
 580 subsystems for the HLT. The separate inputs are synchronized to each other and the LHC orbit  
 581 clock and sent to the global trigger module. Here, Level-1 Trigger algorithms are performed  
 582 within 1  $\mu\text{s}$  to decide whether to keep the event.

### 583 CMS HLT Trigger

584 The HLT is an array of commercially available computers with a programmable menu that has  
 585 an output rate of on average 400 Hz for off-line event storage. The data processing is based on  
 586 an HLT path. This is a set of algorithmic steps to reconstruct objects to define selection criteria.  
 587 Here, the information of all subdetectors can be used to perform algorithms on higher level  
 588 reconstructed objects.

### 589 2.2.4 Phase 1 upgrades

590 Before the start of taking collision data for 13 TeV operations on 3 June 2015, CMS had a long  
 591 shutdown (LS1) [78]. During this shutdown, the section of the beryllium beam pipe within CMS  
 592 was replaced by a narrower one. This operation required the pixel to be removed and reinserted  
 593 into CMS. In Run 2, higher particle fluxes with respect to Run 1 are expected. To avoid long  
 594 damage caused by the intense particle flux at the heart of CMS, the tracker is been made ready  
 595 to operate at much lower temperature than during Run 1. The electromagnetic calorimeter  
 596 preshower system had been damaged during Run 1, therefore the preshower discs were removed,  
 597 repaired and reinstalled successfully inside CMS in 2014. To help the discrimination between  
 598 interesting low momentum muons coming from collisions and muons caused by backgrounds, a

599 fourth triggering and measurement station for muons was added in each of the end caps. Several  
 600 new detectors were installed into CMS for measuring the collision rate within the detector and  
 601 monitors beam related backgrounds.

602 During the LS1, the muon system underwent major upgrades [79, 80]. In the fourth station  
 603 of each end cap, the outermost rings of CSC and RPC chambers were completed, providing an  
 604 angular coverage of  $1.2 < |\eta| < 1.8$  for Run 2, increasing the system redundancy, and allowing  
 605 tighter cuts on the trigger quality. In order to reduce the environmental noise, outer yoke discs  
 606 have been placed on both sides for the end caps. At the innermost rings of the first station,  
 607 the CSCs have been upgraded by refurbishing the readout electronics to make use of the full  
 608 detector granularity instead of groups of three as was the case for Run 1. In Figure 2.6 (right),  
 609 the refurbishing of the CSCs is shown.

610 Since the HF experiences intense particle fluxes, it became clear during Run 1 that the glass  
 611 windows of the PMTs need replacing. For the ECAL in Run 1, the energy reconstruction happened  
 612 via a weighted sum of the digitized samples [81]. For Run 2 however, the reconstruction had  
 613 to be made more resistant for out of time pile up and a multi-fit approach has been set into  
 614 place. In this approach, the pulse shape is modelled as a sum of one in-time pulse plus the out  
 615 of time pulses [73]. The energy resolution is better than 2% in the central barrel region and  
 616 2-5 % elsewhere.

During the first data taking period of the LHC (2010 to 2013), the tracker operated at  $+4^\circ\text{C}$ . With the higher LHC beam intensities from 2015 onwards, the tracker needs to be operated at much lower temperatures. The reason for this is that with intense irradiation, the doping concentration changes, the leakage current increases proportional to the fluence and the charge collection efficiency decreases due to charge trapping. Mostly the leakage current ( $I$ ) is affected by the temperature change:

$$I \propto T^2 e^{-\frac{E_g}{2kT}}, \quad (2.6)$$

617 where  $T$  is the operating temperature,  $E_g$  the band gap and  $k$  the Boltzmann constant. There is  
 618 approximately a factor 15 between the leakage currents at room temperatures and at  $-10^\circ\text{C}$ .

619 During the LS1, the CMS cooling plant was refurbished [82] and the fluorocarbon cooling  
 620 system overhauled. To help to suppress the humidity inside the tracker, new methods for vapour  
 621 sealing and insulation were applied. Furthermore, several hundred high-precision sensors are  
 622 used to monitor the humidity and temperature. In order to get as dry air as possible, a new  
 623 dry-gas plant provides eight times more dry gas (air or nitrogen) than during the first run, and  
 624 allows regulation of the flow. As a final addition, the cooling bundles outside the tracker are  
 625 equipped with heater wires and temperature sensors in order to maintain safe operations above  
 626 the cavern dew point. For the data taking in 2015-2016, the tracker operated at  $-15^\circ\text{C}$ .

627 In Run 2, with the increase in centre of mass energy and a higher luminosity, a larger number  
 628 of simultaneous inelastic collisions per crossing is expected with respect to Run 1. For this, the  
 629 CMS Level-1 has been upgraded [83]. All hardware, software, databases and the timing control  
 630 system have been replaced for Run 2, where the main changes are that the muon system now  
 631 uses the redundancy of the muon detector system earlier to make a high resolution muon trigger.

632 Other upgrades are that the calorimeter system isn't bound any more for streaming data and  
633 the global trigger has more Level-1 Trigger algorithms.

634 After the first half of Run 2, the innermost part of detection material in CMS (pixel) was  
635 upgraded by adding a fourth layer , enhancing the particle tracking capabilities of CMS. The  
636 data used in the framework of this thesis however is from before this upgrade. More information  
637 on the Pixel upgrade can be found in Refs. [84, 85].

638 **2.2.5 CMS computing model**

639 The selected data is stored, processed and dispersed via the Worldwide Large Hadron Collider  
640 GRID (WLCG) [86, 87]. This has a tiered structure that functions as a single, coherent system.

641 At CERN and the Wigner Research Center for physics, a single Tier-0 is located. The raw data  
642 collected by CMS is archived here, and a first reconstruction of the data is done. This data is  
643 then already in a file format usable for physics analysis. Furthermore, it is able to reprocess  
644 data when new calibrations become available. The Tier-0 site distributes this data to a total of  
645 14 Tier-1 centres. They carry out data reprocessing and store real data as well as simulated  
646 data. The Tier-1 further distributes the data to over 150 Tier-2 centres. These make the data  
647 accessible for physics analysis and are also being used for the production of simulated data. The  
648 data is made accessible for physicists around the world.

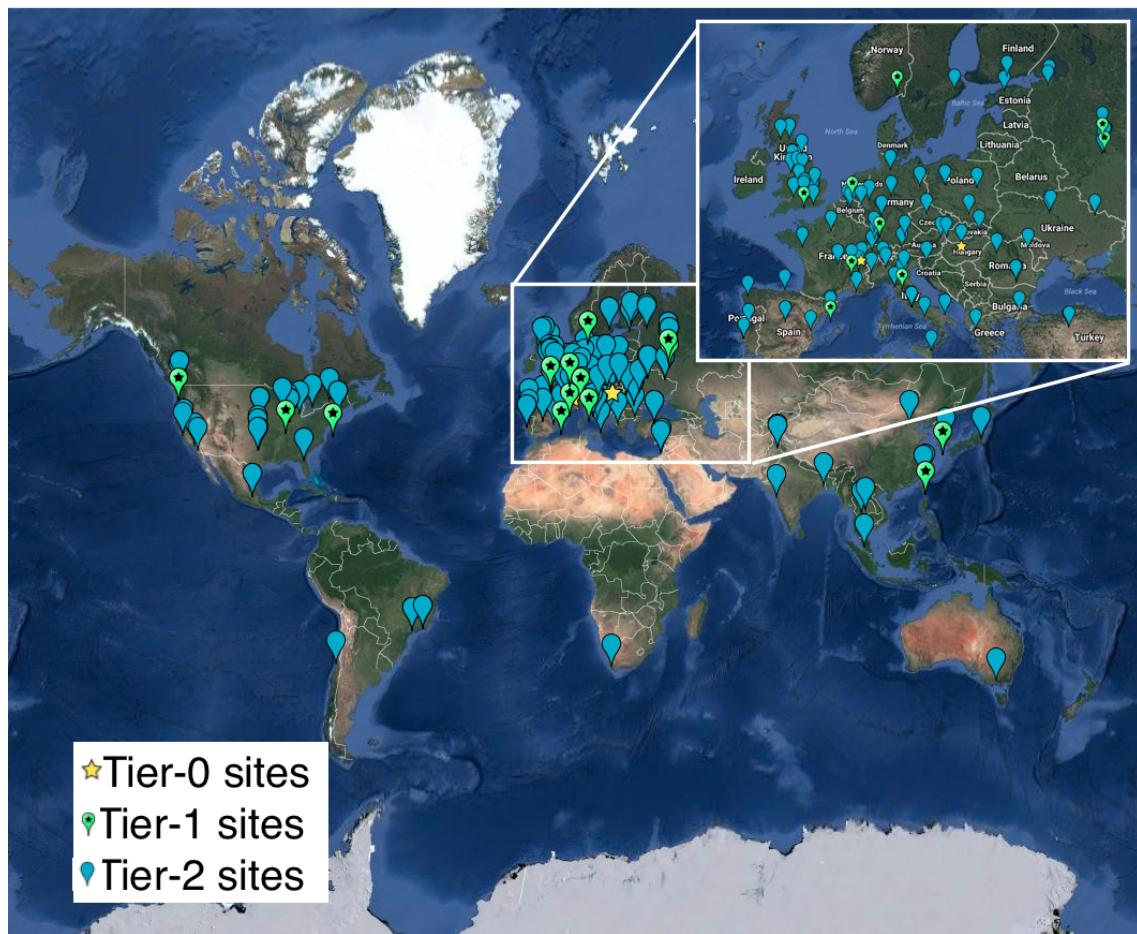


Figure 2.13: Worldwide LHC Computing Grid in 2017 [88].



# Analysis techniques

# 3

650 In order to disentangle the collisions coming from high energy experiments, many tools have  
 651 been developed. In [Section 3.1](#), the predictions behind hadron collision at high energies are  
 652 presented. These are used to generate events via Monte Carlo event generators, explained in  
 653 [Section 3.2](#). Machine learning helps to differentiate between signal- and background like events.  
 654 In [Section 3.3](#), the multivariate technique of boosted decision trees is explained. This yields  
 655 powerful discriminants for separating signal and background events and provides distributions  
 656 that go through template-based maximum likelihood fits. The fitting method used in the search  
 657 presented in this thesis is discussed in [Section 3.4](#).

## 658 3.1 Hadron collisions at high energies

In hadron collisions at sufficiently high momentum transfer, all partons can be approximated as free making it possible to treat hadron-hadron scattering as a single parton-parton interaction. The momentum of the parton can then be expressed as a fraction of the hadron momentum

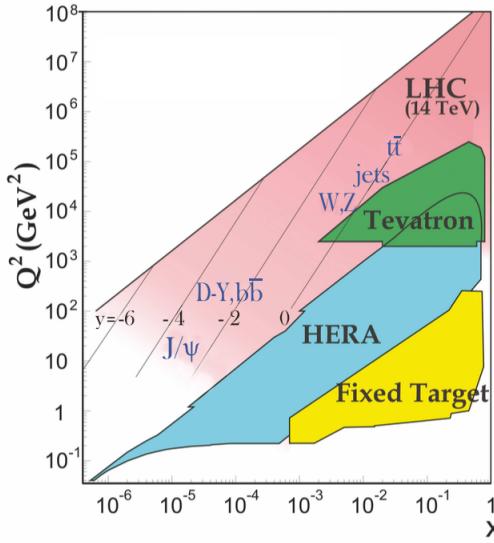
$$\vec{p}_{\text{parton}} = x \vec{p}_{\text{hadron}}, \quad (3.1)$$

where  $x$  is referred to as the Björken scaling variable. The interaction  $p_A p_B \rightarrow X$  can then be factorised in terms of partonic cross sections  $\hat{\sigma}_{ij \rightarrow X}$  [89]

$$\sigma_{p_A p_B \rightarrow X} = \sum_{ij} \iint dx_1 dx_2 f_i^A(x_1, Q^2) f_j^B(x_2, Q^2) d\hat{\sigma}_{ij \rightarrow X}, \quad (3.2)$$

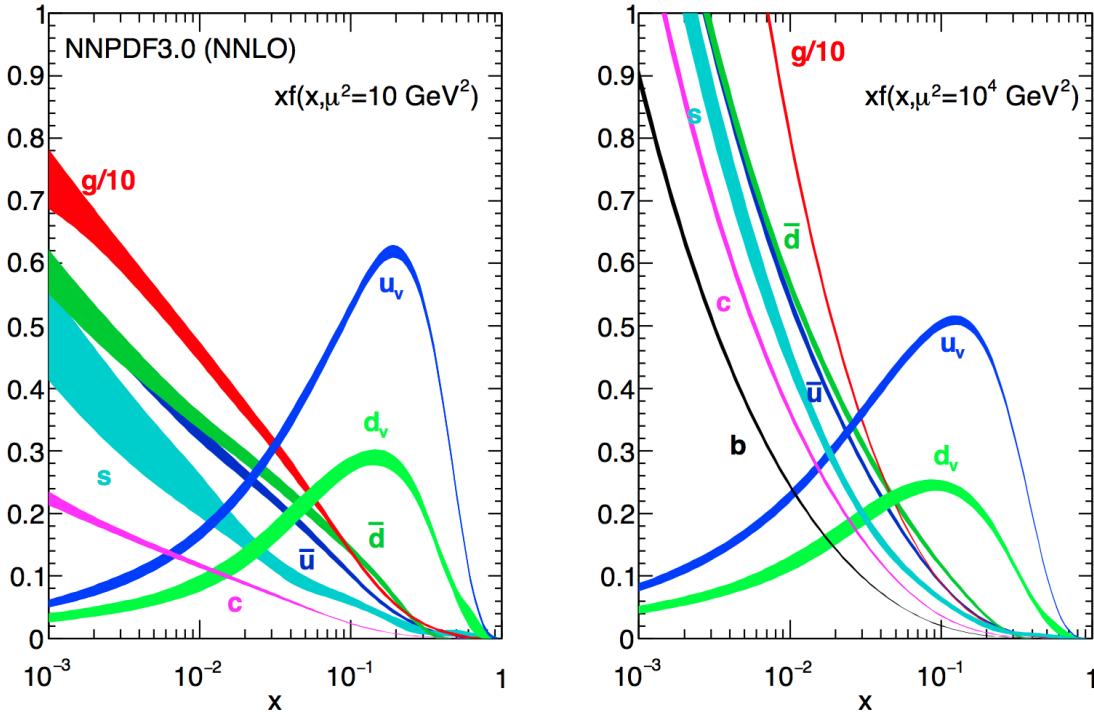
659 where  $i$  and  $j$  are the partons resolved from protons A and B,  $f_i(x_i, Q^2)$  the parton density  
 660 functions (PDF), and  $Q^2$  the factorisation scale more commonly denoted as  $\mu_F$ . The factorisation  
 661 scale is the scale at which the hadronic interaction can be expressed as a product of the partonic  
 662 cross section and the process independent PDF. In [Figure 3.1](#), the kinematic regions in  $x$  and  
 663  $\mu_F$  are shown for fixed target and collider experiments.

664 The parton density functions (PDF) [90–92] give the momentum distribution of the proton  
 665 amongst its partons at an energy scale  $\mu_F$ . These function can not be determined from first prin-  
 666 ciples and have to obtained from global fits to data. The PDFs are obtained from measurements on



**Figure 3.1:** Kinematic regions in momentum fraction  $x$  and factorisation scale  $Q^2$  probed by fixed-target and collider experiments. Some of the final states accessible at the LHC are indicated in the appropriate regions, where  $y$  is the rapidity. In this figure, the incoming partons have  $x_{1,2} = (M/14\text{TeV})e^{\pm y}$  with  $Q = M$  where  $M$  is the mass of the state shown in blue in the figure. For example, exclusive  $J/\psi$  and  $\Upsilon$  production at high  $|y|$  at the LHC may probe the gluon PDF down to  $x \sim 10^{-5}$ . Figure taken from [4].

667 deep inelastic scattering using lepton-proton collision by the HERA collider [93], supplemented  
 668 with proton-antiproton collisions from Tevatron at Fermi lab [94], and proton collision data  
 669 from the ATLAS, CMS and LHCb collaborations at the LHC (Run 1) [95]. These measurements  
 670 are included in global PDF sets known as the PDF4LHC recommendation [92]. From their mea-  
 671 surement at scale  $\mu_F$  these PDFs can be extrapolated using the DGLAP equations [96]. The PDFs  
 672 are used to calculate the cross section of a certain process and are therefore used as input for the  
 673 Monte Carlo generators used to make the simulated data samples at the LHC. In the framework  
 674 of this thesis, the NLO PDF4LHC15\_100 set is used. This set is an envelope of three sets, CT14,  
 675 MMHT2014 and NNPDF3.0 [92]. In Figure 3.2 the dependency of the PDFs on the momentum  
 676 fraction  $x$  is shown for the NNPDF3.0 set on hadronic scale ( $\mu_F^2 = (10\text{GeV})^2$ ) and LHC scale  
 677 ( $\mu_F^2 = (10^4\text{GeV})^2$ ). For most values of the momentum fraction, the gluon density dominates,  
 678 meaning that it is easier to probe muons than the quarks. For  $x$  close to one, the parton densities  
 679 of the up and down quarks (the valence quarks of the proton) dominate over the gluon density.  
 680 The charm, anti-up, and anti-down quarks have lower densities in general since those are sea  
 681 quarks which originate in the proton only through gluon splitting. The resolution scale  $Q^2$  is  
 682 typically taken to be the energy scale of the collision. For the top quark pair production a scale  
 683 of  $Q^2 = (350\text{GeV})^2$  is chosen, meaning that the centre-of-mass energy of the hard interaction is  
 684 about twice the top quark mass. The uncertainty on the parton distributions is evaluated using  
 685 the Hessian technique [97], where a matrix with a dimension identical to the number of free  
 686 parameters needs to be diagonalised. In the case of PDF4LHC15\_100 set, this translates into  
 687 100 orthonormal eigenvectors and 200 variations of the PDF parameters in the plus and minus  
 688 direction.



**Figure 3.2:** The momentum fraction  $x$  times the parton distribution functions  $f(x)$ , where  $f = u_v, d_v, \bar{u}, \bar{d}, s, c$ , or  $g$  as function of the momentum fraction obtained in the NNLO NNPDF3.0 global analysis at factorisation scales  $\mu^2 = 10 \text{ GeV}^2$  (left) and  $\mu^2 = 10^4 \text{ GeV}^2$  (right), with  $\alpha_s(M_Z^2) = 0.118$ . The gluon PDF has been scaled down by a factor of 0.1. Figure taken from [4].

At high energies, divergences can appear from quantum fluctuations. For the theory still to be able to describe the experimental regime, a renormalization scale  $\mu_R$  is used to redefine physical quantities. A consequence of this method is that the coupling constants will run as function of  $\mu_R$ . Beyond this scale, the high energy effects such as the loop corrections to propagators (self energy) are absorbed in the physical quantities through a renormalization of the fields. In particular the running behaviour of the strong coupling constant<sup>1</sup>  $\alpha_s$  is found to be

$$\alpha_s = \frac{\alpha_s(\mu_0^2)}{1 + \alpha_s(\mu_0^2) \frac{33-2n_f}{12\pi} \ln\left(\frac{|\mu_R^2|}{\mu_0^2}\right)}, \quad (3.3)$$

with  $n_f$  the number of quarks and  $\mu_0$  the reference scale on which the coupling is known. The current world average of the strong coupling constant at the  $Z$  boson mass is  $\alpha_s(\mu_R = m_Z) = 0.1181 \pm 0.0011$  [4]. From Equation 3.3 one can see easily that the coupling strength decreases with increasing renormalization scale, this known as asymptotic freedom. Additionally, following the behaviour of  $\alpha_s(\mu_R^2)$ , a limit  $\Lambda_{\text{QCD}} \approx 200 \text{ MeV}$  is found for which  $\alpha_s$  becomes larger than one. Under this limit, the perturbative calculations of observables can no longer be done.

<sup>1</sup>The strong coupling constant is defined as  $\alpha_s = \frac{g_s^2}{4\pi}$ .

Cross sections can be written in terms of interacting vertices contributing to the matrix element (ME) originating from elements of a perturbative series [98], allowing them to be expanded as a power series of the coupling constant  $\alpha$

$$\sigma = \sigma_{\text{LO}} \left( 1 + \left( \frac{\alpha}{2\pi} \right) \sigma_1 + \left( \frac{\alpha}{2\pi} \right)^2 \sigma_2 + \dots \right). \quad (3.4)$$

695 Leading order (LO) accuracy contains the minimal amount of vertices in the process, then  
 696 depending on where the series is cut off one speaks of next-to-leading order (NLO), or next-  
 697 to-next-to-leading order (NNLO) accuracy in  $\alpha$ . Predictions including higher order correction  
 698 tend to be less affected by theoretical uncertainties originating from a variation of the chosen  
 699 renormalization and factorisation scales.

## 700 3.2 Event generation

701 In order to compare reconstructed data with theoretical predictions, collision events are gener-  
 702 ated and passed through a simulation of the CMS detector and an emulation of its readout. For  
 703 the detector simulation, a so-called Full Simulation package [99, 100] based on the Geant4  
 704 toolkit [101] is employed. It allows a detailed simulation of the interactions of the particles  
 705 with the detector material.

### 706 3.2.1 Fundamentals of simulating a proton collision

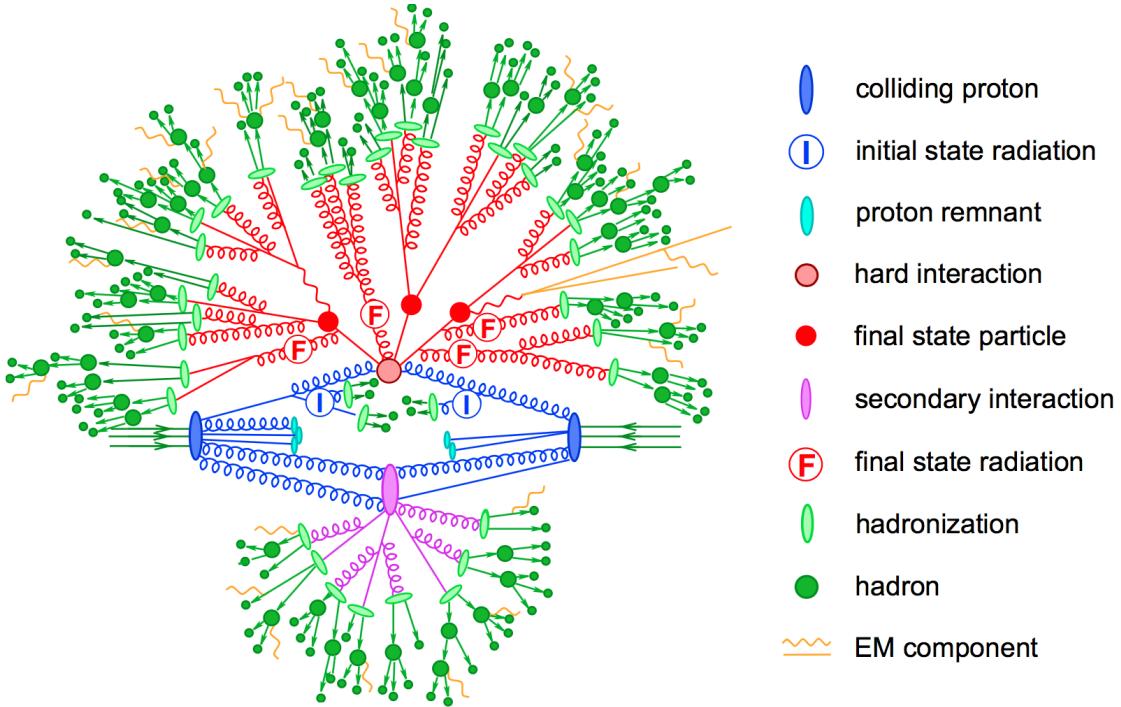
707 The procedure of to generate  $\text{pp} \rightarrow \text{X}$  events can be subdivided into sequential steps [102–104],  
 708 as shown in Figure 3.3.

709 The interaction of two incoming protons is often soft and elastic leading to events that are not  
 710 interesting in the framework of this thesis. More intriguing are the hard interaction between two  
 711 partons from the incoming protons. The matrix elements of a hard scattering process of interest  
 712 is the starting point of the generation of events. Monte Carlo techniques are used to sample the  
 713 corresponding cross section integral and the resulting sample of events reflect the probability  
 714 distribution of a process over its final state phase space. After obtaining the sample of events of  
 715 the hard interaction, a parton shower (PS) program is used to simulate the hadronisation of  
 716 final state partons into hadrons which then decay further. Additionally, radiation of soft gluons  
 717 or quarks from initial or final state partons is simulated. These are respectively referred to as  
 718 initial state radiation (ISR) or final state radiation (FSR). Contributions from soft secondary  
 719 interactions, the so-called underlying event (UE), and colour reconnection effects are also taken  
 720 into account. A brief overview of the employed programs used for the event generation of the  
 721 signal and main background processes used in the search presented in the thesis are given in  
 722 Section 3.2.2.

**NOTE:** 720  
Should I  
add more 721  
details? 722

### 723 3.2.2 Programs for event generation

724 The FEYNRULES package [105] allows the calculation of the Feynman rules in momentum space  
 725 for any quantum field theory model. By use of a Lagrangian, the set of Feynman rules associated  
 726 with this Lagrangian are calculated. Via the Universal FeynRules Output (UFO) [106] the  
 727 results are then passed to matrix element generators.



**Figure 3.3:** Sketch of a hadron collision as simulated by a Monte-Carlo event generator. The red blob in the centre represents the hard collision, surrounded by a tree-like structure representing Bremsstrahlung as simulated by parton showers. The purple blob indicates a secondary hard scattering event. Parton-to-hadron transitions are represented by light green blobs, dark green blobs indicate hadron decays, while yellow lines signal soft photon radiation. Figure taken from [104].

728     The MadGraph program [107] is used to interpret the physics model and calculate the cor-  
 729     responding Feynman diagrams and matrix elements. After this, MadEvent [108] is used to  
 730     calculate the corresponding partons. These generated parton configurations are then merged  
 731     with Pythia [109–111] parton showers using the MLM merging scheme [112].

732     The MadGraph5\_aMC@NLO program [113] combines the LO MadGraph [107] and the aMC@NLO  
 733     program into a common framework. This combination supports the generation of samples  
 734     at LO or NLO together with a dedicated matching to parton showers using the MLM [112]  
 735     or FXFX [114] schemes respectively. The FXFX scheme produces a certain fraction of events  
 736     with negative weights originating from the subtraction of amplitudes that contain additional  
 737     emissions from the NLO matrix element to prevent double-counting.

738     The POWHEG box (versions 1,2) [115–120] contains predefined implementations of various  
 739     processes at NLO. It applies the POWHEG method for ME- to PS- matching, where the hardest  
 740     radiation generated from the ME has priority over subsequent PS emission to remove the overlap  
 741     with the PS simulation.

742     The JHU generator (version 7.02) [121–124] is used to generate the parton level information  
 743     including full spin and polarization correlations. It is commonly used for studying the spin and  
 744     parity properties of new resonances such as  $ab \rightarrow X \rightarrow VV$ , where  $V = Z, W, \gamma$ ).

745 The generation of events from processes involving the production and decay of resonances  
 746 creates a computational heavy load, especially at NLO. The narrow width approximation  
 747 assumes that the resonant particle is on-shell. This makes the production and decay amplitude  
 748 factorize, allowing to perform the simulation of the production and decay of heavy resonances  
 749 like top quarks or Higgs bosons to be performed in separate steps. The MadSpin program [125]  
 750 extends this approach and accounts for off-shell effects through a partial reweighting of the  
 751 events. Additionally, spin correlation effects between production and decay products are taken  
 752 into account.

753 The Pythia program (versions 6,8) [109–111] generates events of various processes at LO.  
 754 However more commonly it is only used for its PS simulation and is then interfaced with other  
 755 LO and NLO event generators to perform subsequent parton showering, hadronisation, and  
 756 simulation of the underlying event. In this thesis the underlying event tunes [126] are the  
 757 CUETP8M2T4, CUETP8M1 and CUETP8M2.

758 The detector response is simulated via the Geant4 [101] program. This program tracks the  
 759 particles through the detector material via a detailed description of the detector and generates  
 760 several hits throughout several sensitive layers. In addition, the response of the detector  
 761 electronics to these hits are simulated.

### 762 3.2.3 Generating FCNC top-Z interactions

763 The FCNC processes are generated by interfacing the Lagrangian in [Equation 1.25](#) with  
 764 MadGraph5\_aMC@NLO by means of the FeynRules package and its Universal FeynRules  
 NOTE: W<sub>765</sub>  
 RH and not<sub>766</sub> LH?  
 767 Output format. The complex chiral parameters are arbitrary chosen to be  $f_{Xq}^L = 0$  and  $f_{Xq}^R = 1$ .  
 768 The signal rates are estimated by use of the MadGraph5\_aMC@NLO program for estimating the  
 partial widths. The anomalous couplings are left free to float for this estimation, and only one  
 coupling allowed to be non-vanishing at a time. The results are presented in [Table 3.1](#).

769 The anomalous single top cross sections are calculated by convolution of the hard scattering  
 770 matrix elements with the NLO order set of CTEQ6 partons densities [127]. The NLO effects are  
 771 modelled by multiplying each LO cross section by a global  $k$ -factor. The LO single top production  
 772 cross section and the global  $k$ -factors for the top-Z production are shown in [Table 3.2](#). The hard  
 773 scattering events are then matched to parton showers to Pythia to account for the simulation  
 774 of the QCD environment relevant for hadronic collisions.

The top pair cross sections are derived from the SM  $t\bar{t}$  cross section, calculated with MadGraph5\_aMC@NLO at NLO ( $\sigma_{t\bar{t}} = 6.741 \cdot 10^2 \text{ pb}$ ), and considering the decay  $t\bar{t} \rightarrow (bW^\pm)(X_{qt})$ . The branching ratio  $\mathcal{B}(t \rightarrow bW^\pm)$  is assumed to be equal to one and the FCNC branching ratio is calculated as

$$\mathcal{B}(t \rightarrow qX) = \frac{\Gamma_{t \rightarrow qX}}{\Gamma_t^{\text{SM}} + \Gamma_t^{\text{FCNC}}} \approx \frac{\Gamma_{t \rightarrow qX}}{\Gamma_t^{\text{SM}}}, \quad (3.5)$$

NOTE: 775  
 these par-  
 tial widths  
 are at LO,  
 how does  
 this relate  
 to NLO that  
 is used? Or  
 is there no  
 difference?

776 where  $\Gamma_{t \rightarrow qX}$  is given in [Table 3.1](#), and the assumption  $\Gamma_t^{\text{FCNC}} \ll \Gamma_t^{\text{SM}}$  is made. In [Table 3.3](#) the resulting NLO cross sections for the top-Z FCNC interactions are given.

**Table 3.1:** Leading order partial widths related to the anomalous decay modes of the top quark, where the new physics scale  $\Lambda$  is given in GeV.

Anomalous coupling	vertex	Partial decay width (GeV)	
$\kappa_{gqt}/\Lambda$	$t g u$	$3.665220 \cdot 10^5$	$(\kappa_{tg_u}/\Lambda)^2$
	$t g c$	$3.664620 \cdot 10^5$	$(\kappa_{tg_c}/\Lambda)^2$
$\kappa_{t\gamma q}/\Lambda$	$t\gamma u$	$1.989066 \cdot 10^4$	$(\kappa_{t\gamma u}/\Lambda)^2$
	$t\gamma c$	$1.988904 \cdot 10^4$	$(\kappa_{t\gamma c}/\Lambda)^2$
$\kappa_{tZq}/\Lambda$	$tZ u$	$1.637005 \cdot 10^4$	$(\kappa_{tZ u}/\Lambda)^2$
	$tZ c$	$1.636554 \cdot 10^4$	$(\kappa_{tZ c}/\Lambda)^2$
$\zeta_{tZq}$	$tZ u$	$1.685134 \cdot 10^{-1}$	$(\zeta_{tZ u})^2$
	$tZ c$	$1.684904 \cdot 10^{-1}$	$(\zeta_{tZ c})^2$
$\eta_{tHq}$	$tH u$	$1.904399 \cdot 10^{-1}$	$(\eta_{tH u})^2$
	$tH c$	$1.904065 \cdot 10^{-1}$	$(\eta_{tH c})^2$

**Table 3.2:** Leading order single top production cross section for  $pp \rightarrow tZ$  or  $\bar{t}Z$ , where the new physics scale is given in GeV. The NLO  $k$ -factors [128] are given in the last column.

Anomalous coupling	Cross section (pb)	NLO $k$ -factor
$\kappa_{tg_u}/\Lambda$	$3.272 \cdot 10^7$	$(\kappa_{tg_u}/\Lambda)^2$
$\kappa_{tg_c}/\Lambda$	$3.021 \cdot 10^6$	$(\kappa_{tg_c}/\Lambda)^2$
$\kappa_{t\gamma u}/\Lambda$	$2.260 \cdot 10^5$	$(\kappa_{t\gamma u}/\Lambda)^2$
$\kappa_{t\gamma c}/\Lambda$	$2.654 \cdot 10^4$	$(\kappa_{t\gamma c}/\Lambda)^2$
$\kappa_{tZ u}/\Lambda$	$1.728 \cdot 10^6$	$(\kappa_{tZ u}/\Lambda)^2$
$\kappa_{tZ c}/\Lambda$	$2.040 \cdot 10^5$	$(\kappa_{tZ c}/\Lambda)^2$
$\zeta_{tZ u}$	7.484	$(\zeta_{tZ u})^2$
$\zeta_{tZ c}$	1.038	$(\zeta_{tZ c})^2$

**Table 3.3:** Next to leading order top pair cross section for the top-Z FCNC interactions with with a full leptonic decay.

Anomalous coupling	Process	Cross section (pb)
$\kappa_{tZu}/\Lambda$	$t\bar{t} \rightarrow (b\ell^+\nu)(\bar{u}\ell^+\ell^-)$	$2.727008 \cdot 10^5 \left(\frac{\kappa_{tZu}}{\Lambda}\right)^2$
	$t\bar{t} \rightarrow (\bar{b}\ell^-\bar{\nu})(u\ell^+\ell^-)$	$2.727008 \cdot 10^5 \left(\frac{\kappa_{tZu}}{\Lambda}\right)^2$
$\kappa_{tZc}/\Lambda$	$t\bar{t} \rightarrow (b\ell^+\nu)(\bar{c}\ell^+\ell^-)$	$2.726257 \cdot 10^5 \left(\frac{\kappa_{tZc}}{\Lambda}\right)^2$
	$t\bar{t} \rightarrow (\bar{b}\ell^-\bar{\nu})(c\ell^+\ell^-)$	$2.726257 \cdot 10^5 \left(\frac{\kappa_{tZc}}{\Lambda}\right)^2$
$\zeta_{tZu}$	$t\bar{t} \rightarrow (b\ell^+\nu)(\bar{u}\ell^+\ell^-)$	$2.827184 \left(\zeta_{tZu}\right)^2$
	$t\bar{t} \rightarrow (\bar{b}\ell^-\bar{\nu})(u\ell^+\ell^-)$	$2.827184 \left(\zeta_{tZu}\right)^2$
$\zeta_{tZc}$	$t\bar{t} \rightarrow (b\ell^+\nu)(\bar{c}\ell^+\ell^-)$	$2.806801 \left(\zeta_{tZc}\right)^2$
	$t\bar{t} \rightarrow (\bar{b}\ell^-\bar{\nu})(c\ell^+\ell^-)$	$2.806801 \left(\zeta_{tZc}\right)^2$

### 3.2.4 Generating SM background events

The SM tZq events were generated using the MadGraph5\_aMC@NLO generator, interfaced with Pythia version 8.2 [111] for parton showering and hadronisation. The WZ+jets, tZ, tZq, and tW samples are produced using the MadGraph5\_aMC@NLO(version 5.222) [113], which includes up to one hadronic jet at next to leading order (NLO) QCD accuracy. Other minor background (e.g. WW, ZZ, tWZ and tH) are simulated using different generators such as MadGraph [107], MadSpin [125] and JHU [121–124]. All events are interfaced to Pythia for parton shower and hadronisation.

**NOTE:** Add source

The complete list of SM samples is given in Table 3.4, along with their cross sections. The cross sections without a reference are coming from the generator with which the sample has been made, for some of them the uncertainties are provided by the Generator Group. For each MC sample, the integrated luminosity that the sample represents is estimated as the number of simulated events divided by the cross section of the generated process. For processes generated with MadGraph5\_aMC@NLO, the effective number of simulated events is used, taking into account positive and negative event weights. The correction factor for those events is defined as

$$C = \frac{\text{Nb. of pos. weights} + \text{Nb. of neg. weights}}{\text{Nb. of pos. weights} - \text{Nb. of neg. weights}} \times \text{mc baseweight} \quad (3.6)$$

**NOTE:** Add source

**Table 3.4:** SM MC samples used in this analysis with their corresponding cross section and MadGraph5\_aMC@NLO correction C when applicable. The generators used for each sample are indicated.

Process	Generator	Cross section (pb)	C
$WZ \rightarrow 3\ell\nu$	MadGraph5_aMC@NLO+Pythia	5.26	1.61
$tZq$ with $Z \rightarrow \ell^+\ell^-$	MadGraph5_aMC@NLO+Pythia	0.0758	3.77
$tqH$ with $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$	JHU+Pythia	$8.80 \cdot 10^{-6}$	-
$t\bar{t}W + \text{jets}$ with $W \rightarrow \ell\nu$	MadGraph5_aMC@NLO+MadSpin+Pythia	$0.2043 \pm 0.0020$	1.94
$t\bar{t}Z \rightarrow 2\ell + 2\nu + \text{other}$ , with $m_{\ell\ell} > 10$ GeV	MadGraph5_aMC@NLO+Pythia	$0.2529 \pm 0.0004$	2.15
$t\bar{t}H, \text{no } b\bar{b} \text{ decays}$	POWHEG+Pythia	0.2151	-
$t\bar{t}H, b\bar{b} \text{ decays}$	POWHEG+Pythia	0.2934	-
$WW \rightarrow 2\ell 2\nu$	POWHEG+Pythia	12.178	-
$ZZ \rightarrow 4\ell$	POWHEG+Pythia	0.3366	-
$WZZ$	MadGraph5_aMC@NLO+Pythia	0.05565	1.14
$ZZZ$	MadGraph5_aMC@NLO+Pythia	0.01398	1.17
single top $tWZ$ , with $Z_\mu \rightarrow \ell^+\ell^-$	MadGraph+Pythia	0.001123	-
single top t-channel $\bar{t}$	POWHEG+MadSpin+Pythia	$44.33^{+1.76}_{-1.49}$	-
single top t-channel $t$	POWHEG+MadSpin+Pythia	$26.38^{+1.32}_{-1.18}$	-
single top $\bar{t}W$	POWHEG+Pythia	$35.85 \pm 0.90 \text{ (scale)} \pm 1.70 \text{ (PDF)}$	-
single top $tW$	POWHEG+Pythia	$35.85 \pm 0.90 \text{ (scale)} \pm 1.70 \text{ (PDF)}$	-
$t\bar{t}$	POWHEG+Pythia	$831.76^{+19.77+35.06}_{-29.20-35.06}$	-
$Z/\gamma^* + \text{jets}$ , with $m_{\ell\ell} > 50$ GeV	MadGraph5_aMC@NLO+Pythia	$3 \times (1921.8 \pm 0.6 \pm 33.2)$	1.49
$Z/\gamma^* + \text{jets}$ , with $10 \text{ GeV} < m_{\ell\ell} < 50$ GeV	MadGraph+Pythia	18610	-

### 785 3.3 Multivariate analysis techniques: Boosted Decision Trees

786 The need of processing large quantities of data and discriminating between events with largely  
 787 similar experimental signatures makes multivariate statistical analysis (MVA) a largely used  
 788 method in the physics community. Multivariate classification methods based on machine  
 789 learning techniques are a fundamental ingredient to most analyses. The advantage of using  
 790 a MVA classifier is that it can achieve a better discrimination power with respect to a simple  
 791 cut and count analysis with poorly discriminating variables. These variables are referred to  
 792 as weak variables and have similar distributions for signal and background samples. A risk of  
 793 using MVA classifiers is overtraining. This happens when there are too many model parameters  
 794 of an algorithm adjusted to too few data points. This leads to an increase in the classification  
 795 performance over the objectively achievable one.

796 There are many software tools that exist for MVA. In this thesis the Tool for Multivariate  
 797 Analysis (TMVA) [129] is used. This software is an open source project included into  
 798 ROOT [130]. All multivariate techniques in TMVA belong to supervised learning algorithms. By  
 799 training on events for which the outcome is known, a mapping function is determined that  
 800 describes a classification or an approximation of the underlying behaviour defining the target  
 801 value (regression).

802 In this thesis boosted decision trees (BDT) are employed for the classification of events as  
 803 implemented in the TMVA framework [129]. This multivariate technique is based on a set of  
 804 decision trees where each yields a binary output depending on the fact that an event is signal- or  
 805 background-like. The advantage of such a multivariate technique is that several discriminating  
 806 variables can be combined into a powerful one-dimensional discriminant D.

In Figure 3.4 a schematic view of a decision tree is shown. The starting point is the root node. Then a consecutive set of a total of  $i$  questions (nodes) regarding discriminating variables  $x_i$  are asked with only two possible answers per question (binary splits). The decision tree is constructed by training on a dataset for which the outcome is already provided, such as simulation dataset with signal and background processes (supervised learning). For each node a criterion  $x_i > C_i$  is found by maximizing the separation gain between nodes

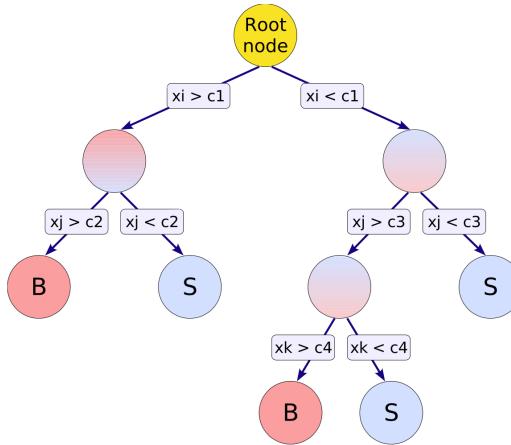
$$\text{separationgain} \approx \text{gain}(\text{parent}) - \text{gain}(\text{daughter, Signal}) - \text{gain}(\text{daughter, Background}), \quad (3.7)$$

with the gain computed using the Gini index

$$\text{gain}(\text{cell}) \approx p(1-p), \quad (3.8)$$

807 where  $p$  denotes the purity of a selection  $x > C$ . This is repeated until the maximum of nodes is  
 808 reached and at the end of the sequence, the leaf nodes are labelled either signal S or background  
 809 B, depending on the majority of events that end up on those nodes.

Different trees can be combined into a forest where the final output is determined by the majority vote of all trees, forming the sum of so-called weak learners into one strong learner. From one training collection, trees are derived by reweighting events, and combined into a single classifier as the weighted average of each individual decision tree. A method for making such forests is boosting a tree. In this method, misclassified events are weighted higher so



**Figure 3.4:** Schematic view of a decision tree. Figure taken from [129].

that future learner concentrate on these events. This has as advantage that the response of the decision trees are stabilised against fluctuations in the training sample which enhances the performance. Additionally, the trees can be kept very shallow, in this thesis the maximal number of nodes is set the three, which improves the robustness against overtraining. Examples of such boosting algorithms are Adaptive Boosting (AdaBoost) and Gradient Boosting [131]. In AdaBoost, each weight of the misclassified events are enhanced while reducing the weight of correctly classified events after each training such that future events learn those better

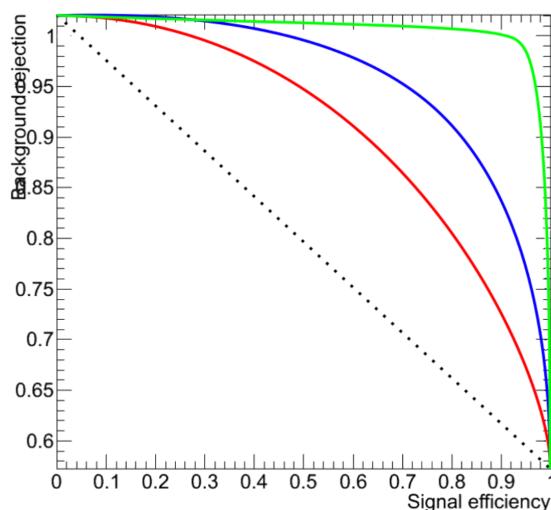
$$\alpha_{n+1} = \left( \frac{1 - \epsilon_n}{\epsilon_n} \right)^\beta, \quad (3.9)$$

where  $\epsilon_n$  denotes the misclassification error of the current tree  $n$  and  $\beta$  is a learning rate. The weight  $w_i$  at node  $i$  is then equal to  $w_i = \ln \alpha_i$ . The final weight is the sum of all classifiers weighted by their errors. The learning rate is typically chosen to be  $\beta \leq 0.5$  to allow more boosting steps. Gradient boosting has a similar approach and combines a gradient descent with boosting. Instead of fitting the base-learner to the reweighted data as in AdaBoost, it is fitted to the negative gradient vector of the loss function evaluated at the previous node. Misclassified events will result in a majority vote with large gradients of the loss function. Also for the Gradient boost, the learning rate is typically slow, this also known as shrinkage. In this thesis Gradient boost is used with a shrinkage of 0.2-0.3.

Additionally, the Gradient boost is used in combination with bagging, so-called stochastic gradient boosting. Bagging is a resampling technique draws a subset of events from the training data where the same event is allowed to be randomly picked several times from the parent sample. The tree is then trained on this subset and this is repeated many times. It is based on the assumption that sampling from a dataset that follows a distribution is the same as sampling from the distribution itself [132]. If one draws an event out of the parent sample, it is more likely to draw an event out of the phase space that has a high probability density, as the original dataset will have more events in the regions. Since the selected event is kept in the original sample, the parent sample stays unchanged so that randomly extracted samples have

828 the same parent distribution, albeit statistically fluctuated. Bagging smears over the statistical  
 829 fluctuations in the training data, making it suitable for stabilising the response of the classifier  
 830 and increasing the performance by eliminating overtraining. In stochastic gradient boosting the  
 831 bagging resampling procedure uses random sub-samples of the training events for growing the  
 832 trees.

833 The discriminating power of a BDT is assessed by analysing the receiver operating characteristic  
 834 (ROC) curve. These curves show the background rejection over the signal efficiency of the  
 835 remaining sample. By looking at the area under the curve with respect to random guessing  
 836 (AUC), the best classifier can be identified. This follows the Neyman-Pearson lemma that  
 837 the best ROC curve is given by the likelihood ratio  $\mathcal{L}(x|Signal)/\mathcal{L}(x|Background)$  [132]. No  
 838 discrimination power will result in an AUC of 0%, while 50% means fully separated event  
 classes. In Figure 3.5 an example of ROC curve is shown.



**Figure 3.5:** Example of ROC curves. In this example, the green method is better than the red one, which is better than the blue one. The dashed line represents a case where there is no separation. Figure taken from [133].

839

### 840 3.4 Statistical methodology

841 The search performed in the framework of this thesis requires the simultaneous analysis of data  
 842 from different decay channels. The statistical methodology used for this search is developed by  
 843 the ATLAS and CMS collaborations in the context of the LHC Higgs Combination group. The  
 844 description of the methodology can be found in Refs. [134–137].  
 845 The Higgs Combined Tool [138] is a RooStats [139] framework which runs different statistical  
 846 methods. In this section, only the statistical tools necessary for the performed search are  
 847 described. The results presented in this thesis are obtained using the asymptotic formulae [140].

848 In general the event yields of signal and background processes are denoted as  $s$  and  $b$   
 849 respectively. These represent event counts in multiple bins or unbinned probability density

functions. By use of simulation, predictions on both signal and background yields are made. These predictions are subject to multiple uncertainties that are accounted for by introducing nuisance parameters  $\theta$  such that  $s = s(\theta)$  and  $b = b(\theta)$ . In the following, the actual observed events are denoted as data or observation.

### 3.4.1 The absence of signal: limits

The absence of a signal is characterised in high energy physics by the Bayesian and modified classical frequentist statistical approaches. They allow to quantify the level of incompatibility of data with a signal hypothesis in terms of confidence levels (CL). The convention is to require a 95% CL for excluding a signal.

An analysis targeting a certain signal production mechanism can either set approximate model-independent limits on signal cross sections times branching ratio ( $\sigma \times \mathcal{B}$ ) or on the signal cross section times branching ratio times detector acceptance ( $\sigma \times \mathcal{B} \times \mathcal{A}$ ). In order to test various theories, the latter is not useful unless the acceptance  $\mathcal{A}$  is provided. However, many analysis are not able to present result in a form of limits on  $\sigma \times \mathcal{B} (\times \mathcal{A})$ , therefore an alternative is adopted to set limits in the signal strength modifier  $\mu$ . The signal strength modifier is defined to equally change all the cross sections of all production mechanisms of the signal by the same scale.

In this thesis, the modified frequentist approach for confidence levels is used [141, 142]. The classical frequentist uses a test statistic  $q_\mu$  based on the profile likelihood ratio to determine how signal- or background-like the data is. However, it does not allow nuisance parameters and is modified to incorporate these. First a likelihood  $\mathcal{L}(\text{data} | \mu, \theta)$  is constructed as

$$\mathcal{L}(\text{data} | \mu, \theta) = \text{Poisson}(\text{data} | \mu s(\theta) + b(\theta)) p(\tilde{\theta} | \theta). \quad (3.10)$$

The probability density function (pdf)  $p(\tilde{\theta} | \theta)$  describes all sources of uncertainty and is described in Section 3.4.2. The data in Equation 3.10 represents either the actual observation or pseudo-data to construct sampling distributions. For a binned likelihood, the Poisson probabilities to observe  $n_i$  events in bin  $i$  is given as

$$\text{Poisson}(\text{data} | \mu s(\theta) + b(\theta)) = \prod_i \frac{(\mu s_i(\theta) + b_i(\theta))^{n_i}}{n_i!} e^{-\mu s_i(\theta) - b_i(\theta)}. \quad (3.11)$$

At the LHC, the test statistic is defined as

$$q_\mu = -2 \ln \frac{\mathcal{L}(\text{data} | \mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data} | \hat{\mu}, \hat{\theta}_\mu)}, \quad (3.12)$$

where the likelihood is maximised in the numerator (maximum likelihood estimator, MLE) for a given  $\mu$  and (pseudo) data at  $\hat{\theta}_\mu$ , while  $\hat{\mu}$  combined with  $\hat{\theta}$  defines the point for which the likelihood reaches its global maximum. The estimated signal strength modifier  $\hat{\mu}$  can not become negative since a signal rate is positive defined by physics. Furthermore, an upper constraint on the MLE  $\hat{\mu} \leq \mu$  is imposed to guarantee a one sided confidence interval. This has

as consequence that upward fluctuations of the data ( $\hat{\mu} > \mu$ ) are not considered against the signal hypothesis of data with a signal with strength  $\mu$ .

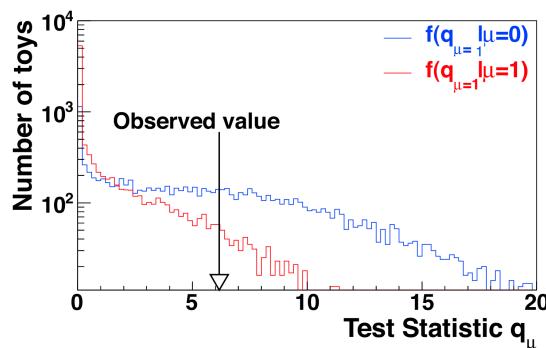
The criterion for excluding the signal at  $1 - \alpha$  confidence level is the ratio of the probabilities to observe a value of the test statistic at least as large as the one observed in data  $q_\mu^{\text{obs}}$ , under the signal plus background ( $s + b$ ) and background only ( $b$ ) hypothesis is defined as

$$\text{CL} = \frac{P(q_\mu \geq q_\mu^{\text{obs}} | \mu s + b)}{P(q_\mu \geq q_\mu^{\text{obs}} | b)} \leq \alpha. \quad (3.13)$$

These probabilities are defined as

$$\begin{aligned} p_\mu &= P(q_\mu \geq q_\mu^{\text{obs}} | \mu s + b) = \int_{q_\mu^{\text{obs}}}^{\infty} f(q_\mu | \mu, \theta_\mu^{\text{obs}}) dq_\mu, \\ 1 - p_b &= P(q_\mu \geq q_\mu^{\text{obs}} | b) = \int_{q_{\mu=0}^{\text{obs}}}^{\infty} f(q_\mu | \mu = 0, \theta_{\mu=0}^{\text{obs}}) dq_\mu, \end{aligned} \quad (3.14)$$

where  $p_\mu$  and  $p_b$  are called the p-values associated to the two hypothesis, and  $f(q_\mu | \mu, \theta_\mu^{\text{obs}})$  and  $f(q_\mu | \mu = 0, \theta_{\mu=0}^{\text{obs}})$  are the pdfs of the signal plus background and background only hypothesis constructed from toy Monte Carlo pseudo data. These pdfs are shown in Figure 3.6 and are generated with nuisance parameters fixed to  $\hat{\theta}_{\mu=0}^{\text{obs}}$  and  $\hat{\theta}_\mu^{\text{obs}}$ . These values of the nuisance parameters for the background only  $\hat{\theta}_{\mu=0}^{\text{obs}}$  and signal plus background  $\hat{\theta}_\mu^{\text{obs}}$  hypothesis that best describe the data are found by maximising the likelihood from Equation 3.10. The 95% CL level upper limit on  $\mu$  is achieved by adjusting  $\mu$  until  $\text{CL} = 0.05$



**Figure 3.6:** Test statistic distributions for pseudo data generated for the signal plus background ( $\mu = 1$ ) and background only ( $\mu = 0$ ) hypothesis. Figure taken from [137].

880

The expected median upper limit and the  $\pm 1\sigma$  and  $\pm 2\sigma$  bands for a hypothesis is generated by a large set of pseudo data and calculate the CLs and the value of  $\mu$  at 95% CL for each of them. A cumulative probability distribution can be build by starting the integration from the

884 side corresponding to low event yields. The median expected value is where the cumulative  
 885 distribution function crosses the 50% quantile. The  $\pm 1\sigma$  (68%) and  $\pm 2\sigma$  (95%) bands are  
 886 defined by the crossings of the 16% and 84%, and 2.5% and 97.5% quantiles.

### 887 3.4.2 Adding sources of uncertainty

888 In this thesis, all sources of uncertainties are assumed to be either 100% correlated or uncor-  
 889 related. Partially correlated uncertainties are broken down to subcomponents that fit those  
 890 requirements, allowing to include all constraints in the likelihoods in a clean factorised form.

A systematic uncertainty pdf  $p(\theta|\tilde{\theta})$  for the nuisance  $\theta$  with nominal value  $\tilde{\theta}$  is used. It reflects the degree of belief of what the true value of the  $\theta$  is. In this thesis, the approach from the Higgs Combined Tool is used where the pdfs  $p(\theta|\tilde{\theta})$  are re-interpret as posteriors of real or imaginary measurements  $\tilde{\theta}$

$$p(\theta|\tilde{\theta}) \sim p(\tilde{\theta}|\theta) \pi_\theta(\theta), \quad (3.15)$$

891 where  $\pi_\theta(\theta)$  is the hyper prior for the (imaginary) measurements. For the pdfs used by the  
 892 Higgs Combine Tool (normal, log normal, gamma distribution), hyper priors can remain flat.  
 893 This allows to use the pdf  $p(\tilde{\theta}|\theta)$  to constrain the likelihood of the main measurement in a  
 894 frequentist calculation. Additionally this allows to build a sampling distribution of the test  
 895 statistic [137].

The statistical uncertainties on the Monte Carlo prediction in each bin are obtained following the Barlow-Beeston-light approach [143]. In this approach a single Gaussian constrained nuisance parameter is assigned to scale the sum of the process yields in each bin, constrained by the total uncertainty. This method has as advantage that it minimises the number of parameters required in the maximum likelihood fit. Considering  $n_{\text{tot}}$  events in a bin with background process  $i$  in the bin

$$n_{\text{tot}} = \sum_{i \in \text{bkg}} n_i, \quad (3.16)$$

the total uncertainty  $e_{\text{tot}}$  is given by

$$e_{\text{tot}} = \sqrt{\sum_{i \in \text{bkg}} e_i^2}, \quad (3.17)$$

896 with  $e_i$  the uncertainty on background  $i$  and is given by the sum of squares of weights used to  
 897 fill the bins. The Gaussian constrained parameter  $x$  has then a nominal value of zero and scales  
 898 the yield as  $n_{\text{tot}} + x e_{\text{tot}}$ .

### 899 Choices of systematic uncertainty density functions

For uncertainties that are unconstrained by a priori measurements that do not involve the data going into the statistical analysis, flat priors are used. When there are a priori measurements available such as those from control regions, one can use either a Gaussian pdf, a log-normal pdf, or a gamma distribution. The Gaussian pdf is suited for describing uncertainties on parameters

with both positive and negative values. This prior is however not suitable for positively defined observables such as cross sections, cut efficiencies, luminosity, etc. and is not used in this thesis. An alternative option is the log normal pdf which is used in the rest of this thesis

$$\rho(\theta) = \frac{1}{\sqrt{2\pi} \ln(\kappa)} \exp\left(-\frac{(\ln(\theta/\tilde{\theta}))^2}{2(\ln \kappa)^2}\right) \frac{1}{\theta}. \quad (3.18)$$

The parameter  $\kappa$  characterises the width of the log normal pdf. For example  $\kappa = 1.10$  implies that the observable can be larger or smaller by a factor 1.10, both deviation having a chance of 16%. The gamma distribution is used for describing statistical uncertainties associated with a number of Monte Carlo events in simulation or a number of observed events in a data control sample. In this thesis, the gamma distribution is only used for the latter. The event rate in the signal region  $n$  is related to the number of events in the control region  $N$  as  $n = \alpha N$ . Ignoring the uncertainties on  $\alpha$ , the predicted rate follows

$$\rho(n) = \frac{1}{\alpha} \frac{n/\alpha)^N}{N!} \exp(-n/\alpha). \quad (3.19)$$

900 The mapping between the posteriors  $\rho(\theta|\tilde{\theta})$  and the auxiliary measurement pdfs  $p(\tilde{\theta}|\theta)$  are  
901 given in [137].

### 902 3.4.3 Asymptotic approximation of the CL method

903 In order to significantly reduce computing time, the Asymptotic CL method is used. This method  
904 avoids an ensemble of toy Monte Carlo samples and instead replaces it by one representative  
905 dataset, called Asimov dataset. This dataset is constructed such that all observed quantities are  
906 set equal to their MLE values ( $\hat{\theta}_{\text{Asimov}} = \theta_0$ ). More information about this procedure can be  
907 found in Refs. [135].

### 908 3.4.4 Extracting the signal model parameters

From a scan of the profile likelihood ratio,

$$q(a) = -2 \ln \frac{\mathcal{L}(\text{obs} | s(a) + b, \hat{\theta}_a)}{\mathcal{L}(\text{obs} | s(\hat{a}) + b, \hat{\theta})}, \quad (3.20)$$

the signal model parameters are evaluated. The likelihood is maximised by the parameters  $\hat{a}$  and  $\hat{\theta}$ . The likelihood

$$\mathcal{L}_{\max} = \mathcal{L}(\text{obs} | s(\hat{a}) + b, \hat{\theta}) \quad (3.21)$$

909 is called the best-fit set.

910 The 68% and 95% CL on a given parameter of interest  $a_i$  is then evaluated from  $q(a_i) = 1$  or  
911  $q(a_i) = 3.84$  respectively, where all other unconstrained model parameters are treated in the  
912 same way as the nuisance parameters [136].

# Event reconstruction and selection

4

---

914 After the detector simulation described in [Section 3.2](#), the simulated data has the exact same  
 915 format as the real collision data recorded at the CMS experiment. Therefore the same software  
 916 can be used for the reconstruction of both simulation and real data. In [Section 4.1](#), the object  
 917 reconstruction for physics analysis is shown. After reconstructing the objects, the objects are  
 918 connected to physics objects need to be identified. This identification is explained in [Section 4.2](#).  
 919 A basic event selection is made for selecting signal like events. The necessary event requirement  
 920 are discussed in [Section 4.7](#).

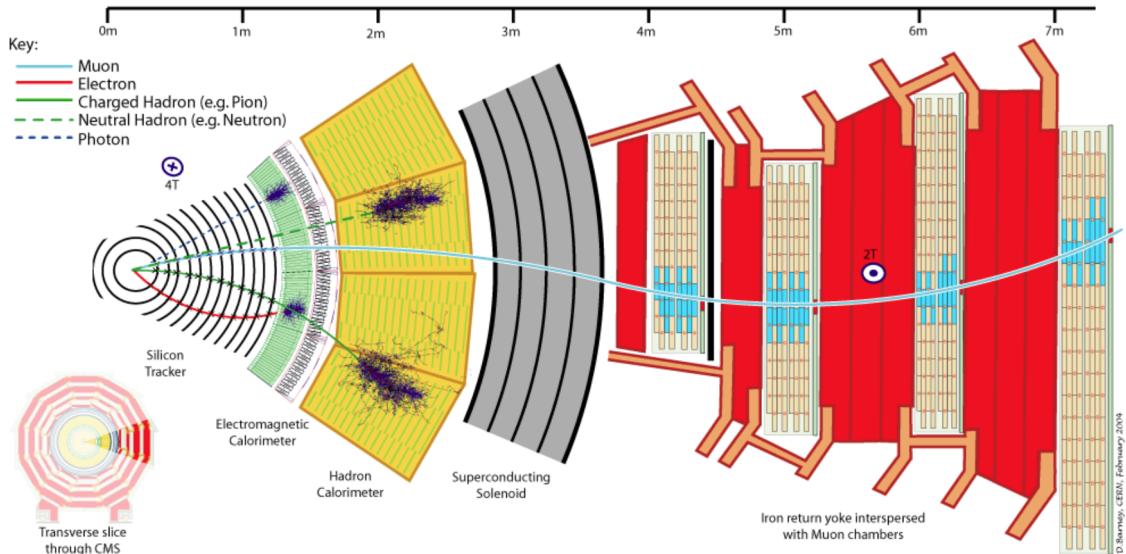
921 The analysis uses signal and background regions to constrain the huge SM background  
 922 compared to the expected signal. [Section 4.8](#) discusses each region that is entering the analysis.  
 923 On top of the use of background estimation from control regions, backgrounds that have prompt  
 924 leptons contaminated by real leptons either from decays of tau leptons or from hadronized  
 925 mesons or baryons (collectively commonly referred as “non-prompt leptons”) as well as by  
 926 hadrons or jets misidentified as leptons<sup>1</sup> are evaluated with a data-driven method discussed in  
 927 [Section 4.9](#).

## 928 4.1 Object Reconstruction

929 In [Figure 4.1](#), the particle interaction in a transverse slice of the CMS detector is shown. The  
 930 particles enter first the tracker where charged particle trajectories, so-called tracks, and origins  
 931 or vertices are reconstructed from signals (hits) in the sensitive layers. Charged particles get  
 932 bent by the magnetic field making it able to measure the electric charges and momenta of  
 933 charged particles. In the ECAL, the electron and photons are absorbed and the corresponding  
 934 electromagnetic showers are detected as clusters of energy in adjacent cells. From this, the  
 935 energy and the direction of the particles can be determined. The charged and neutral hadrons  
 936 can initiate a hadronic shower in the ECAL that is fully absorbed in the HCAL. The clusters  
 937 from these showers are also used to estimate the energy and direction. Muons and neutrino’s  
 938 pass through the calorimeters without little to no energy loss. The neutrino’s escape the CMS  
 939 detector undetected while muons produce hits in the muon detectors.

---

<sup>1</sup>These two classes of contamination will be referred to as not prompt-lepton (NPL) samples.



**Figure 4.1:** Cross-section of the CMS detector with all parts of the detector labelled. This sketch shows the specific particle interactions from a beam interaction reign to the muon detector. The muon and charged pion are positively charged, the electron is negatively charged. Figure taken from [144].

940 The traditional hadron colliders reconstruction is as follows. The reconstruction of isolated  
 941 photons and electrons is primarily done by the ECAL, while the identification of muons is based  
 942 on the muon detectors. Hadrons and photons form jets which are measured by the calorimeters  
 943 without any contribution from the tracker or muon detectors. Jets can be tagged using the  
 944 tracker as coming from hadronic  $\tau$  decays or b hadronisation based on the properties of the  
 945 properties the relevant charged particle tracks. The missing transverse energy is defined as  
 946 the vectorial sum of the undetectable particle transverse momenta, and can be reconstructed  
 947 without any information from the tracker. The particle flow (PF) [144] reconstruction correlates  
 948 the tracks and clusters from all detector layers with the identification of each final state particle,  
 949 and combining the corresponding measurements to reconstruct the properties. Here, the muon  
 950 is identified by a track in the inner tracker connected to a track in the muon detector as described  
 951 in Section 4.1.2. The electrons are identified by a track and ECAL cluster, and not connected to  
 952 an HCAL cluster as described in Section 4.1.3. The ECAL and HCAL clusters without a track  
 953 link identify the photons and neutral hadrons, while the addition of the tracker determines the  
 954 energy and direction of a charged hadron.

955 Coarse-grained detectors can cause signals of different particles to merge and reduce the  
 956 ability of identifying and reconstructing the particles. Therefore, particle flow identification  
 957 requires sufficiently segmented subdetectors such that a global event description is possible.  
 958 From a list of identified particles that are reconstructed from a combined fit of all relevant  
 959 measurements, the physics objects are determined. The CMS detector is built to meet to  
 960 requirements of the particle flow reconstruction. It has an efficient and pure muon identification  
 961 system, a hermetic HCAL with coarse segmentation, a higher segmented ECAL, a fine-grained  
 962 tracker and a large magnetic field to separate the calorimeter deposits of charged and neutral  
 963 particles in jets.

964 **4.1.1 Charged particle tracks**

965 An iterative tracking algorithm is responsible for the reconstruction of the tracks made by  
 966 charged particles in the inner tracking system. Each iteration consists of four steps [64]: the  
 967 track-seed generation, the pattern recognition algorithm, removal of track-hit ambiguities and  
 968 a final track fit.

969 The seed generation is the first step. It consists of finding reconstructed hits that are usable  
 970 for seeding the subsequent track-finding algorithm. They are identified from a group of at  
 971 least three reconstructed hits in the tracker, or from a pair of hits while requiring the origin  
 972 of the track segment to be compatible with the nominal beam-collision point. Since the pixel  
 973 has a higher granularity compared to the strip tracker, its seed generation efficiency is higher.  
 974 The overall efficiency exceeds 99%. The second step of each iteration, the pattern recognition  
 975 algorithm, uses the seeds as a starting point for a Kalman filter method [145, 146]. This  
 976 algorithm extrapolates the seed trajectory towards the next tracker layer taking into account  
 977 the magnetic field and multiple scattering effects. The track parameters are updated when a  
 978 compatible hit in the next layer is found. This procedure continues until the outermost layer is  
 979 reached. Since the Kalman filter method can result in multiple tracks associated to the same  
 980 seed, or different tracks sharing the same hits, a removal of ambiguities is necessary. This  
 981 ambiguity resolving is done by removing tracks that are sharing too many hits from the list  
 982 of track candidates. The tracks with the highest number of hits or with the lowest  $\chi^2$  in the  
 983 track fit is kept. The updated track parameters are then refitted using the Kalman filter method,  
 984 where all hits found in the pattern recognition step are taken into account. The fit is done twice  
 985 - once outwards from the beam line towards the calorimeters, and inwards from the outermost  
 986 track hit to the beam line -, improving the estimation of the track parameters.

987 All hits that are unambiguously associated to the final track are removed from the list of  
 988 available hits. In order to associate the remaining hits, the procedure is repeated with looser  
 989 track reconstruction criteria. The use of the iterative track reconstruction procedure has a  
 990 high track finding efficiency, where the fake track reconstruction rate is negligible. For muons,  
 991 this results in a global track reconstruction efficiency exceeding 98%, and 75-98% for charged  
 992 hadrons.

993 **4.1.2 Following the Muon's Footsteps**

994 The muon reconstruction [147] has three subdivisions: local reconstruction, regional reconstruc-  
 995 tion and global reconstruction. The local reconstruction is performed on individual detector  
 996 elements such as strip and pixel hits in the inner tracking system, and muon hits and/or seg-  
 997 ments in the muon chambers. Independent tracks are reconstructed in the inner tracker - called  
 998 tracker tracks - and in the muon system, called standalone muon tracks. Based on these tracks,  
 999 two reconstructions are considered.

1000 The outside-in approach is referred to as Global Muon reconstruction. For each standalone  
 1001 muon track, a inner tracker track is found by comparing the parameters of the two tracks prop-  
 1002 agated onto a common surface. Combining the hits from the tracker track and the standalone  
 1003 track, gives a fit via the Kalman filter technique [145, 146] for a global muon track.

1004     The second approach is an inside-out reconstruction, creating tracker muons. All candidate  
 1005    tracker tracks with a  $p_T > 0.5$  GeV and total momentum  $p > 2.5$  GeV are extrapolated to the  
 1006    muon system taking into account the magnetic field, the average expected energy losses, and  
 1007    multiple Coulomb scattering in the detector material. The extrapolated track and the muon  
 1008    segments are considered matched when the difference in the position in the x coordinates is  
 1009    smaller than 3 cm, or when the ratio of this distance to its uncertainty is smaller than four. When  
 1010    at least one muon segment - DT or CSC hits - matches the extrapolated track, the corresponding  
 1011    tracker track is indicated as a tracker muon.

1012    For low transverse momenta ( $p_T \lesssim 5$  GeV), the tracker muon reconstruction is more efficient  
 1013    than the global muon approach. This is due to the fact that tracker muons only require a  
 1014    single muon segment in muon system, while the global muon approach requires typically  
 1015    segments in at least two muon stations. These tracker muons are used for identifying muons  
 1016    from the hadronisation of b or c quarks. The global muon approach typically improves the  
 1017    tracker reconstruction for  $p_T \gtrsim 200$  GeV. These are labelled isolated when in a cone of  
 1018     $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.3$  around the muon, the sum of the transverse momenta of additional  
 1019    tracker tracks and energy deposits in the calorimeter is less than 10% of the muon's transverse  
 1020    momentum.

### 1021    4.1.3 The path of the Electron

1022    The electrons in CMS radiate more than 70% of their energy in the inner track through  
 1023    bremsstrahlung before reaching the ECAL. This has as consequence that the electron tracks are  
 1024    increasingly curved in the magnetic field as a function of its flight distance. Standard tracking  
 1025    algorithms are based on Kalman filtering which assume that the energy loss is Gaussian dis-  
 1026    tributed, and are therefore not suitable to fit the electron tracks. A different filtering algorithm,  
 1027    the Gaussian sum filter (GSF) is used in the electron track reconstruction instead.

**NOTE:** [Add 1027](#)  
source

1028    In CMS, the electrons are reconstructed in two ways. The older ECAL based tracking is  
 1029    developed to identify high energy, isolated electrons. This tracking algorithm starts from ECAL  
 1030    clusters with a transverse energy above 4 GeV and extrapolates from these cluster the position  
 1031    of the hits in the tracker. In order to account for bremsstrahlung, neighbouring clusters in  $\eta$   
 1032    and  $\phi$  are grouped together into a supercluster from which then the direction is determined  
 1033    to find the position of the particles in the tracker. This has as consequence that for electrons  
 1034    or positrons in jets, energy deposits of surrounding particles will be entering the supercluster  
 1035    leading to a wrong position of the electron/positron in the tracker. Another disadvantage of the  
 1036    ECAL based tracking is that for low  $p_T$  electrons, the trajectories will be very curved and the  
 1037    supercluster will not contain all of the energy deposit, leading to a higher misconstruction rate.

1038    The faults of the ECAL based tracking are lifted by adding a tracker based algorithm. This  
 1039    algorithm uses all the tracks with a  $p_T$  higher than 2 GeV found with iterative tracking as  
 1040    seeds. Iterative tracking uses the Kalman Filter algorithm several times with an average track  
 1041    reconstruction efficiency but high purity. In contrary with a global combinatorial fit, the iterative  
 1042    tracking accepts tracks with a small transverse momentum that are not leaving any energy  
 1043    in the ECAL, and tracks from particles that only interact with the inner tracker layers. When  
 1044    the electron or positron radiated a small amount of energy, the corresponding track can be  
 1045    reconstructed across the whole tracker and safely propagated to the ECAL surface. When there

1046 is a larger amount of energy radiated however, the pattern recognition might fail to accommodate  
 1047 for the change in the electron momentum leading to a track reconstructed with a small number  
 1048 of hits. The solution for this is a preselection based on the  $\chi^2$  and number of hits and the  
 1049 selected tracks are fitted again with Gaussian-Sum-Filter which can accommodate substantial  
 1050 energy losses across the trajectory.

1051 The electron seeds from the ECAL- and tracker-based procedures are merged into a unique  
 1052 collection and are then refitted by using the summed Gaussian distributions as uncertainty per  
 1053 hit in the track fit.

1054 The electron efficiency is measured in 8 TeV proton collision data to be better than 93% for  
 1055 electrons with an ECAL supercluster energy of  $E_T > 20$  GeV. For electrons with an  $E_T > 25$  GeV  
 1056 in 13 TeV proton collision data, the efficiency is about 96% .

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#### 1057 4.1.4 Primary Vertex Reconstruction

1058 The primary vertex (PV) reconstruction should be able to measure the location of all proton  
 1059 interaction vertices in each event: the signal vertex and all vertices from pile up events. It  
 1060 consists of a vertex finding and a vertex fitting algorithm and happens in three steps. Tracks are  
 1061 selected to be consistent with being produced promptly in the primary interaction by imposing  
 1062 requirements on the track parameters [74]. By grouping reconstructed tracks according to the  
 1063  $z$  coordinate of their closest approach to the beam line, vertices for all interaction in the same  
 1064 beam crossing are found, at CMS this is done by a deterministic annealing algorithm [148]  
 1065 . On top of this, a vertex fitting algorithm like the Adaptive Vertex fitter [149], is performed.  
 1066 This creates the three-dimensional primary-vertex position. With this fit, the contribution from  
 1067 long-lived hadron decays is reduced by down weighting the tracks with a larger distance to  
 1068 the vertex. The primary vertex corresponding to the highest sum of squared track transverse  
 1069 momenta is noted as the point of the main interaction. The resolution on the primary vertex is  
 1070 about 14  $\mu\text{m}$  in  $r\phi$  and about 19  $\mu\text{m}$  in the  $z$  direction for primary vertices with the sum of  
 1071 the track  $p_T > 100$  GeV for 2016 data taking.

**NOTE:** Check text with PFlow paper!

#### 1072 4.1.5 Calorimeter clusters

1073 The cluster algorithm in the calorimeter

- 1074 1. detects and measures the energy and direction of stable neutral particles such as photons  
   1075 and neutral hadron,
- 1076 2. separates neutral particles from charged hadron energy deposits, /item reconstructs and  
   1077 identifies electrons and their bremsstrahlung photons,
- 1078 3. contributes to the energy measurements of charged hadrons that don't have accurate  
   1079 tracks parameters, e.g. for low quality and high transverse momentum tracks.

1080 The clustering is performed separately in each subdetector: ECAL barrel and endcaps, HCAL  
 1081 barrel and end caps, and the two preshower layers. The HF has no clustering algorithm since  
 1082 the electromagnetic or hadronic components give rise to an HF EM or HF HAD cluster.

1083 The clustering algorithm consist of different steps. First seeds are identified when cells have  
 1084 an energy larger than the seeding threshold and lager than their neighbouring cells. Then  
 1085 topological clusters are made by accumulating cells that share at least a corner with a cell  
 1086 already in the cluster and an energy above a cell threshold set to twice the noise level. The third  
 1087 step is a expectation maximization algorithm that reconstructs the cluster [144]. This algorithm  
 1088 assumes that the energy deposits are Gaussian distributed and is an iterative algorithm with  
 1089 two steps at each iteration. A first step calculated the expected fraction if the energy in a certain  
 1090 step, while the second step performs a maximum likelihood fit. The positions and energies of  
 1091 the Gaussian functions are then taken as cluster parameters.

1092 The calorimeter clusters are used for reconstructing photons and neutral hadrons. The clusters  
 1093 that are not in the vicinity of the extrapolated charged tracks are easily identified as neutral  
 1094 hadrons or photons. For the energy deposits that overlap with charged hadrons however, the  
 1095 neutral particle energy deposit can only be detected as an excess over the charged particle  
 1096 deposit. For this reason, a good calibration of the electromagnetic and hadronic calorimeter is  
 1097 vital.

1098 The ECAL calibration is performed before the hadron cluster calibration or particle identifi-  
 1099 cation<sup>2</sup>. For Run 1, the ECAL response to electrons and photons as well as the cell-to-cell  
 1100 relative calibration is determined with test beam data, radio active sources, and cosmic ray  
 1101 measurements. For Run 2, the collision data collected at 7 and 8 TeV was used to refine the  
 1102 calibration. The effect of the thresholds in the clustering algorithm are estimated from simulated  
 1103 single photons with energies varying from 0.25 to 100 GeV. The photons used for the calibration  
 1104 should not have a conversion prior to their entrance to ensure the calibration of single clusters.  
 1105 In all ECAL regions and for all energies, the calibrated photon energies agree with the true  
 1106 photon energies within 1%.

1107 In contrary to the photons, the hadrons deposit in general energy in both ECAL and HCAL.  
 1108 Since the calorimeter responce in the HCAL depends on the fraction of shower energy deposited  
 1109 in the ECAL, the ECAL and HCAL cluster energyes are recalibrated together to get an estimate  
 1110 of the true hadron energy. Since now the calibration is done for hadrons, single neutral hadrons  
 1111 such as  $K_L^0$  are used for determining the calibration constants. The hadrons interactiong with  
 1112 the tracker material are rejected for the calibration purposes. This calibration is checked with  
 1113 isolated charged hadron selected from early data recorded at  $\sqrt{s} = 0.9, 2.2$  and 7 TeV.

## 1114 4.2 Putting the pieces together

1115 A link algorithm connects the several PF elements from the various CMS subdetectors. It tests  
 1116 any pair of elements in an event and is restricted to considering nearest neighbours in the  
 1117  $\eta\phi$ -plane. The quality of the link is determined via the distance between the two elements  
 1118 and PF blocks of elements are formed from elements with a direct link or indirect link through  
 1119 common elements.

1120 The link between a central tracker track and a calorimeter clusters is made by extrapolating  
 1121 the tracker track to the two layers of the preshower, the ECAL, and the HCAL. If this extrapolated

---

<sup>2</sup>Specifically electron and photon energy corrections are performed after the identification step.

position is within the cluster area, the two are linked. When there are several ECAL or HCAL clusters for the same track, the link with the smallest distance is kept. A dedicated cluster algorithm accounts for the energy of the photons emitted through bremsstrahlung and for photons that have converted to an electron-positron pair.

The ECAL to HCAL cluster and ECAL to preshower cluster links are established when the cluster position in the more granular calorimeter, ECAL or preshower, is in accordance with the cluster envelope of the less granular calorimeter (HCAL or ECAL). When there are multiple HCAL clusters linked to the same ECAL cluster, the link with the smallest distance is kept. This is also true for multiple ECAL clusters with the same preshower clusters. The ECAL supercluster is linked with the ECAL cluster when they share at least one ECAL cell.

Nuclear interactions in the tracker can lead to kinks in hadron trajectories as well as the production of secondary particles. This leads to charged particle tracks linked together via a common displaced vertex. The displaced vertices considered should have at least three tracks, with at most one incoming track, and the invariant mass of the outgoing tracks should exceed 0.2 GeV.

The link between a track and the muon detectors is done via local, regional, and global reconstruction as explained in Section 4.1.2.

## 4.3 Particle flow identification

In each PF block the identification and reconstruction follows a particular order where after each identification and reconstruction the corresponding PF elements (tracks and clusters) are removed from the PF block. The muons are the first to be identified and reconstructed. These are reconstructed if their momenta are compatible with corresponding track only momenta. Then the electron and its corresponding brehmstrahlung photons, are identified and reconstructed by using of the GSF tracking. At the same time, the energetic and isolated photons are identified as well. The remaining element in the PF block are subjected to a cross identification of charged hadrons, neutral hadrons, and photons that arise from parton fragmentation, hadronisation, and decays in jets. The charged hadron candidate is made from the remaining candidates that have a charged particle track associated with them. Then the charged particle energy fraction is subtracted from the calibrated energy of the linked calorimeter clusters and the remaining energy is assigned to the neutral energy. Depending on the excess of neutral energy in the ECAL and HCAL clusters, a photon or a neutral hadron is assigned respectively. The pseudorapidity range of the inner tracker limits the information on the particles charge to  $|\eta| < 2.4$ . Outside this range a simplified identification is done for hadronic and electromagnetic candidates only.

### 4.3.1 Muons

A set of selection requirements based on the global and tracker muon properties is responsible for muon identification. The muons are considered isolated when the additional inner tracks and calorimeter energy deposits within a distance to the muon direction in the  $\eta\phi$ -plane is smaller than 0.3. The muons coming from charged hadron decays or heavy flavour decays need more stringent criteria. This due to the fact that charged hadrons can be misidentified as muons because of e.g. punch-through, or muons can be seen as charged hadrons, and will absorb the energy deposits of nearby particles.

1162 **4.3.2 Electrons and isolated photons**

1163 The electrons and photons are reconstructed together as discussed before. An electron candidate  
 1164 seeded from a GFS track is considered an electron when the linked ECAL cluster is not linked  
 1165 to three or more additional tracks. The photon seeds are ECAL superclusters with transverse  
 1166 energies above 10GeV that have no links with a GSF track. After associating photons from  
 1167 brehmstrahung with the associated electrons, the remaining energy is associated to the photons  
 1168 and the photon direction is taken to be that of the supercluster. The electron direction is  
 1169 chosen to be that of the GSF track and its energy is a combination of the ECAL energy with  
 1170 the momentum of the GSF track. Photons are retained if they are isolated, while electrons  
 1171 should satfisy additional criteria based on a multivariate analysis for isolated and non-isolated  
 1172 electrons.

1173 **4.3.3 Hadrons and non-isolated photons**

1174 After muon, electron and isolated photon identification, the remaining particles are hadrons  
 1175 from jet fragmentation and hadronisation. These can show up ad charged hadrons (e.g.  $\pi^\pm$ ,  
 1176  $K^\pm$ , or protons), netural hadrons (e.g.  $K_L^0$  or neutrons), non isolated photons (e.g. from  $\pi^0$   
 1177 decays), and additional muons from early decays of charged hadrons.

1178 The photons and neutral hadrons are assigned to calorimeter clusters without any link to  
 1179 tracks. When the calorimeter clusters between the ECAL and HCAL are linked, the clusters are  
 1180 assumed to aris from the same hadron shower. if their is not such a link, HCAL clusters are  
 1181 assigned to neutral hadrons, while the ECAL clusters are assigned to photons based on the fact  
 1182 that neutral hadrons leave only 3% of their energy in the ECAL.Then the HCAL clusters linked  
 1183 with tracks, that are not linked with other HCAL clusters, are assigned to charged hadrons.  
 1184 These tracks can be linked with remaining ECAL clusters.

1185 Hadron interactions can result in the creation of extra particles originating from a secondary  
 1186 vertex. These extra particles are identified by having a common secondary vertex and replaced  
 1187 in the PF list as one single primary charged hadron.

1188 **4.3.4 Post processing**

1189 After identification and reconstruction of all particles as described above. An artificial large  
 1190 missing transverse momentum  $\vec{p}_T^{\text{miss}}$  can be reconstructed. The cause of the  $\vec{p}_T^{\text{miss}}$  is mostly  
 1191 misidentified or misreconstructed high- $p_T$  muons originating from cosmic rays, misconstruction  
 1192 of the muon's momentum, or punch-throuvh charged hadrons. A post processing step is applied  
 1193 to solve this  $\vec{p}_T^{\text{miss}}$ . Events with genuine large  $\vec{p}_T^{\text{miss}}$  due to the presence of neutrino's are  
 1194 unaffected by this post processing.

## 1195 4.4 Pile up mitigation

1196 The particle flow algorithm is design without taking pile up into account. For the 8 TeV dataset,  
 1197 an avarage of about 21 pile up interactions of pile up interactions happened per bunch cross  
 1198 section. For the dataset taken at 13 TeV, the number of pile up interactions increased to about  
 1199 27 interactions per bunch crossing. THese interactions are spread around the beam axis around  
 1200 the centre of the CMS coordinate system and follow a normal distribution with a standard  
 1201 deviation of about 5 cm [144]. The number of pile up interactions is iestimated from th enumner  
 1202 of interaction vertices reconstructed from charged particle tracks , or from the instantaneous  
 1203 luminosity of the given bunch crossing with dedicated detectors and the inelastic proton-proton  
 1204 crossing . This minimum bias cross section is measured to be  $69.2 \text{ mb} \pm 4.6\%$  [150]. The  
 1205 distribution of the number of pile up interaction is reweighted to take care of discrepancies.  
 1206 The uncertainty on the minimum bias cross section measurement results in a systematic shift in  
 1207 the pileup distribution.

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1208 The pile up vertices are seperated from the primary vertex by requiring that the primary vertex  
 1209 is the vertex with the highest quadratic sum of the transverse momenta of the corresponding  
 1210 tracks. The charged hadrons coming from these pile up vertices are identified via their tracks  
 1211 and are removed from the list of reconstructed particles to be used for physics analysis. This  
 1212 method is the so-called pile up charged hadron subtraction and denoted as CHS [151]. For the  
 1213 reconstructed particles outside the tracker acceptance as well as photons and neutral hadrons,  
 1214 the CHS method doesn't work. Therefore, the transverse density from pile up interactions  
 1215 is estimated using jet clustering techniques and their effect is subtracted from the particles  
 1216 transverse momenta. Additionally, the pile up contribution can be estimated locally as described  
 1217 for the Muons and electrons described in [Section 4.5.1](#) and [Section 4.5.2](#).

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## 1218 4.5 Physics object reconstruction and identification

1219 The particle flow objects are used for building physics objects that are used for analysis. These  
 1220 objects are jets, muons, electrons, photons, taus and missing transverse momentum  $\vec{p}_T^{\text{miss}}$ . They  
 1221 are used to compute other quantities such as particle isolation and have extra requirements  
 1222 that are analysis dependent. In the following section, only the physics objects used throughout  
 1223 this thesis are discussed.

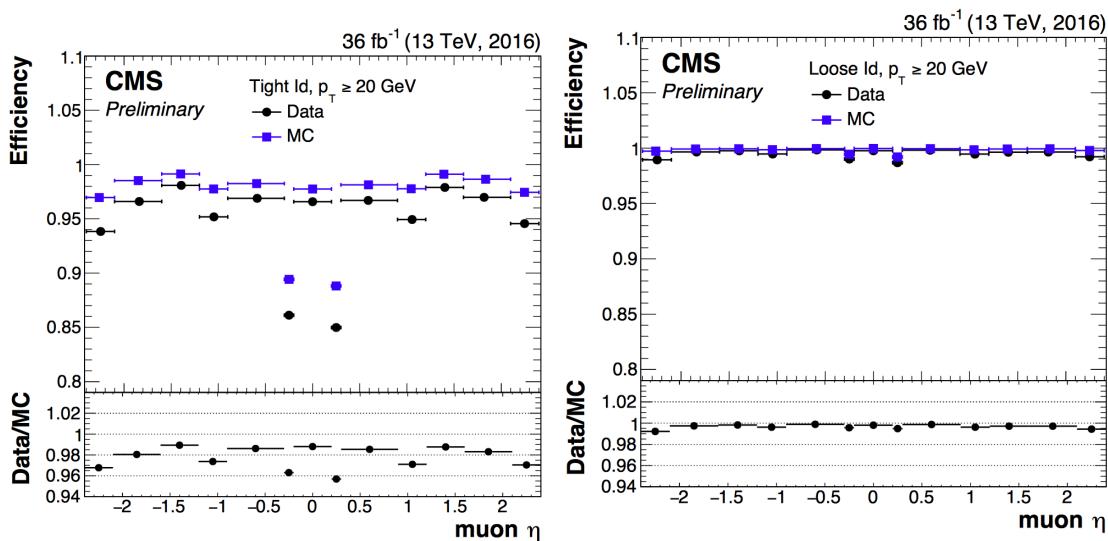
### 1224 4.5.1 Muons

1225 The muon candidates used for analysis in this thesis correspond to the tight and loose working  
 1226 points. The tight working point yields the most genuine muons and rejects falsely reconstructed  
 1227 ones. While the loose working point yields as many reconstructed muons as possible. Detailed  
 1228 reports on the performance can be found in .

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1229 In order to reject objects wrongly reconstructed as muons from hadron showers that reach he  
 1230 muon system (punch-throughs), the global muon fit is required to include at least one valid  
 1231 hit in the muon chambers and for which at least two muon segments in two muon stations  
 1232 is present. Additionally, the muon tracks should have a global fit yielding a goodness-of-fit of  
 1233  $\chi^2/\text{ndof} < 10$ . The decay of muons in flight is suppressed by requiring at least one pixel hit in

the muon track. Furthermore, a minimum of five hits in the tracker is required. Cosmic muons and muons originating from pile up interactions are rejected by constricting the distance of the muon with respect to the primary vertex by putting limits on  $d_{x,y} < 2$  mm and  $d_z < 5$  mm. Also muons according to the loose muon ID will be used in the thesis. These are either global muons or tracker muons reconstructed from the particle flow muon object. In Figure 4.2, the muon efficiencies for data and simulation is presented. These efficiencies are estimated from tag-and-probe methods that select  $Z \rightarrow \mu^-\mu^+$  and tag one muon that passes the identification criteria. The other muon is used as probe and one measures how many times it passes the identification criteria to get the efficiency. Overall, the efficiency is about 95-100%, with two drops due to the crack between the wheels of the DT system. The differences between data and simulation are corrected by applying  $p_T$ - and  $\eta$ -dependent scale factors ( $\epsilon_{\text{data}}/\epsilon_{\text{MC}}$ ) to simulated events. In Table 4.1, the muon requirements for the muons used throughout this theses are summarised.



**Figure 4.2:** Comparison of the muon tight ID (left) and loose ID (right) efficiencies in data and simulation as a function of the pseudorapidity of the muon using the full 2016 dataset. Figure taken from [152].

1246

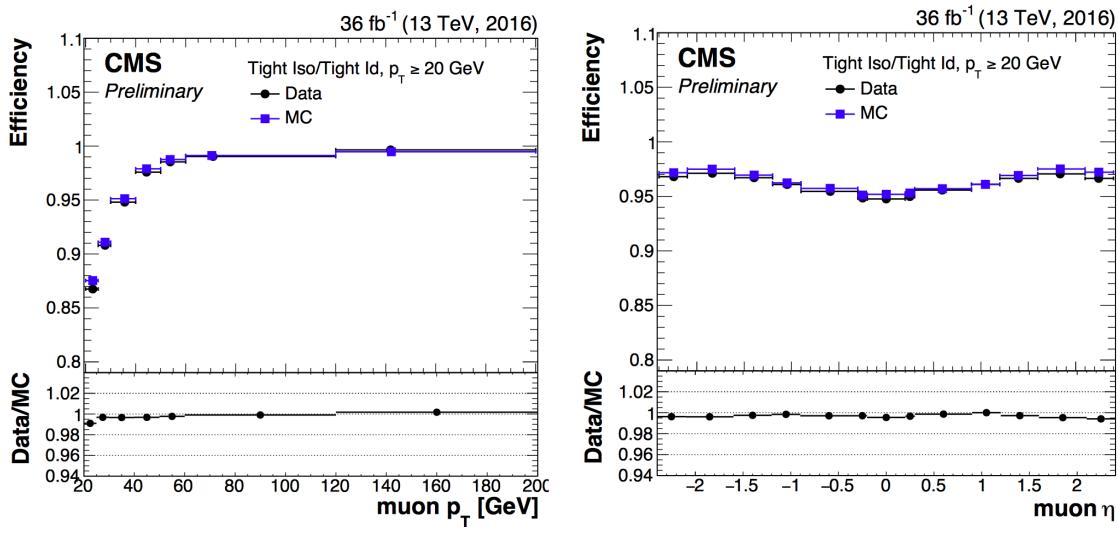
In addition to the identification criteria, the muons are required to be spatially isolated from EM and hadronic activity. The lepton isolation is defined as estimating the total transverse energy of the particles emitted around the direction of the lepton by defining a cone of radius  $\Delta R$  in  $\eta\phi$  plane around the lepton direction. Then a summed energy is calculated from the charged hadrons (CH), neutral hadrons (NH), photons ( $\gamma$ ), excluding the lepton itself. This sum is then corrected to remove the energy coming from pile up interactions. The relative isolation for muons  $\mathcal{I}$  is defined as

$$\mathcal{I}_\mu = \frac{\sum p_T(\text{CH}) + \max(0, \sum E_T(\text{NH}), \sum E_T(\gamma) - 0.5 \times \sum E_T(\text{CH}))}{p_T(\mu)}, \quad (4.1)$$

1247 where a cone of  $\Delta R = 0.4$  is adopted and the pile up mitigation is based on the  $\Delta\beta$  correction.  
 1248 The  $\Delta\beta$  correction estimates the pile up energy as half of the contribution coming from charged

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hadrons. For tight ID muons, this relative isolation should  $\mathcal{I}_\mu < 0.15$ , while for loose muons this should be  $\mathcal{I}_\mu < 0.25$ . In Figure 4.3, the isolation efficiencies as a function of the pseudo rapidities using the tag and probe method are shown for the tight muon ID. The efficiencies are 85-100% with a decline for low- $p_T$  muons since they are most likely coming from hadronic or heavy flavour decays. The differences between data and simulation are accounted for by applying  $\eta$ - and  $p_T$ -dependent scale factors on the simulation.



**Figure 4.3:** Comparison of the muon tight isolation requirement with the muon tight ID efficiencies in data and simulation as a function of the transvers emomentum (left) or pseudorapidity (right) of the muon using the full 2016 dataset. Figure taken from [152].

**Table 4.1:** Muon requirements for the tight and loose working points, used throughout this thesis.

Property	Loose Muons	Tight Muons
Global muon or Tracker Muon	One or the other	Both
Particle Flow muon	Y	Y
$\chi^2/\text{ndof}$ of global muon track fit	N/A	< 10
Nb. of hit muon chambers	N/A	> 0
Nb. of muon stations contained in the segment	N/A	> 1
Size of the transverse impact parameter of the track wrt. to the PV	N/A	$d_{xy} < 2 \text{ mm}$
Longitudinal distance wrt. the PV	N/A	$d_z < 5 \text{ mm}$
Nb. of pixel hits	N/A	> 0
Nb. of tracker layers with hits	N/A	> 5
Relative Isolation	<0.25	<0.15

1255 **4.5.2 Electrons**

1256 The electrons candidates used correspond to the tight and veto working points. The study of  
 1257 the electron reconstruction and identification performance can be found in [153].

1258 Starting from an electron PF candidate with a GSF track that is outside the barrel-endcap  
 1259 transition region ( $1.4443 < |\eta| < 1.5660$ ), several requirements are set. The electrons from  
 1260 photon conversions are dismissed by requiring the electron track to have not have more than one  
 1261 (two or three) missing hit in the innermost layer for the tight (veto) working point. Additionally,  
 1262 a photon conversion veto is applied by testing if a pair of electron tracks is originating from a  
 1263 common displaced vertex. For the 8 TeV datasets more refined cuts are placed on the electron  
 1264 object using a multivariate analysis. For the 13 TeV dataset this is replaced with more refined  
 1265 cuts on the shower shape variables such as the difference in  $\eta$  or  $\phi$  between the energy weighted  
 1266 supercluster position in the ECAL and the track direction in at the innermost tracker position  
 1267 ( $\Delta\eta_{in}$ ,  $\Delta\phi_{in}$ ), and the ECAL crystal based shower covariance in the  $\eta$  direction ( $\sigma_{\eta\eta}$ ). These  
 1268 cuts also include energy related variables such as the absolute difference between the inverse  
 1269 electron energy measured in the ECAL and the inverse momentum measured in the tracker  
 1270 ( $|1/E - 1/p|$ ), and the ratio of the energy measured in the HCAL and ECAL (H/E). Unlike the  
 1271 muon case, the identification criteria also contain requirements on the isolation of the electrons.

Similar to the muons, the electron relative isolation is determined from the sum of the particles in a cone around the electron itself. The cone radius used for electrons is  $\Delta R = 0.3$  and a  $\rho$  correction for pile up mitigation is applied. For this correction, the expected pile up energy inside the isolation cone is estimated from the median density energy per area of pile up contamination ( $\rho$ ), computed event by event, and the effective area ( $A_{eff}$ ). This effective area is estimated from simulation and denotes the expected amount of neutral energy from pile up interactions per  $\rho$  within the isolation cone as a function of the pseudo rapidity of the associated ECAL superclusters. Table 4.2 shows the values used for 13 TeV data. The relative electron isolation  $\mathcal{I}_e$  is calculated as

$$\mathcal{I}_e = \frac{\sum p_T(CH) + \max(0., \sum E_T(NH), \sum E_T(\gamma) - \rho \times A_{eff})}{p_T(e)} \quad (4.2)$$

**Table 4.2:** The effective areas  $A_{eff}$  used for the electron relative isolation [154].

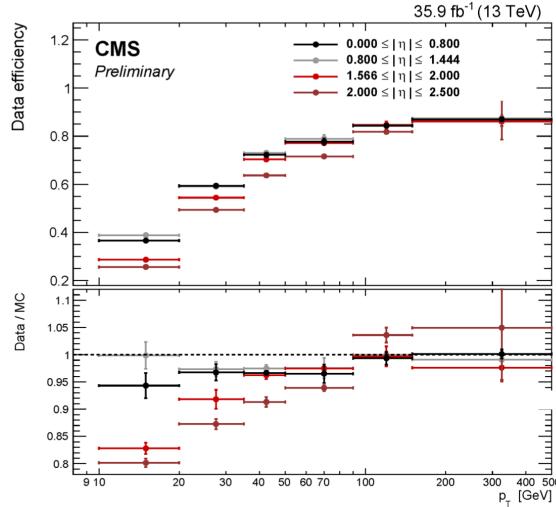
$\eta$ region	$A_{eff}$
$0 <  \eta  < 0.1752$	0.1703
$1.0 <  \eta  < 0.1479$	0.1715
$1.479 <  \eta  < 2.0$	0.1213
$2.0 <  \eta  < 2.2$	0.1230
$2.2 <  \eta  < 2.3$	0.1635
$2.3 <  \eta  < 2.4$	0.1937
$2.4 <  \eta  < 2.5$	0.2393

1272

1273 The efficiency of electron identification is estimated from  $Z \rightarrow e^- e^+$  events via the tag-and-  
 1274 probe method and is shown in Figure 4.4 for the tight working point. The efficiencies reach

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<sup>1275</sup>  $\approx 95 - 100\%$ . The difference between data and simulation are corrected by dedicated  $p_T$ - and  $\eta$  dependent scale factors as well.



**Figure 4.4:** Electron identification efficiency as function of the electron transverse momentum from the full 2016 dataset. Figure taken from [153].

<sup>1276</sup>

**Table 4.3:** Electron requirements used in this analysis. The requirements are set in the barrel ( $|\eta_{supercluster}| \leq 1.479$ ) and the end caps ( $|\eta_{supercluster}| > 1.479$ ).

Properties	$ \eta_{supercluster}  \leq 1.479$		$ \eta_{supercluster}  > 1.479$	
	Veto electron	Tight electron	Veto electron	Tight electron
$\sigma_{\eta\eta}$	< 0.0115	< 0.00998	< 0.037	< 0.0292
$ \Delta\eta_{inl} $	< 0.00749	< 0.00308	< 0.00895	< 0.00605
$ \Delta\phi_{in} $	< 0.228	< 0.0816	< 0.213	< 0.0394
H/E	< 0.356	< 0.0414	< 0.211	< 0.0641
relative isolation	< 0.175	< 0.0588	< 0.159	< 0.0571
$ 1/E - 1/p $	$< 0.299 \text{ GeV}^{-1}$	$< 0.0129 \text{ GeV}^{-1}$	$< 0.15 \text{ GeV}^{-1}$	$< 0.0129 \text{ GeV}^{-1}$
expected missing inner hits	$\leq 2$	$\leq 1$	$\leq 3$	$\leq 1$
pass conversion veto	Y	Y	Y	Y

1277 **4.5.3 Jets**

Jets are reconstructed from all reconstructed particles without the charged hadrons associated to pile up vertices (PF+CHS jets). The clustering is done via the anti- $k_T$  algorithm [155] with a radius parameter for the cone size of the resulting jet of  $R = 0.5$  for 8 TeV data and  $R = 0.4$  for the more boosted 13 TeV dataset. The initial step of the anti- $k_T$  algorithm considers all candidates as protojets and starts to calculate the distances for protojets  $i$  and  $j$  as

$$d_{ij} = \min\left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2}\right),$$

$$d_i = \frac{1}{p_{T,i}^2}. \quad (4.3)$$

1278 For each iteration the two distances are calculated. When  $d_{ij} < d_i$ , the two protojets are merged  
 1279 and their four momentum is summed. If  $d_i$  is the smallest distance, the protojet is renamed  
 1280 as final jet and ignored in the subsequent steps. More information about the jet algorithm  
 1281 performance can be found in [156].

1282 The jets used for the analysis discussed in this thesis uses the loose identification working point  
 1283 given. The criteria on the constituents of the jets are given in Table 4.4. These requirements  
 1284 find their origin on the assumption that a proper jet originating from the hadronisation of a  
 1285 quark or gluon consists of multiple PF particles and types. The jet should consist of more than  
 1286 one constituent and the neutral hadron fraction and neutral EM energy fractions should be less  
 1287 than 99%. For the jets within the tracker acceptance ( $|\eta| < 2.4$ ), at least one constituent has to  
 1288 be a charged hadron resulting in a charged hadron energy fraction above 0%. Additionally the  
 1289 charged EM energy fraction should be less than 99%. On top of these requirements, objects  
 1290 that are labelled as jets and found in vicinity of any isolated lepton,  $\Delta R < 0.3$ , are removed  
 1291 from the jet collection in that event.

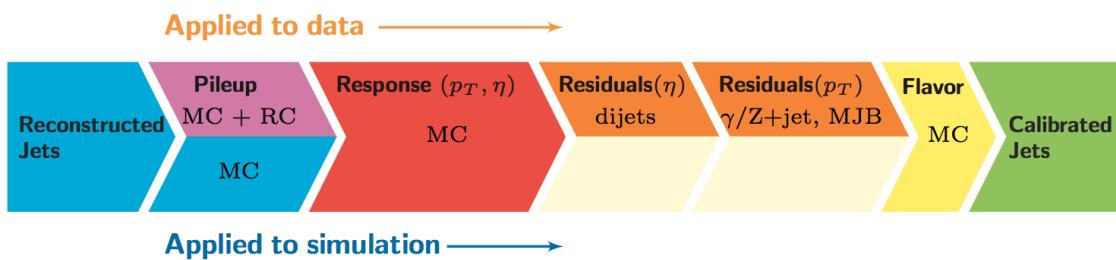
**Table 4.4:** Jet criteria used throughout the thesis. The last three requirements are only for jets within the tracker acceptance.

Properties	Loose Jet ID
Neutral hadron fraction	< 0.99
Neutral EM fraction	< 0.99
Number of constituents	> 1
Charged hadron fraction	> 0
Charged multiplicity	> 0
Charged EM fraction	< 0.99

1292 The energy of the reconstructed jets deviate from the energies of the corresponding jets  
 1293 clustered from the hadronisation products of true partons from simulations due to non linear  
 1294 subdetector response and efficiencies. The jet energy corrections (JEC) calibrate the jets in  
 1295 order to have the correct energy scale. Jet energy scale corrections (JES) are determined as  
 1296 a function of pseudorapidity and the transverse momentum from data and simulated events  
 1297 by combining several channels and methods. This is extensively described in [157]. These

1298 corrections account for the effects of pile up, the uniformity of the detector response, and  
 1299 residual data-simulation jet energy scale differences. Furthermore, the jet energy resolution  
 1300 (JER) is measured in data and simulation as function of pile up, jet size and jet flavour. A  
 1301 detailed understanding of both the energy scale and the transverse momentum resolution of the  
 1302 jets is crucial for many physics analysis, and these are commonly the main source of systematic  
 1303 uncertainty. The performance of the jet energy corrections for the 13 TeV dataset can be found  
 1304 in [158].

1305 The JEC are factorised and subsequently correct for the offset energy due to pile up, the  
 1306 detector response to hadrons, and residual differences between data and simulation as a function  
 1307 of the jet pseudorapidity and transverse momentum. The consecutive steps of JEC are shown  
 in Figure 4.5. The off set corrections remove the dependence of the jet energy response of



**Figure 4.5:** The sequence of the JEC for data and simulations. The corrections marked with MC are derived from simulation studies, while RC stands for random cone, and MJB for the analysis of multi-jet events. Figure taken from [157].

1308 additional pile up activity. It is based on the jet area method, which uses the effective area  
 1309 of the jets multiplied by the average density in the event to calculate the offset energy to  
 1310 be subtracted of the jets. The correction factors are derived by comparing the jet response  
 1311 with and without pile up events overlaid. The residual differences between data and detector  
 1312 simulation are determined using the random cone method (RC). For this method, many jets  
 1313 are reconstructed in each event by clustering particles through placing random cones. This  
 1314 provides a mapping of the  $\eta\phi$ -space and the average  $p_T$  of those jets gives the average energy  
 1315 offset due to pile up [157]. The next level of corrections have as goal to have an uniform  
 1316 energy response independent of the transverse momentum or pseudorapidity of the jet. These  
 1317 corrections are determined from simulated events by matching the reconstructed to true particle  
 1318 jets and comparing their momenta. The residual corrections between data and simulation are  
 1319 determined by comparing the transverse momentum balance in various types of events (multi-  
 1320 jet, Z + jets, and  $\gamma$  + jets), using a reference jet in the barrel region. The jet flavour corrections  
 1321 are optional and not used for this thesis. More information on the jet flavour corrections can be  
 1322 found in [157]. For jets with a transverse momentum above 30 GeV, the uncertainties from the  
 1323 various corrections are 3-5% for the 13 TeV dataset [158].

After applying JEC, the transverse momentum resolution of the jet is extracted from data and simulated events. There are two methods used to rescale the reconstructed four momentum chosen based on whether or not the simulated jet can be matched to a true jet in simulation.

The factors are defined as

$$c_{\text{matched}} = 1 + \frac{p_T^{\text{reco.}} - p_T^{\text{true}}}{p_T^{\text{reco.}}} (s_{\text{JER}} - 1),$$

$$c_{\text{unmatched}} = 1 + N(0, \sigma_{\text{JER}}) \sqrt{\max(s_{\text{JER}}^2 - 1, 0)},$$
(4.4)

where  $N(0, \sigma_{\text{JER}})$  denotes a sample value from a normal distribution centred at zero with standard deviation the relative resolution in simulation  $\sigma_{\text{JER}}$ , and  $s_{\text{JER}}$  the  $\eta$ -dependent resolution scale factors. These scale factors are derived from data from di-jet or  $\gamma + \text{jets}$  events and analyzing the  $p_T$  balance. The resolution scale factors are found to be 1.1-1.2 except for the transition regions around  $|\eta| = 3$  and  $|\eta| = 1.4$  [158].

#### 4.5.4 Jets with displaced vertices

**NOTE:** Add 1331  
source 1332 The jets originating from b hadron are tagged using the CSVv2 algorithm , which combines the information of displaced tracks with information of secondary vertices associated to the jet using a multivariate technique. The jets are tagged as a jet coming from a b quark (b-tagged) if the CSVv2 discriminator is above a certain threshold. These thresholds define working points and are given in Table 4.5 . This analysis uses the loose working point which has an average efficiency of 83% and a misidentification rate of 10%.

1333  
1334  
**NOTE:** Add 1335  
source 1336

1337

**Table 4.5:** Working points used for tagging jets as coming from b quarks.

WP id	WP descr cut
Loose	> 0.5426
Medium	> 0.8484
Tight	> 0.9535

#### 4.6 Summary of corrections

1339 1. Muon ID, Iso see [Section 4.5.1](#)

#### 4.7 Event selection

#### 4.8 Regions and channels

#### 4.9 Data driven background simulation

# The search for FCNC involving a top quark and a Z boson

1343

5

1344 5.1 Construction of template distributions

1345 5.2 Systematic uncertainties

1346 5.3 Limit setting procedure

1347 5.4 Result and discussion



# Denouement of the top-Z FCNC hunt at 13 TeV

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6

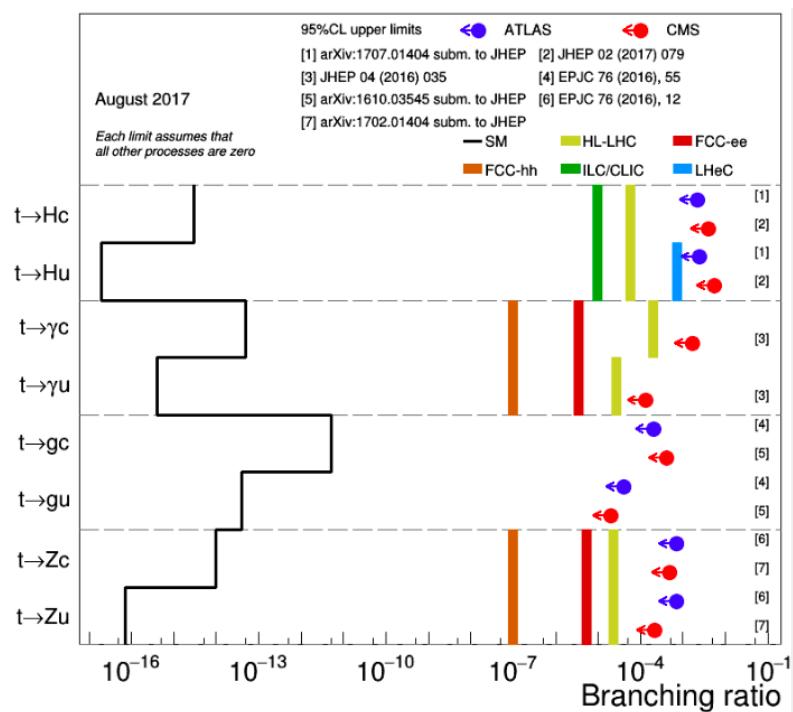


Figure 6.1:



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