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

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Theoretical basis

1

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

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

83 1.1 Getting to the nature of things

84 The interactions in nature can be described by four forces, the strong force, the electromagnetic
 85 (EM) force, the weak force and the gravitational force. These interactions happen via particles
 86 with an integer spin known as bosons. The strong interaction is mediated by eight gluons g ,
 87 while the electromagnetic force is mediated by photons γ , and the weak force by Z and W^\pm
 88 bosons. In [Table 1.1](#), the forces and their characteristics are shown. The gravitational force is
 89 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	∞	photon
Weak force	$10^{\text{-}18}$ m	W^\pm , Z bosons
Gravitational force	∞	unknown

91 The fermions are the particles that make up the visible matter in the universe. They carry
 92 half integer spin and can be subdivided into leptons and quarks, where leptons don't interact
 93 strongly. Each fermion has a corresponding anti-fermion which has the same mass and is
 94 oppositely charged. The electron e^- is the first elementary particle discovered [3] and belongs
 95 to the first generation of leptons together with the electron neutrino ν_e . The second generation
 96 compromises the muon μ^- and muon neutrino ν_μ , whereas the third generation consists of
 97 the tau τ and tau neutrino ν_τ . The neutrino's are neutral particles, while the other leptons
 98 have charge $\pm q_e$ where q_e represents the elementary charge of $1.602 \cdot 10^{-19}$ C. The masses of
 99 charged leptons differ by four orders of magnitude between the first and third generations. In
 100 the SM the neutrino's are assumed to be massless, nonetheless it is experimentally established
 101 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	$-q_e$
	ν_e	≈ 0	0
Second	μ^-	106 MeV	$-q_e$
	ν_μ	≈ 0	0
Third	τ	1 777 MeV	$-q_e$
	ν_τ	≈ 0	0

102

103 The quarks can also be divided into three generations. Unlike the leptons, they carry colour
 104 charge and can interact via the strong interaction. The top quark, discovered in 1995 at the
 105 Tevatron [[observationtopD0](#), [observationtopCDF](#)], is the heaviest SM particle with a mass
 106 close to 173.1 ± 0.6 GeV¹ [4]. The quarks and their properties are summarized in [Table 1.3](#). In
 107 nature, only colour neutral objects can exist. This has as consequence that quarks are bound
 108 through gluons into mesons (quark+anti-quark) and baryons (three quarks). These mesons
 109 and baryons are mostly short-lived and unstable particle that rapidly decay through W^\pm and Z
 110 bosons, associated with a fermion. The only known stable baryon is the proton, made up of two
 111 up quarks and one down quark.

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

115 1.2 Standard Model Lagrangian, connecting fields with particles

116 The SM is a quantum field theory and thus describes the dynamics and kinematics of particles
 117 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

¹In 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 ± 0.03 GeV	$\frac{2}{3} q_e$	
	strange s	96^{+8}_{-4} MeV	$\frac{-1}{3} q_e$	
Third	top t	173.1 ± 0.6 GeV	$\frac{2}{3} q_e$	
	bottom b	$4.18^{+0.04}_{-0.03}$ GeV	$\frac{-1}{3} q_e$	

118 symmetry, where $SU_L(2) \times U_Y(1)$ describes the electroweak interaction and $SU_C(3)$ the strong
 119 coupling. The indices refer to colour C, the left chiral nature of the $SU_L(2)$ coupling L, and the
 120 weak hypercharge Y. Its Lagrangian is constructed such that contains symmetries representing
 121 physics conservation laws such as conservation of energy, momentum and angular momentum.
 122 The symmetries under local group transformations are sustained by demanding gauge invariance
 123 .

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

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

The generators T^a satisfy the Lie algebra:

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

124 where ϵ^{abc} is an antisymmetric tensor. The gauge fields of $SU_L(2)$ only couple to left-handed
 125 fermions as required by the observed parity violating nature of the weak force. The $SU_C(3)$
 126 group represents quantum chromodynamics (QCD). It has eight generators corresponding to
 127 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:

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

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 ϕ 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_μ , the Z boson field Z_μ^0 , and the W field W_μ^\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 θ_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.

141 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}_ϕ 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:
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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 λ 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:

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

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

148 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_{weak} , where d_{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 θ_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_{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_{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

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

- 149 and is diagonal in flavour space. This has as consequence that no flavour changing neutral
150 currents occur at tree-level Feynmann diagrams².

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

²Feynmann 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 3×3 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}_{CKM} represents the transition probability of a quark i going to a quark j , and is experimentally determined to be [4]

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

151 From Equation 1.15 follows that top quarks predominantly decay via charged weak currents to
 152 bottom quarks, with a probability consist with unity. In the SM, FCNC can only occur via higher
 153 loop Feynmann diagrams which are highly suppressed. The expected transition probabilities for
 154 a top quark decaying via a FCNC interaction in the SM are given in Table 1.4, where it is clear
 155 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
$t \rightarrow uZ$	$8 \cdot 10^{-17}$	$t \rightarrow cZ$	$1 \cdot 10^{-14}$
$t \rightarrow u\gamma$	$4 \cdot 10^{-16}$	$t \rightarrow c\gamma$	$5 \cdot 10^{-14}$
$t \rightarrow ug$	$4 \cdot 10^{-14}$	$t \rightarrow cg$	$5 \cdot 10^{-12}$
$t \rightarrow uH$	$2 \cdot 10^{-17}$	$t \rightarrow cH$	$3 \cdot 10^{-15}$

156

157 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 ± 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.

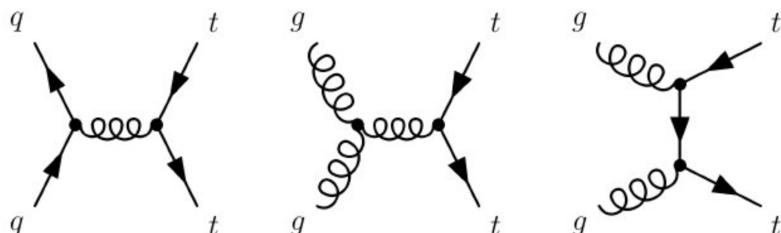


Figure 1.1: Leading order diagrams of the top pair production. Gluon fusion (right and middle) are the dominant processes at the LHC, while quark fusion (left) is the dominant one at Tevatron.

185

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	$\sigma_{t\bar{t}} = 816.0^{+19.4+34.4}_{-28.6-34.4}$

190 the top pair production cross sections since the electroweak coupling strength is smaller than
 191 the strong coupling strength. In addition, for the single top production, there is the need of sea
 192 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.

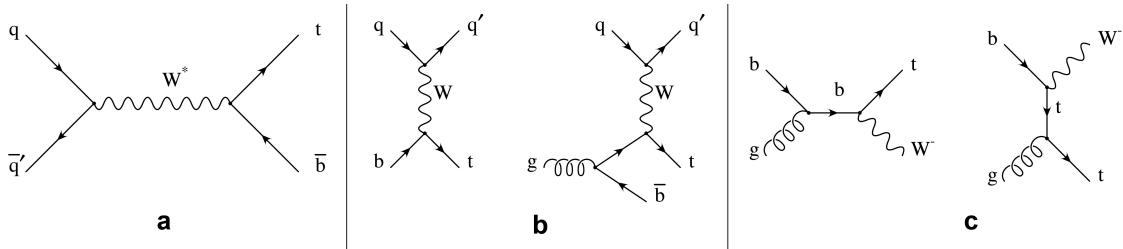


Figure 1.2: Leading order Feynman diagrams of the electroweak production of single top quarks in the s -channel (left), t -channel (middle), and for the tW associated production. Figure taken from [15].

193

194 The production via the t -channel has a virtuality of the W boson $Q^2 > 0$, making it space-like.
 195 It is produced via the scattering of the W boson of a bottom quark coming from a proton or
 196 from gluon splitting ($g \rightarrow b\bar{b}$). This process is also known as W -gluon fusion production. It has
 197 the highest single top quark cross section in proton collisions and the top quark production is
 198 roughly twice more than the antitop quarks. This is a consequence of the up-down valence
 199 quark composition of the proton. This feature makes the t -channel sensitive to the parton
 200 density functions of the proton. The s -channel is the production mechanism with the smallest
 201 cross section. Here the W boson is time-like ($Q^2 < 0$) which requires the W boson to have a
 202 large virtuality to produce the heavier top quark. It is produced from two quarks belonging
 203 to the same isodoublet (e.g. $u\bar{d}$) and subsequently decays to $t\bar{b}$. This process get enhanced
 204 by many beyond the Standard Model scenarios via the addition of new heavy particles such
 205 as W' . The tW -channel has a top quark produced in association with a W boson produced on
 206 shell $Q^2 = -m_W^2$. This mode is negligible at Tevatron, but of relevant size at the LHC. The
 207 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	$216.99^{+9.04}_{-7.71}$	$10.32^{+0.40}_{-0.36}$	$71.7^{+1.80+3.40}_{-1.80-3.40}$

208 1.5 Hunting down the SM top quark

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

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

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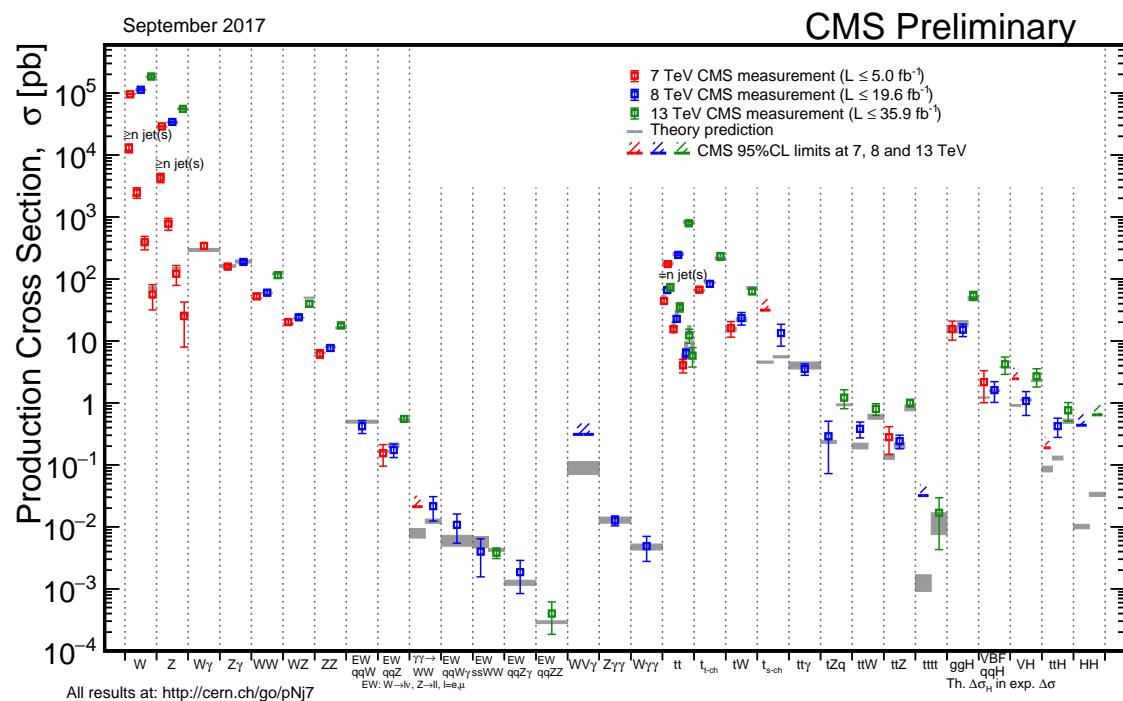


Figure 1.3: Summary of the SM cross section measurements performed by the CMS collaboration. Figure taken from [17]

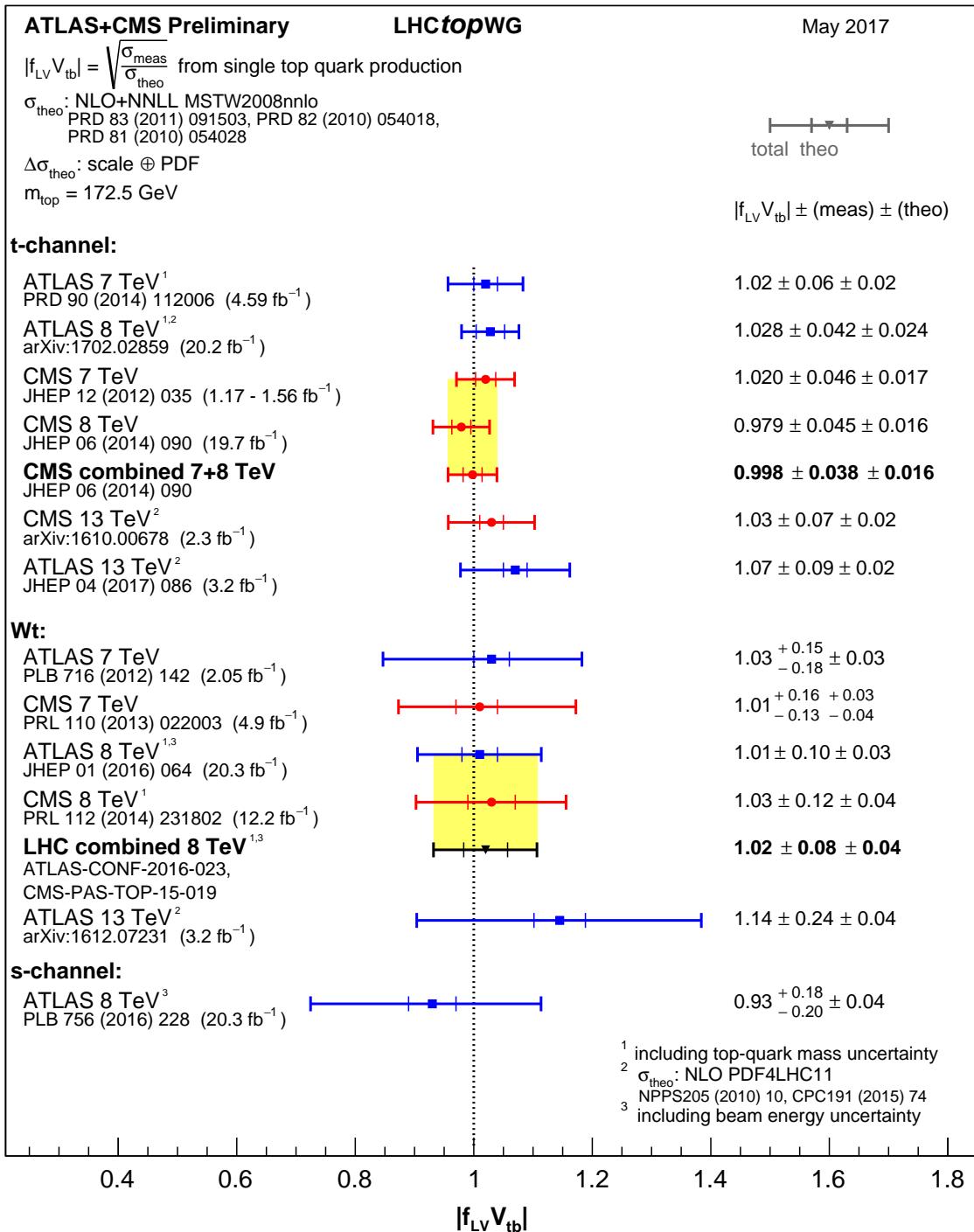


Figure 1.4: Estimations of the SM V_{tb} CKM element from single top cross section measurements. Figure taken from [18].

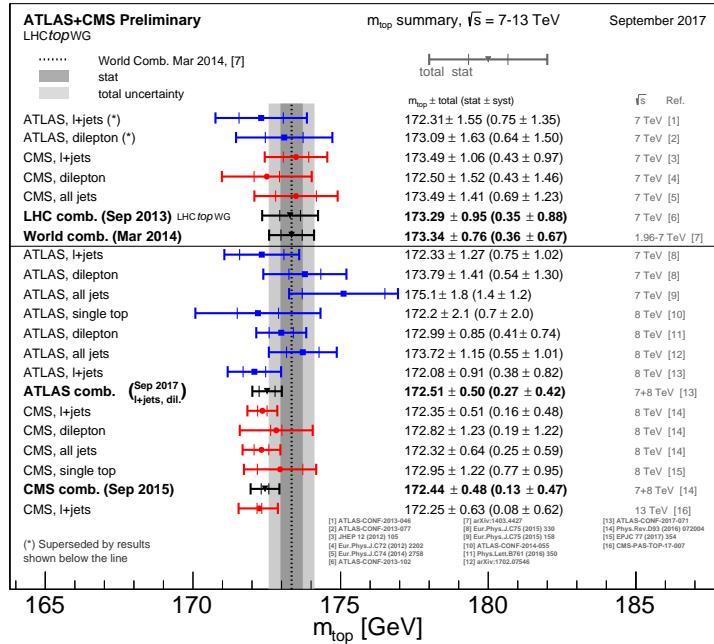


Figure 1.5: Summary of the top mass direct measurements performed by CMS and ATLAS, and compared with the LHC and LHC+Tevatron combinations. The results below the line are produced after the LHC and LHC+Tevatron combinations. Figure taken from [18].

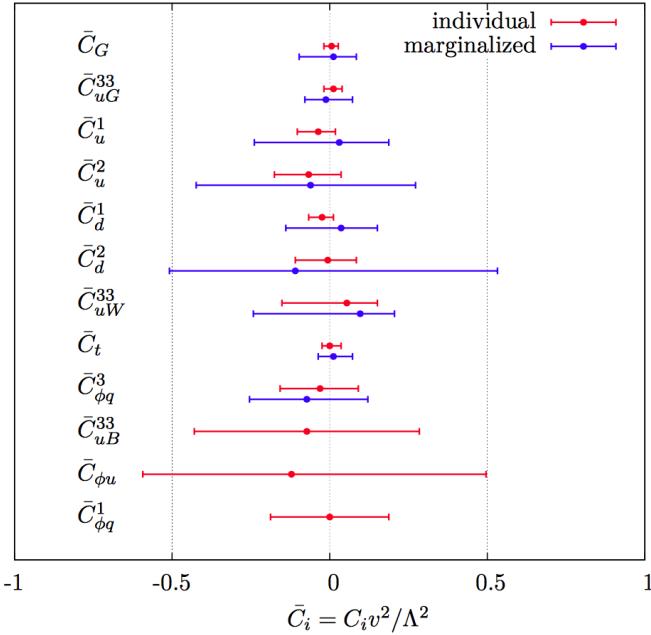


Figure 1.6: Global fit results of top quark effective field theory to experimental data including all constrained operators at dimension six. For the operators, the Warsaw basis of [19] is used. The bounds are set on the Wilson coefficients of various operators contributing to top quark production and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

223 1.6 Why to look beyond the SM

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

232 In the SM, the neutrino is assumed to be massless, whilst experiments with solar, atmospheric,
 233 reactor and accelerator neutrinos have established that neutrinos can oscillate and change
 234 flavour during flight [21, 22]. These oscillations are only possible when neutrino's have masses.
 235 The flavour neutrinos (ν_e , ν_μ , ν_τ) are then linear expressions of the fields of at least three mass
 236 eigenstate neutrinos ν_1 , ν_2 , and ν_3 .

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

246 At the Big Bang matter and antimatter is assumed to be produced in equal quantities. However,
 247 it is clear that we are surrounded by matter. So where did all the antimatter go? In 1967,
 248 Sakharov identified three mechanisms that are necessary to obtain a global matter antimatter
 249 asymmetry [25]. These mechanisms are those of baryon and lepton number violation, that at a
 250 given moment in time there was a thermal imbalance for the interactions in the universe, and
 251 there is charge C and charge parity CP violation³.

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

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

³The 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.

261 proportional to the ultraviolet momentum cut-off Λ_{UV} . This cut-off is at least equal to the energy
 262 to which the SM is valid without the need of new physics. The SM is valid up to the Planck mass
 263 making the correction to m_H^2 about thirty orders of magnitude larger than m_H^2 . This implies that
 264 an extraordinary cancellation of terms should happen. This is also known as the naturalness
 265 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 ϕ with a coupling λ_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

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

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

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

276 1.7 An effective approach beyond the SM: FCNC involving a top 277 quark

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

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

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

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

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

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

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

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where the value of the FCNC couplings at scale Λ are represented by $\kappa_{tZq}, \kappa_{gqt}, \kappa_{t\gamma q}, \zeta_{tZq}$, and η_{Hqt} . These are assumed to be real and positive, with the unit of GeV^{-1} for κ_{tXq}/Λ and no unit for ζ_{xqt} and η_{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 θ_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_μ , the gluon field $G_\mu^{1\dots 8}$, and the Z boson Z_μ^0 are defined as

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

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

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293 **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}

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

294 where $\Gamma_{t \rightarrow qX}$ represents the FCNC decay width⁴ for a coupling strength $\delta_{txq}^2 = 1$, and Γ_t the full 295 decay width of the top quark. In the SM, supposing a top quark mass of 172.5 GeV, the full 296 width becomes $\Gamma_t^{\text{SM}} = 1.32$ GeV [41].

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

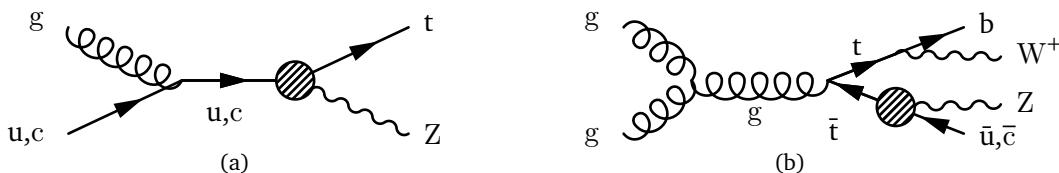


Figure 1.7: Feynman diagrams for the tZq FCNC interaction, where the FCNC interaction is indicated with the shaded dot. (a) Single top production through an FCNC interaction. (b) Top pair production with an FCNC induced decay.

301

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

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⁴The 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	
$t \rightarrow uZ$	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]

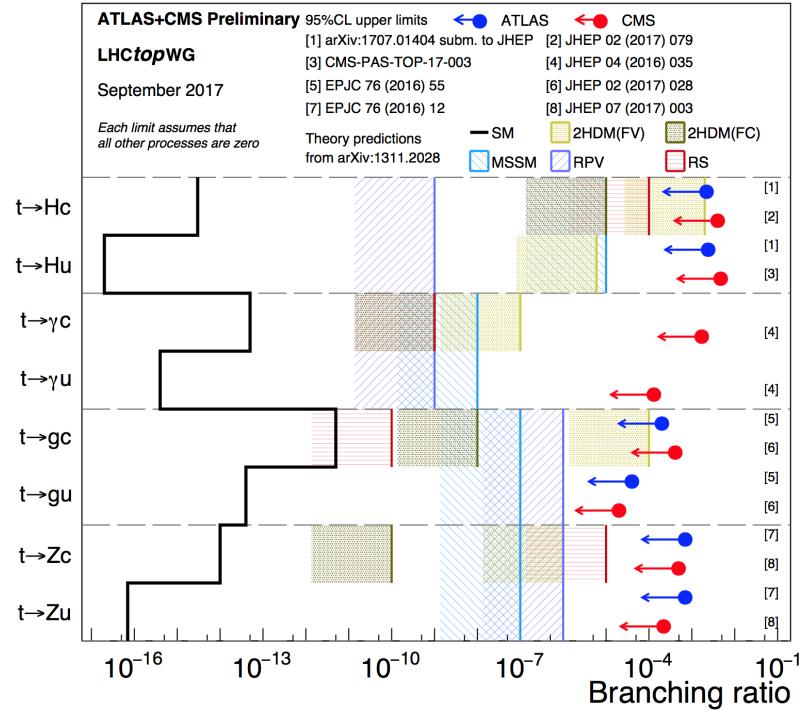


Figure 1.8: Current best limits set by CMS and ATLAS for top-FCNC interactions. Figure taken from [17].

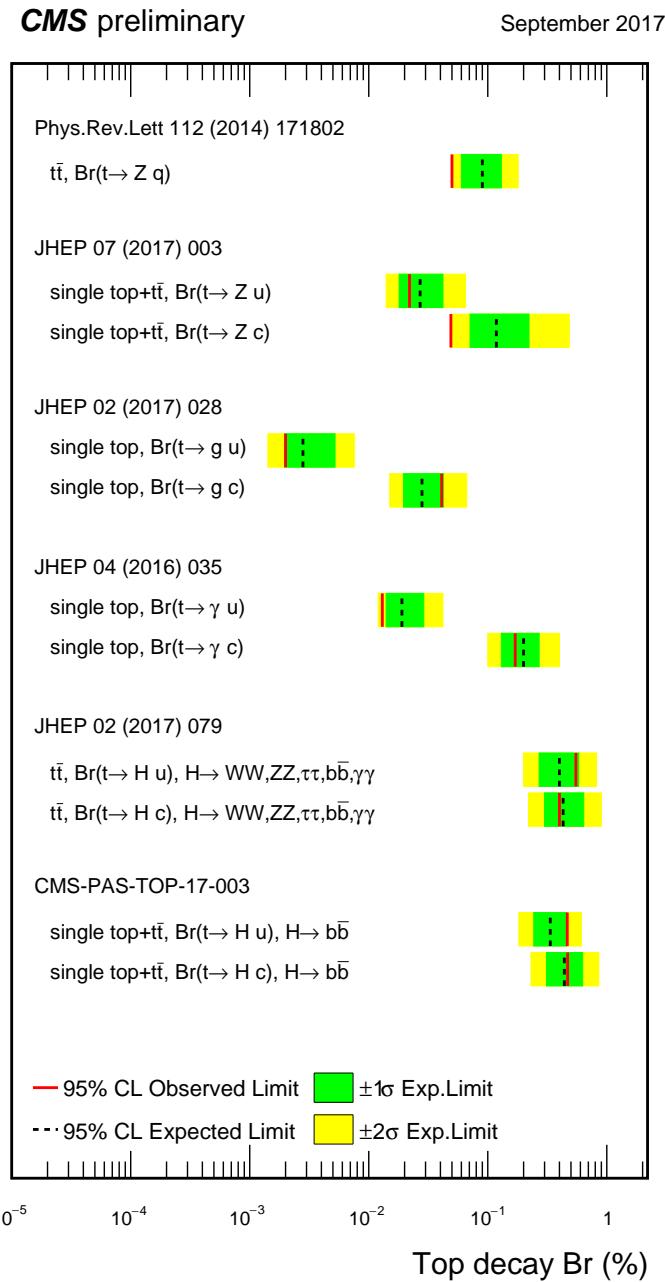


Figure 1.9: Summary of the FCNC branching ratios from CMS searches at 8 TeV. Figure taken from [17].

Experimental set-up

2

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

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

325 2.1 The Large Hadron Collider

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

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

337 accelerated to 1.4 GeV and each pack is split up in twelve bunches with 25 ns spacing for Run 2
 338 (50 ns for Run 1). The proton synchrotron (PS) then increases their energy to 25 GeV before the
 339 super proton synchrotron (SPS) increases the proton energy up to 450 GeV. Each accelerator
 340 ring expands in radius in order to reduce the energy loss of the protons by synchrotron radiation¹
 341 Furthermore, the magnets responsible for the bending of the proton trajectories have to be
 342 strong enough to sustain to higher proton energy. Ultimately, the protons are injected into
 343 opposite directions into the LHC, where they are accelerated to 3.5 TeV (in 2010 and 2011),
 344 4 TeV (in 2012 and 2013) or 6.5 TeV (in 2015 and 2016) [49]. Before the start of the LHC
 345 in 2010, the previous energy record was held by the Tevatron collider at Fermilab, colliding
 346 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).

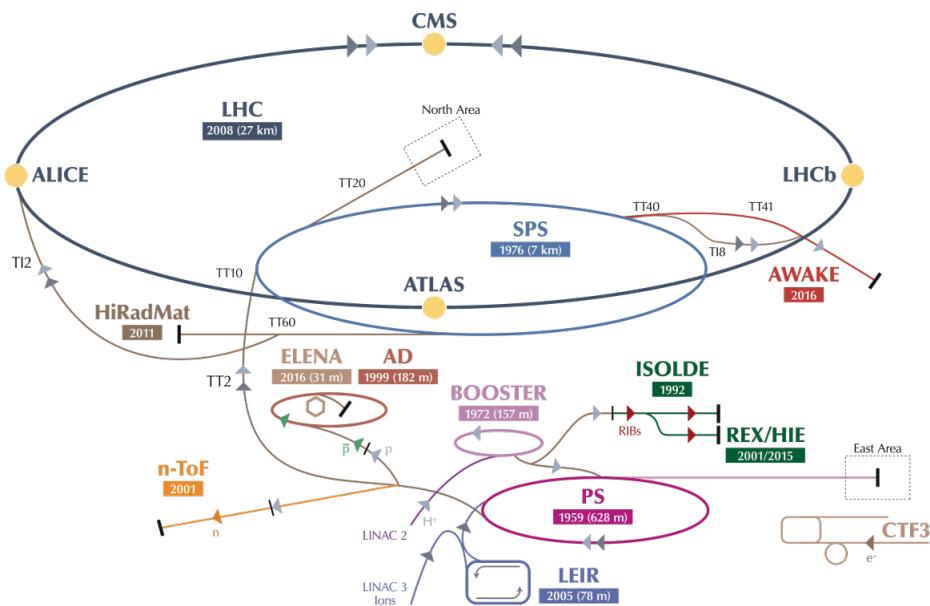


Figure 2.1: Schematic representation of the accelerator complex at CERN [50]. The LHC (dark blue) is the last element in chain of accelerators. Protons are successively accelerated by LINAC 2, the Booster, the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) before entering the LHC.

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

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

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

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

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

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

377 The number of particles per bunch is expressed by N_b , while n_b is the number of bunches
 378 per beam, f_{rev} the revolution frequency, γ_r the relativistic gamma factor, ϵ_n the normalized
 379 transverse beam emittance - a quality for the confinement of the beam , β^* the beta function at
 380 the collision point - a measurement for the width of the beam, θ_c the angle between two beams
 381 at the interaction point, σ_z the mean length of one bunch, and σ^* the mean height of one bunch.

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

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

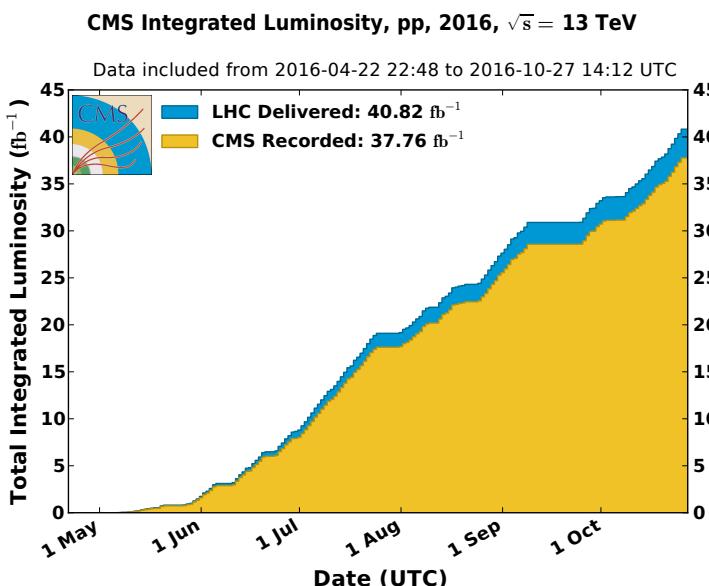


Figure 2.2: Cumulative offline luminosity measured versus day delivered to (blue), and recorded by CMS (orange) during stable beams and for proton collisions at 13 TeV centre-of-mass energy in 2016. The delivered luminosity accounts for the luminosity delivered from the start of stable beams until the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

392

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

398 2.2 The Compact Muon Solenoid

399 At one of the collision points of the LHC, the CMS detector[62–64] is placed. Weighing 14 000 t,
 400 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 energy² were kept into account while designing CMS. In Figure 2.3, an overview of the CMS detector is shown.

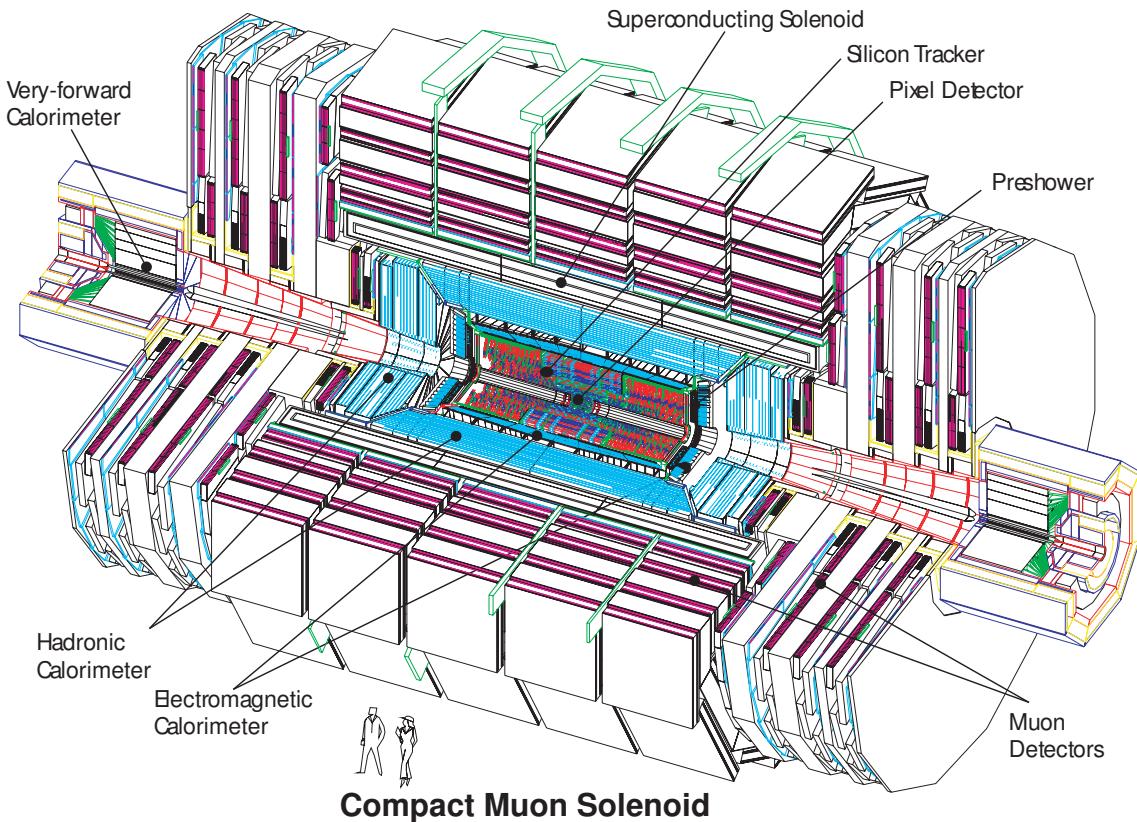


Figure 2.3: Mechanical layout of the CMS detector. Figure taken from [65].

410

411 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

²The 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 angle³ $\phi \in [-\pi, \pi]$, the pseudo-rapidity⁴ η :

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

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

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

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

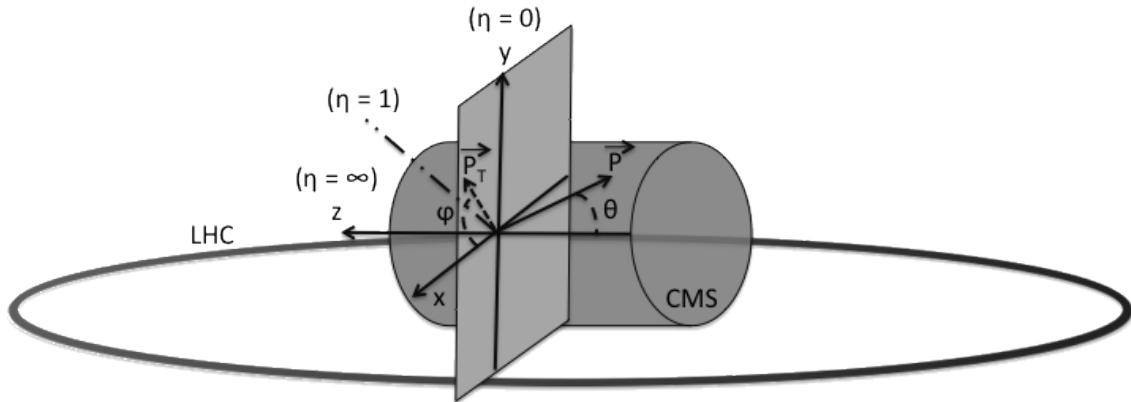


Figure 2.4: Representation of the coordinate system used by CMS. The point of origin is put at the collision point. The x-axis points towards the centre of the LHC ring such that the z-axis lies tangent to the beam axis.

- 413

414 2.2.2 Towards the heart of CMS

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

³The 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 .

⁴The pseudo rapidity is expressed by the polar angle θ between the direction of \vec{p} and the beam.

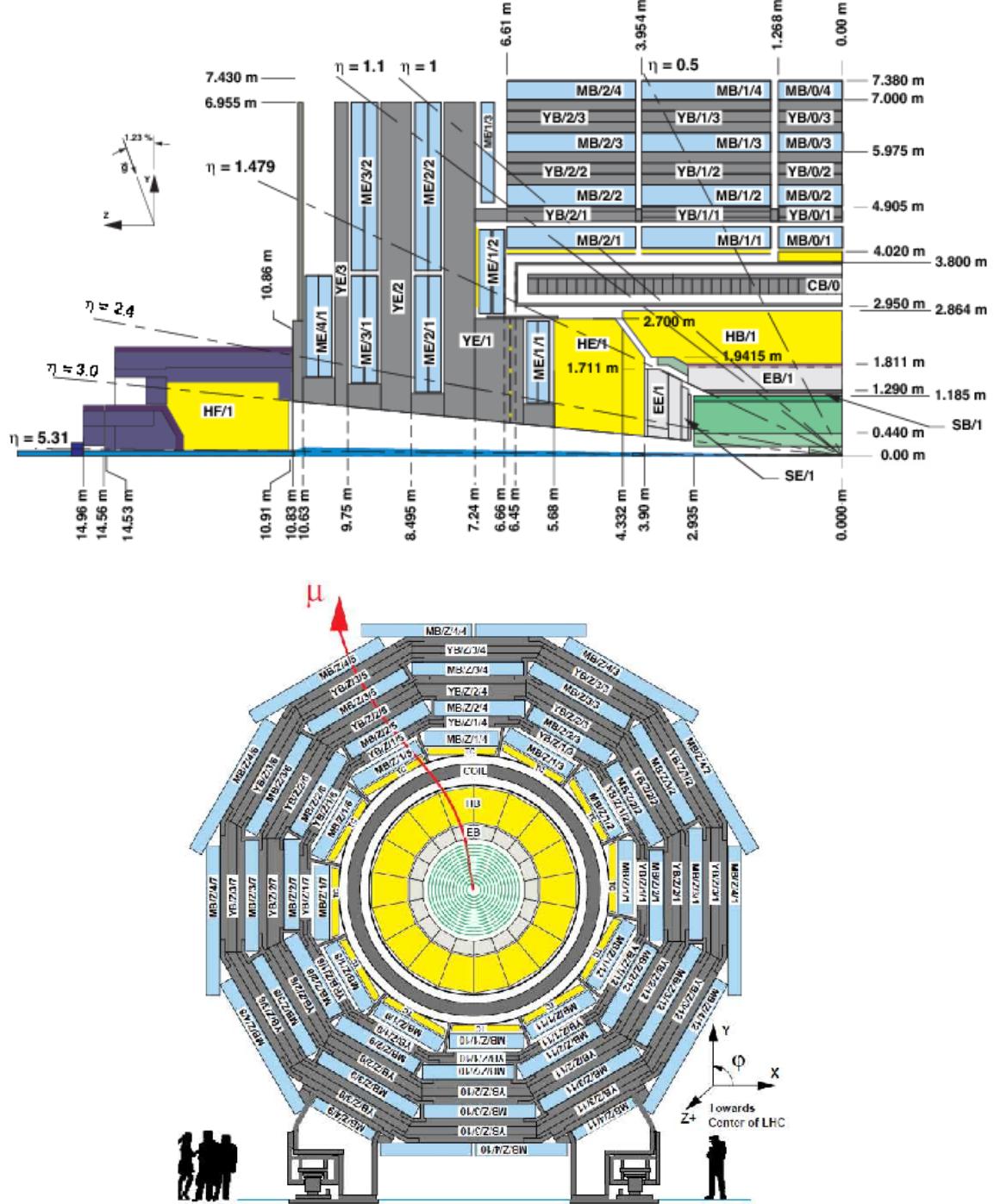


Figure 2.5: Schematic view of the CMS detector in the Run 1 configuration. The longitudinal view of one quarter of the detector is given on top, while the transversal view is shown on the bottom. The muon system barrel elements are denoted as MBZ/N/S, where $z = -2 \dots +2$ is the barrel wheel number, $n = 1 \dots 4$ 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].

425 **2.2.2.1 Muon system**

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

431 The muon system is divided into three parts, shown in Figure 2.6. The muon rate and neutron
 432 induced backgrounds are small and the magnetic field is very low for the barrel, thus CMS can
 433 use drift tube (DT) chambers. For the end caps however, the muon and background flux is much
 434 higher and there is a need to use cathode strip chambers (CSC) which are able to provide a
 435 faster response, higher granularity and have a better resistance against radiation. In order to
 436 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.

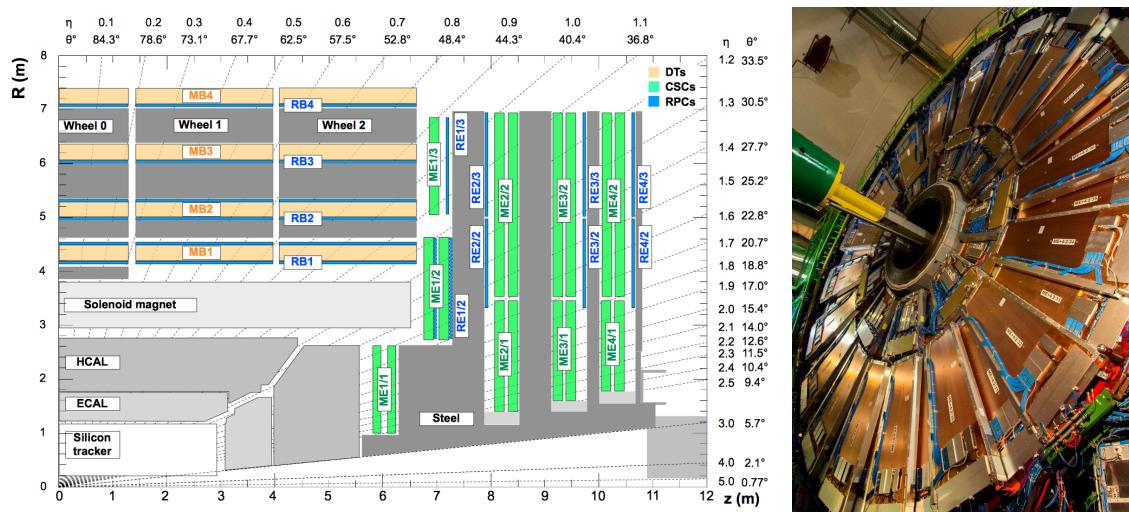


Figure 2.6: (Left) Schematic view of one quarter of the CMS muon system in the Run 1 configuration. The cathode strip chambers (CSC) are shown in green, the drift tubes (DT) are shown in yellow, while the resistive plate chambers (RPC) are shown in blue. Figure taken from [66]. (Right) Cathode strip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

437

438 Providing a measurement for $|\eta| < 1.2$, the DT chambers in the barrel are on average
 439 $2 \times 2.5 \text{ m}^2$ in size and consist of 12 layers of DT cells⁵ arranged in three groups of four. The
 440 $r\phi$ coordinate is provided by the two outside groups, while the middle group measures the
 441 z coordinate. For the outer muon station, the DT chambers contain only 8 layers of DT cells,
 442 providing a muon position in the $r\phi$ plane. There are four CSC stations in each end cap, providing
 443 muon measurements for $0.9 < |\eta| < 2.4$ (Run 1 configuration). These CSCs are multi-wired
 444 proportional chambers that consist of 6 anode wire planes crossed by 7 copper strips cathode
 445 panels in a gas volume. The r coordinate is provided by the copper strips, while the ϕ coordinate
 446 comes from the anode wires, giving a two dimensional position measurement. There are six

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

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

452 The muon system provides triggering on muons, identifying muons and improves the momen-
 453 tum measurement and charge determination of high p_T muons. On top of the muon system,
 454 the muon energy is deposited in the electromagnetic calorimeter, the hadronic calorimeter, and
 455 outer calorimeter. The high magnetic field enables an efficient first level trigger and allows a
 456 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.
 457 There is an efficient muon measurement up to $|\eta| < 2.4$.

NOTE:
check numbers for run
2

458 2.2.2.2 Solenoid

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

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

470 2.2.2.3 Hadronic calorimeter

471 The hadronic calorimeter (HCAL) is dedicated to precisely measure the energy of charged and
 472 neutral hadrons via a succession of absorbers and scintillators. This makes it crucial for physics
 473 analyses with hadronic jets or missing transverse energy. The HCAL barrel extends between
 474 $1.77 < r < 2.95$ m, where r is the radius in the transverse plane with respect to the beam. Due
 475 to space limitations, the HCAL needs to be as small as possible and is made from materials
 476 with short interaction lengths⁶. On top of this, the HCAL should be as hermetic as possible and
 477 extend to large absolute pseudo rapidities such that it can proved a good measurement of the
 478 missing transverse energy.

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

⁶Here 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.

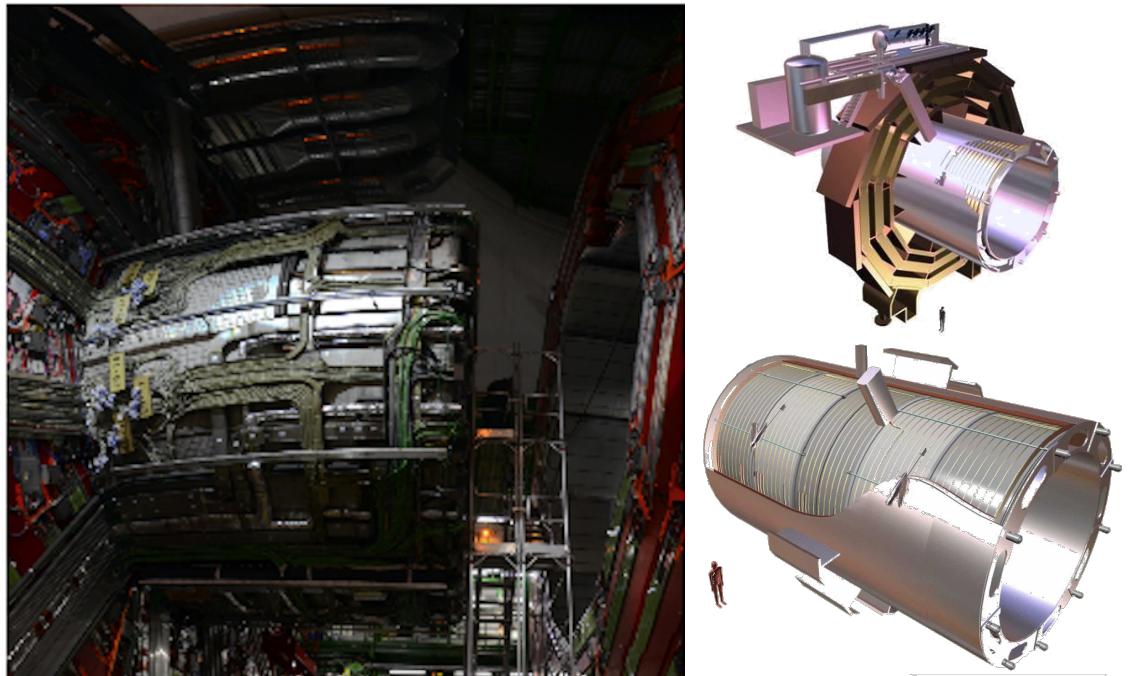


Figure 2.7: (Left) CMS solenoid during the long shutdown in 2013. (Right) An impression of the solenoid magnet taken from [68].

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

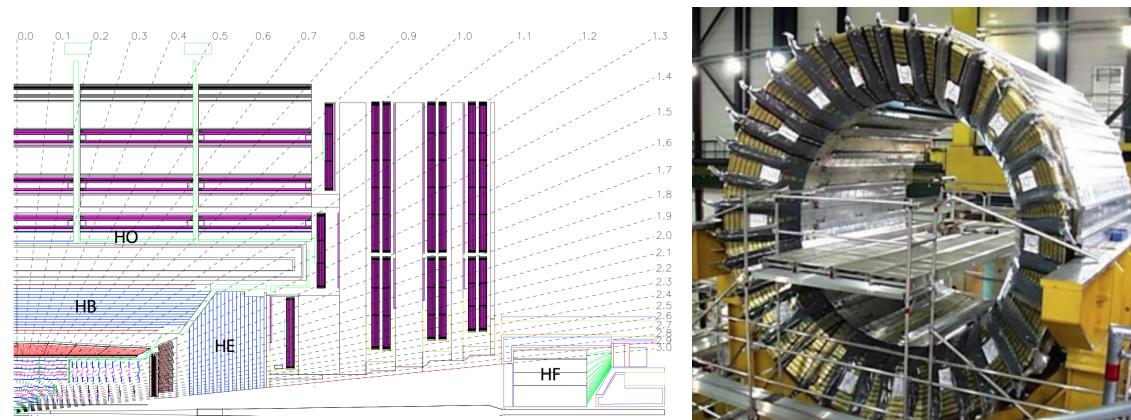


Figure 2.8: (Left) Longitudinal view of the CMS detector showing the locations of the HB, HE, HO, and HF calorimeters. Figure taken from [53]. (Right) CMS barrel calorimeter. Photo taken from [69].

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

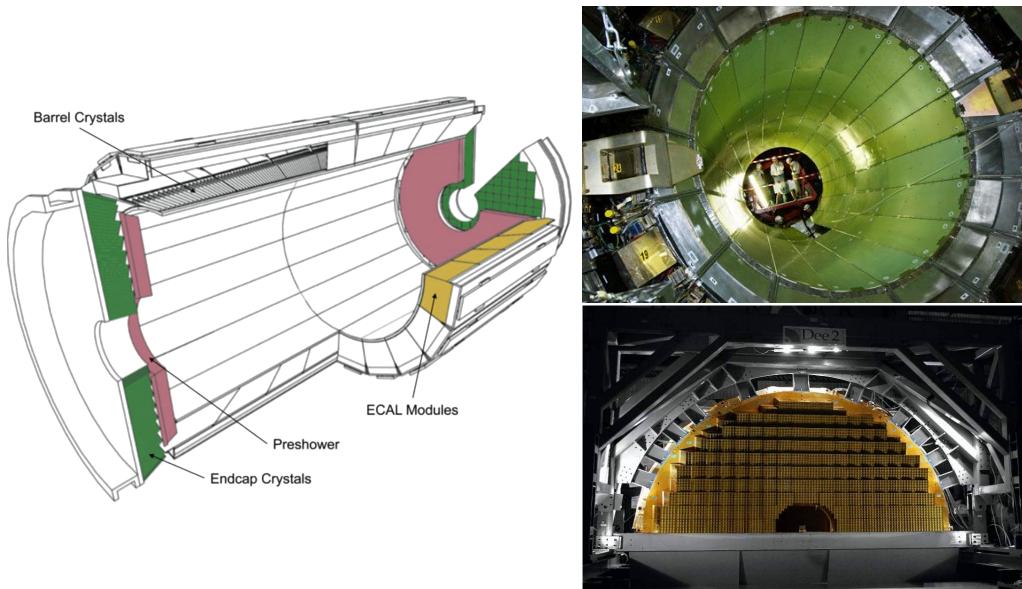


Figure 2.9: (Left) Schematic cross section of the electromagnetic calorimeter taken from [53]. (Right top) The ECAL barrel during construction [71]. (Right bottom) One half of an EE [72].

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 $1.479 <$

513 $|\eta| < 3.0$, are the EE. They consist of semi-circular aluminium plates from which structural
 514 units of 5×5 crystals (super crystals) are supported. The ES is placed in front of the crystal
 515 calorimeter over the end cap pseudo rapidity range with two planes of silicon strip detectors as
 516 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 5×5 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 ϕ and 10^{-3} in η . For the end caps this is 5.10^{-3} rad in ϕ and 2.10^{-3} in η . The energy is reconstructed by a supercluster algorithm, taking into account energy radiated via bremsstrahlung or conversion [53]. The energy resolution is given by

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

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

520 2.2.2.5 Inner tracking system and operations

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

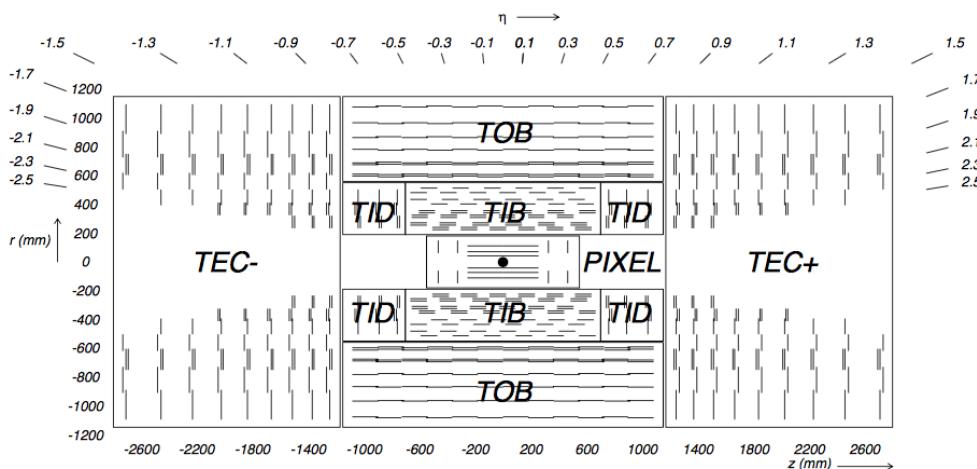


Figure 2.10: Schematic cross section through the CMS tracker. Each line represents a detector module. Double lines indicate back-to-back modules that deliver stereo hits. Figure taken from [53].

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

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

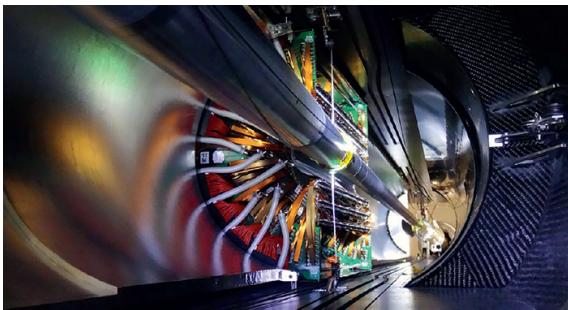


Figure 2.11: The pixel barrel being re-installed after the Long Shutdown in 2015, around the beam pipe at CMS [75].



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

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

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

560 channels and covers an active area of about 198 m^2 .

561 2.2.3 Data acquisition

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

568 CMS Level-1 Trigger

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

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

582 CMS HLT Trigger

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

588 2.2.4 Phase 1 upgrades

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

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

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

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

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

616 where T is the operating temperature, E_g the band gap and k the Boltzmann constant. There is
 617 approximately a factor 15 between the leakage currents at room temperatures and at -10°C .

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

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

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

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

637 **2.2.5 CMS computing model**

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

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

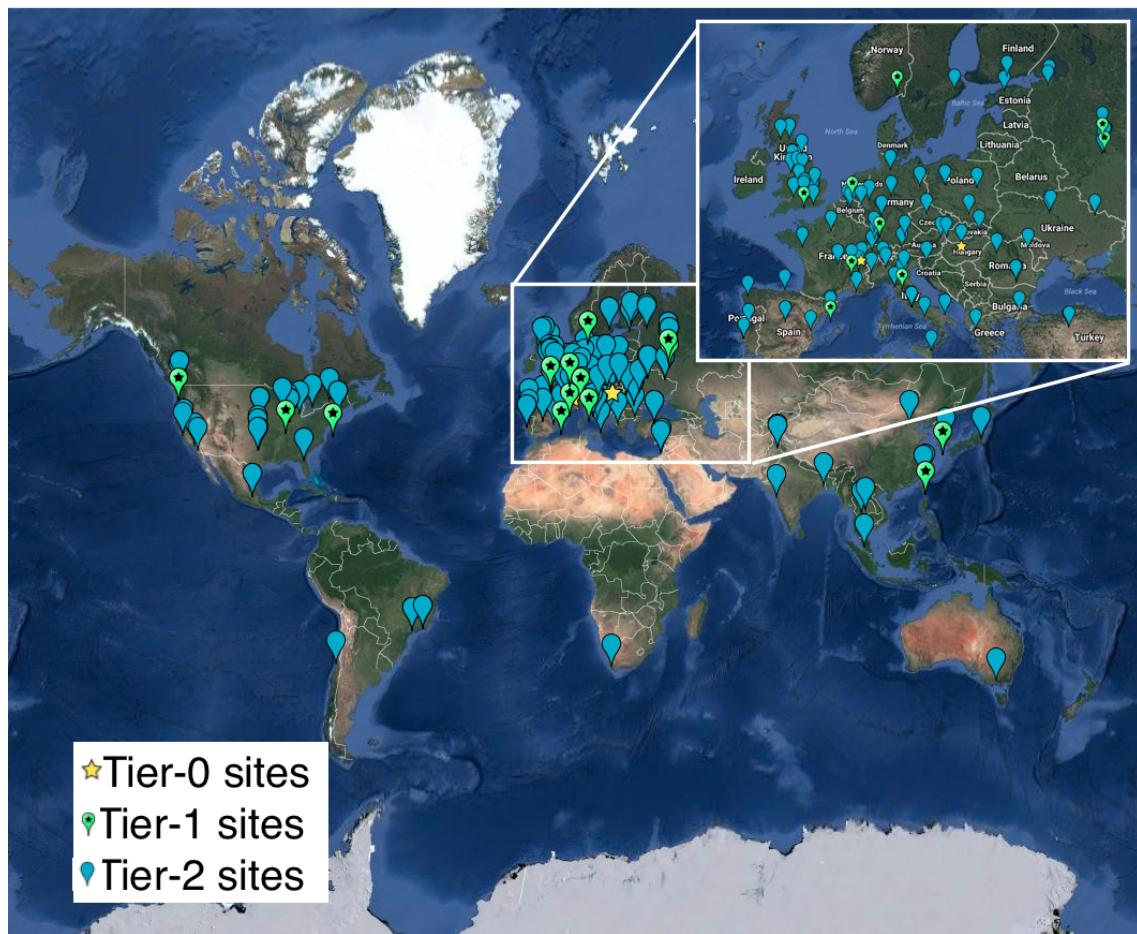


Figure 2.13: Worldwide LHC Computing Grid in 2017 [88].

Analysis techniques

3

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

657 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]

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

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

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

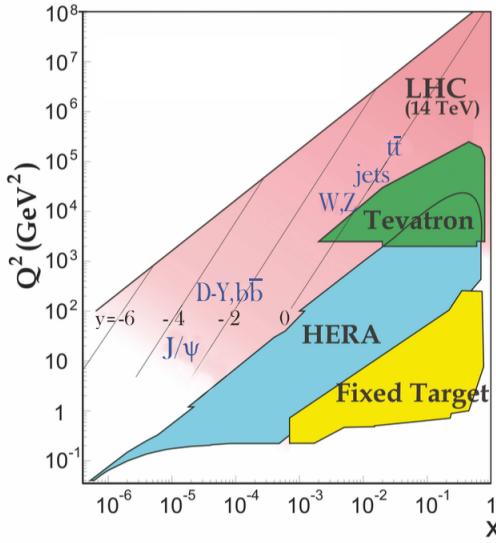


Figure 3.1: Kinematic regions in momentum fraction x and factorisation scale Q^2 probed by fixed-target and collider experiments. Some of the final states accessible at the LHC are indicated in the appropriate regions, where y is the rapidity. In this figure, the incoming partons have $x_{1,2} = (M/14\text{TeV})e^{\pm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

666 deep inelastic scattering using lepton-proton collision by the HERA collider [93], supplemented
 667 with proton-antiproton collisions from Tevatron at Fermi lab [94], and proton collision data
 668 from the ATLAS, CMS and LHCb collaborations at the LHC (Run 1) [95]. These measurements
 669 are included in global PDF sets known as the PDF4LHC recommendation [92]. From their mea-
 670 surement at scale μ_F these PDFs can be extrapolated using the DGLAP equations [96]. The PDFs
 671 are used to calculate the cross section of a certain process and are therefore used as input for the
 672 Monte Carlo generators used to make the simulated data samples at the LHC. In the framework
 673 of this thesis, the NLO PDF4LHC15_100 set is used. This set is an envelope of three sets, CT14,
 674 MMHT2014 and NNPDF3.0 [92]. In Figure 3.2 the dependency of the PDFs on the momentum
 675 fraction x is shown for the NNPDF3.0 set on hadronic scale ($\mu_F^2 = (10\text{GeV})^2$) and LHC scale
 676 ($\mu_F^2 = (10^4\text{GeV})^2$). For most values of the momentum fraction, the gluon density dominates,
 677 meaning that it is easier to probe muons than the quarks. For x close to one, the parton densities
 678 of the up and down quarks (the valence quarks of the proton) dominate over the gluon density.
 679 The charm, anti-up, and anti-down quarks have lower densities in general since those are sea
 680 quarks which originate in the proton only through gluon splitting. The resolution scale Q^2 is
 681 typically taken to be the energy scale of the collision. For the top quark pair production a scale
 682 of $Q^2 = (350\text{GeV})^2$ is chosen, meaning that the centre-of-mass energy of the hard interaction is
 683 about twice the top quark mass. The uncertainty on the parton distributions is evaluated using
 684 the Hessian technique [97], where a matrix with a dimension identical to the number of free
 685 parameters needs to be diagonalised. In the case of PDF4LHC15_100 set, this translates into
 686 100 orthonormal eigenvectors and 200 variations of the PDF parameters in the plus and minus
 687 direction.

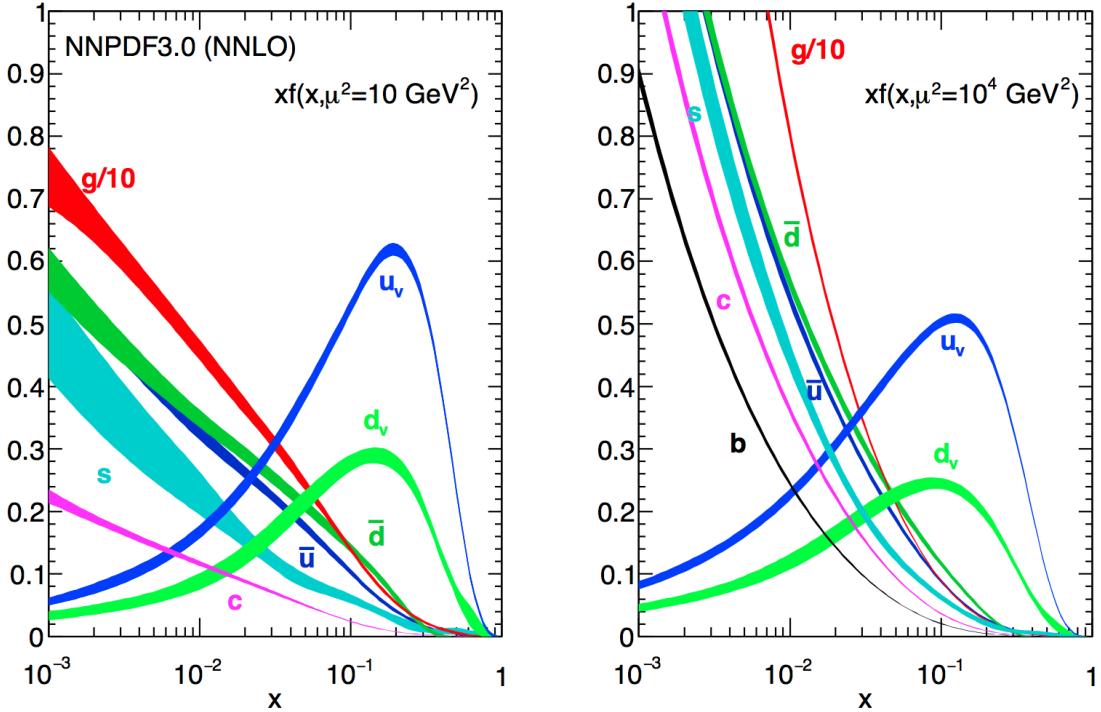


Figure 3.2: The momentum fraction x times the parton distribution functions $f(x)$, where $f = u_v, d_v, \bar{u}, \bar{d}, s, c$, or g as function of the momentum fraction obtained in the NNLO NNPDF3.0 global analysis at factorisation scales $\mu^2 = 10 \text{ GeV}^2$ (left) and $\mu^2 = 10^4 \text{ GeV}^2$ (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 μ_R is used to redefine physical quantities. A consequence of this method is that the coupling constants will run as function of μ_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 constant¹ α_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 μ_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 α_s becomes larger than one. Under this limit, the perturbative calculations of observables can no longer be done.

¹The 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 α

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

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

699 3.2 Event generation

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

705 3.2.1 Fundamentals of simulating a proton collision

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

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

NOTE: Should I add more details?

722 3.2.2 Programs for event generation

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

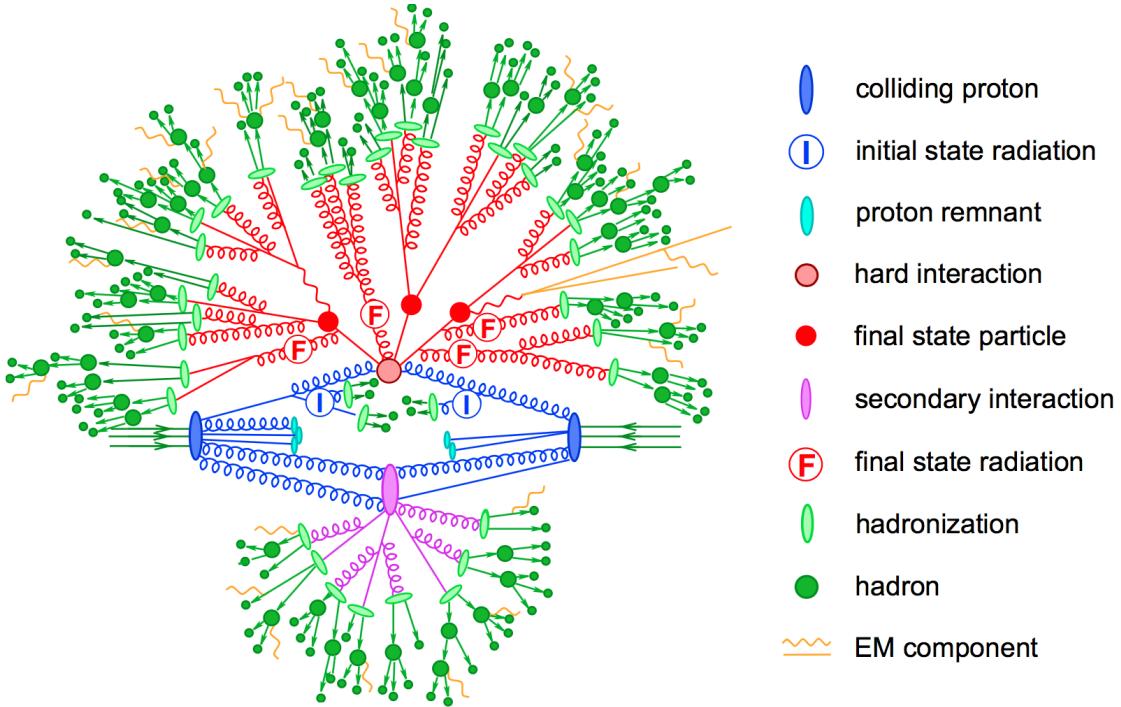


Figure 3.3: Sketch of a hadron collision as simulated by a Monte-Carlo event generator. The red blob in the centre represents the hard collision, surrounded by a tree-like structure representing Bremsstrahlung as simulated by parton showers. The purple blob indicates a secondary hard scattering event. 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].

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

731 The MadGraph5_aMC@NLO program [113] combines the LO MadGraph [107] and the aMC@NLO
 732 program into a common framework. This combination supports the generation of samples
 733 at LO or NLO together with a dedicated matching to parton showers using the MLM [112]
 734 or FXFX [114] schemes respectively. The FXFX scheme produces a certain fraction of events
 735 with negative weights originating from the subtraction of amplitudes that contain additional
 736 emissions from the NLO matrix element to prevent double-counting.

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

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

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

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

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

761 3.2.3 Generating FCNC top-Z interactions

762 The FCNC processes are generated by interfacing the Lagrangian in [Equation 1.25](#) with
 763 MadGraph5_aMC@NLO by means of the FeynRules package and its Universal FeynRules
 NOTE: When
 RH and not LH?
 764 Output format. The complex chiral parameters are arbitrary chosen to be $f_{Xq}^L = 0$ and $f_{Xq}^R = 1$.
 765 The signal rates are estimated by use of the MadGraph5_aMC@NLO program for estimating the
 766 partial widths. The anomalous couplings are left free to float for this estimation, and only one
 767 coupling allowed to be non-vanishing at a time. The results are presented in [Table 3.1](#).

768 The anomalous single top cross sections are calculated by convolution of the hard scattering
 769 matrix elements with the NLO order set of CTEQ6 partons densities [127]. The NLO effects are
 770 modelled by multiplying each LO cross section by a global k -factor. The LO single top production
 771 cross section and the global k -factors for the top-Z production are shown in [Table 3.2](#). The hard
 772 scattering events are then matched to parton showers to Pythia to account for the simulation
 773 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: 774
 these par-
 tial widths
 are at LO,
 how does
 this relate
 to NLO that
 is used? Or
 is there no
 difference?

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 Λ is given in GeV.

Anomalous coupling	vertex	Partial decay width (GeV)	
κ_{gqt}/Λ	$t g u$	$3.665220 \cdot 10^5$	$(\kappa_{tg u}/\Lambda)^2$
	$t g c$	$3.664620 \cdot 10^5$	$(\kappa_{tg c}/\Lambda)^2$
$\kappa_{t\gamma q}/\Lambda$	$t\gamma u$	$1.989066 \cdot 10^4$	$(\kappa_{t\gamma u}/\Lambda)^2$
	$t\gamma c$	$1.988904 \cdot 10^4$	$(\kappa_{t\gamma c}/\Lambda)^2$
κ_{tZq}/Λ	$tZ u$	$1.637005 \cdot 10^4$	$(\kappa_{tZ u}/\Lambda)^2$
	$tZ c$	$1.636554 \cdot 10^4$	$(\kappa_{tZ c}/\Lambda)^2$
ζ_{tZq}	$tZ u$	$1.685134 \cdot 10^{-1}$	$(\zeta_{tZ u})^2$
	$tZ c$	$1.684904 \cdot 10^{-1}$	$(\zeta_{tZ c})^2$
η_{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)
κ_{tZu}/Λ	$t\bar{t} \rightarrow (b\ell^+\nu)(\bar{u}\ell^+\ell^-)$	$2.727008 \cdot 10^5 \left(\kappa_{tZu}/\Lambda\right)^2$
	$t\bar{t} \rightarrow (\bar{b}\ell^-\bar{\nu})(u\ell^+\ell^-)$	$2.727008 \cdot 10^5 \left(\kappa_{tZu}/\Lambda\right)^2$
κ_{tZc}/Λ	$t\bar{t} \rightarrow (b\ell^+\nu)(\bar{c}\ell^+\ell^-)$	$2.726257 \cdot 10^5 \left(\kappa_{tZc}/\Lambda\right)^2$
	$t\bar{t} \rightarrow (\bar{b}\ell^-\bar{\nu})(c\ell^+\ell^-)$	$2.726257 \cdot 10^5 \left(\kappa_{tZc}/\Lambda\right)^2$
ζ_{tZu}	$t\bar{t} \rightarrow (b\ell^+\nu)(\bar{u}\ell^+\ell^-)$	$2.827184 \left(\zeta_{tZu}\right)^2$
	$t\bar{t} \rightarrow (\bar{b}\ell^-\bar{\nu})(u\ell^+\ell^-)$	$2.827184 \left(\zeta_{tZu}\right)^2$
ζ_{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 ± 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 ± 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 $10 \text{ GeV} < m_{\ell\ell} < 50 \text{ GeV}$	MadGraph+Pythia	18610	-

784 3.3 Multivariate analysis techniques: Boosted Decision Trees

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

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

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

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

806 where p denotes the purity of a selection $x > C$. This is repeated until the maximum of nodes is
 807 reached and at the end of the sequence, the leaf nodes are labelled either signal S or background
 808 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

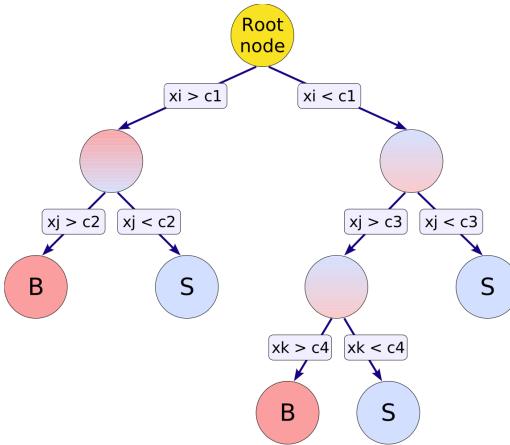


Figure 3.4: Schematic view of a decision tree. Figure taken from [129].

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 ϵ_n denotes the misclassification error of the current tree n and β 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

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

832 The discriminating power of a BDT is assessed by analysing the receiver operating characteristic
 833 (ROC) curve. These curves show the background rejection over the signal efficiency of the
 834 remaining sample. By looking at the area under the curve with respect to random guessing
 835 (AUC), the best classifier can be identified. This follows the Neyman-Pearson lemma that
 836 the best ROC curve is given by the likelihood ratio $\mathcal{L}(x|Signal)/\mathcal{L}(x|Background)$ [132]. No
 837 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.

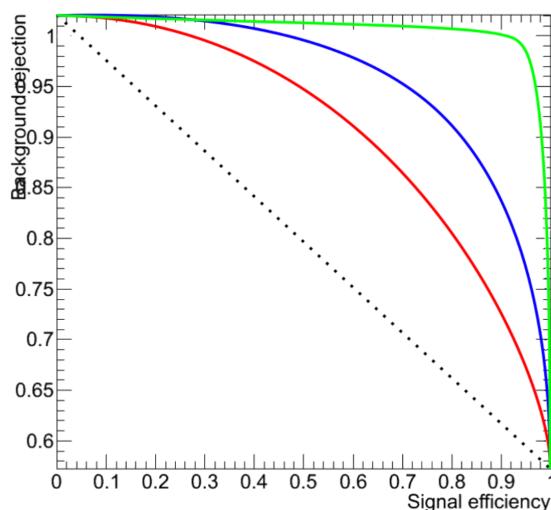


Figure 3.5: Example of ROC curves. In this example, the green method is better than the red one, which is better than the blue one. The dashed line represents a case where there is no separation. Figure taken from [133].

838

839 3.4 Statistical methodology

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

847 In general the event yields of signal and background processes are denoted as s and b
 848 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 θ 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 μ . 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_μ 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 μ 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 μ .

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_μ^{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

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

where p_μ and p_b are called the p-values associated to the two hypothesis, and $f(q_\mu | \mu, \hat{\theta}_\mu^{\text{obs}})$ and $f(q_\mu | \mu = 0, \hat{\theta}_{\mu=0}^{\text{obs}})$ 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 μ is achieved by adjusting μ until $\text{CL} = 0.05$

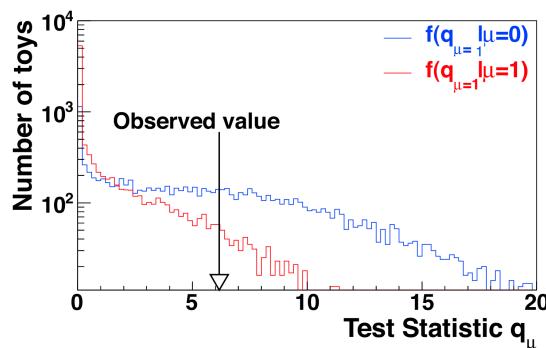


Figure 3.6: Test statistic distributions for pseudo data generated for the signal plus background ($\mu = 1$) and background only ($\mu = 0$) hypothesis. Figure taken from [137].

879

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

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

886 3.4.2 Adding sources of uncertainty

887 In this thesis, all sources of uncertainties are assumed to be either 100% correlated or uncor-
 888 related. Partially correlated uncertainties are broken down to subcomponents that fit those
 889 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 θ with nominal value $\tilde{\theta}$ is used. It reflects the degree of belief of what the true value of the θ 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 $\tilde{\theta}$

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

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

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

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

898 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 κ 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 α , the predicted rate follows

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

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

901 3.4.3 Asymptotic approximation of the CL method

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

907 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

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

908 is called the best-fit set.

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

Event reconstruction and selection

4

912

913 After the detector simulation described in [Section 3.2](#), the simulated data has the exact same
914 format as the real collision data recorded at the CMS experiment. Therefore the same software
915 can be used for the reconstruction of both simulation and real data. In [Section 4.1](#), the object
916 reconstruction for physics analysis is shown. After reconstructing the objects, the objects are
917 connected to physics objects need to be identified. This identification is explained in [Section 4.2](#).
918 A basic event selection is made for selecting signal like events. The necessary event requirement
919 are discussed in [Section 4.6](#).

920 The analysis uses signal and background regions to constrain the huge SM background
921 compared to the expected signal. [Section 4.7](#) discusses each region that is entering the analysis.
922 On top of the use of background estimation from control regions, backgrounds that have prompt
923 leptons contaminated by real leptons either from decays of tau leptons or from hadronized
924 mesons or baryons (collectively commonly referred as “non-prompt leptons”) as well as by
925 hadrons or jets misidentified as leptons¹ are evaluated with a data-driven method discussed in
926 [Section 4.8](#).

927 4.1 Object Reconstruction

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

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

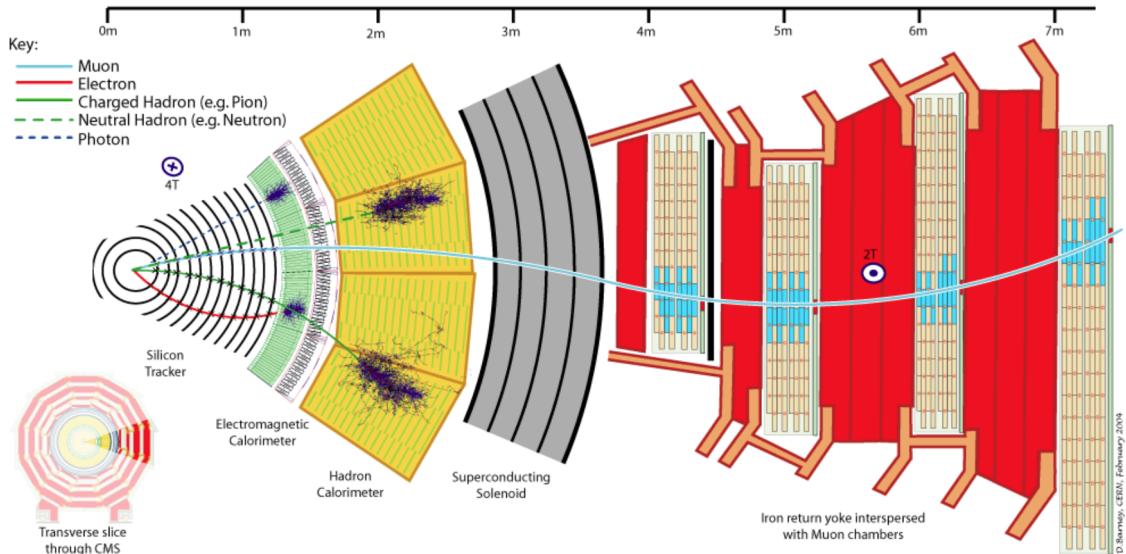


Figure 4.1: Cross-section of the CMS detector with all parts of the detector labelled. This sketch shows the specific particle interactions from a beam interaction reign to the muon detector. The muon and charged pion are positively charged, the electron is negatively charged. Figure taken from [144].

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

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

963 **4.1.1 Charged particle tracks**

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

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

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

992 **4.1.2 Following the Muon's Footsteps**

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

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

1003 The second approach is an inside-out reconstruction, creating tracker muons. All candidate
 1004 tracker tracks with a $p_T > 0.5$ GeV and total momentum $p > 2.5$ GeV are extrapolated to the
 1005 muon system taking into account the magnetic field, the average expected energy losses, and
 1006 multiple Coulomb scattering in the detector material. The extrapolated track and the muon
 1007 segments are considered matched when the difference in the position in the x coordinates is
 1008 smaller than 3 cm, or when the ratio of this distance to its uncertainty is smaller than four. When
 1009 at least one muon segment - DT or CSC hits - matches the extrapolated track, the corresponding
 1010 tracker track is indicated as a tracker muon.

1011 For low transverse momenta ($p_T \lesssim 5$ GeV), the tracker muon reconstruction is more efficient
 1012 than the global muon approach. This is due to the fact that tracker muons only require a
 1013 single muon segment in muon system, while the global muon approach requires typically
 1014 segments in at least two muon stations. These tracker muons are used for identifying muons
 1015 from the hadronisation of b or c quarks. The global muon approach typically improves the
 1016 tracker reconstruction for $p_T \gtrsim 200$ GeV. These are labelled isolated when in a cone of
 1017 $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.3$ around the muon, the sum of the transverse momenta of additional
 1018 tracker tracks and energy deposits in the calorimeter is less than 10% of the muon's transverse
 1019 momentum.

1020 4.1.3 The path of the Electron

1021 The electrons in CMS radiate more than 70% of their energy in the inner track through
 1022 bremsstrahlung before reaching the ECAL. This has as consequence that the electron tracks are
 1023 increasingly curved in the magnetic field as a function of its flight distance. Standard tracking
 1024 algorithms are based on Kalman filtering which assume that the energy loss is Gaussian dis-
 1025 tributed, and are therefore not suitable to fit the electron tracks. A different filtering algorithm,
 1026 the Gaussian sum filter (GSF) is used in the electron track reconstruction instead.

NOTE: [#1026](#)
source

1027 In CMS, the electrons are reconstructed in two ways. The older ECAL based tracking is
 1028 developed to identify high energy, isolated electrons. This tracking algorithm starts from ECAL
 1029 clusters with a transverse energy above 4 GeV and extrapolates from these cluster the position
 1030 of the hits in the tracker. In order to account for bremsstrahlung, neighbouring clusters in η
 1031 and ϕ are grouped together into a supercluster from which then the direction is determined
 1032 to find the position of the particles in the tracker. This has as consequence that for electrons
 1033 or positrons in jets, energy deposits of surrounding particles will be entering the supercluster
 1034 leading to a wrong position of the electron/positron in the tracker. Another disadvantage of the
 1035 ECAL based tracking is that for low p_T electrons, the trajectories will be very curved and the
 1036 supercluster will not contain all of the energy deposit, leading to a higher misconstruction rate.

1037 The faults of the ECAL based tracking are lifted by adding a tracker based algorithm. This
 1038 algorithm uses all the tracks with a p_T higher than 2 GeV found with iterative tracking as
 1039 seeds. Iterative tracking uses the Kalman Filter algorithm several times with an average track
 1040 reconstruction efficiency but high purity. In contrary with a global combinatorial fit, the iterative
 1041 tracking accepts tracks with a small transverse momentum that are not leaving any energy
 1042 in the ECAL, and tracks from particles that only interact with the inner tracker layers. When
 1043 the electron or positron radiated a small amount of energy, the corresponding track can be
 1044 reconstructed across the whole tracker and safely propagated to the ECAL surface. When there

1045 is a larger amount of energy radiated however, the pattern recognition might fail to accommodate
 1046 for the change in the electron momentum leading to a track reconstructed with a small number
 1047 of hits. The solution for this is a preselection based on the χ^2 and number of hits and the
 1048 selected tracks are fitted again with Gaussian-Sum-Filter which can accommodate substantial
 1049 energy losses across the trajectory.

1050 The electron seeds from the ECAL- and tracker-based procedures are merged into a unique
 1051 collection and are then refitted by using the summed Gaussian distributions as uncertainty per
 1052 hit in the track fit.

1053 The electron efficiency is measured in 8 TeV proton collision data to be better than 93% for
 1054 electrons with an ECAL supercluster energy of $E_T > 20$ GeV. For electrons with an $E_T > 25$ GeV
 1055 in 13 TeV proton collision data, the efficiency is about 96% .

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1056 4.1.4 Primary Vertex Reconstruction

1057 The primary vertex reconstruction should be able to measure the location of all proton interaction
 1058 vertices in each event: the signal vertex and all vertices from pile up events. It consists of a vertex
 1059 finding and a vertex fitting algorithm and happens in three steps. Tracks are selected to be
 1060 consistent with being produced promptly in the primary interaction by imposing requirements
 1061 on the track parameters [74]. By grouping reconstructed tracks according to the z coordinate
 1062 of their closest approach to the beam line, vertices for all interaction in the same beam crossing
 1063 are found, at CMS this is done by a deterministic annealing algorithm [148] . On top of this,
 1064 a vertex fitting algorithm like the Adaptive Vertex fitter [149], is performed. This creates the
 1065 three-dimensional primary-vertex position. With this fit, the contribution from long-lived hadron
 1066 decays is reduced by down weighting the tracks with a larger distance to the vertex. The primary
 1067 vertex corresponding to the highest sum of squared track transverse momenta is noted as the
 1068 point of the main interaction. The resolution on the primary vertex is about 14 μm in $r\phi$ and
 1069 about 19 μm in the z direction for primary vertices with the sum of the track $p_T > 100$ GeV
 1070 for 2016 data taking.

NOTE: Check text with PFlow paper!

1071 4.1.5 Calorimeter clusters

1072 The cluster algorithm in the calorimeter

- 1073 1. detects and measures the energy and direction of stable neutral particles such as photons
 1074 and neutral hadron,
- 1075 2. separates neutral particles from charged hadron energy deposits, /item reconstructs and
 1076 identifies electrons and their bremsstrahlung photons,
- 1077 3. contributes to the energy measurements of charged hadrons that don't have accurate
 1078 tracks parameters, e.g. for low quality and high transverse momentum tracks.

1079 The clustering is performed separately in each subdetector: ECAL barrel and endcaps, HCAL
 1080 barrel and end caps, and the two preshower layers. The HF has no clustering algorithm since
 1081 the electromagnetic or hadronic components give rise to an HF EM or HF HAD cluster.

1082 The clustering algorithm consist of different steps. First seeds are identified when cells have
 1083 an energy larger than the seeding threshold and lager than their neighbouring cells. Then
 1084 topological clusters are made by accumulating cells that share at least a corner with a cell
 1085 already in the cluster and an energy above a cell threshold set to twice the noise level. The third
 1086 step is a expectation maximization algorithm that reconstructs the cluster [144]. This algorithm
 1087 assumes that the energy deposits are Gaussian distributed and is an iterative algorithm with
 1088 two steps at each iteration. A first step calculated the expected fraction if the energy in a certain
 1089 step, while the second step performs a maximum likelihood fit. The positions and energies of
 1090 the Gaussian functions are then taken as cluster parameters.

1091 The calorimeter clusters are used for reconstructing photons and neutral hadrons. The clusters
 1092 that are not in the vicinity of the extrapolated charged tracks are easily identified as neutral
 1093 hadrons or photons. For the energy deposits that overlap with charged hadrons however, the
 1094 neutral particle energy deposit can only be detected as an excess over the charged particle
 1095 deposit. For this reason, a good calibration of the electromagnetic and hadronic calorimeter is
 1096 vital.

1097 The ECAL calibration is performed before the hadron cluster calibration or particle identifi-
 1098 cation². For Run 1, the ECAL response to electrons and photons as well as the cell-to-cell
 1099 relative calibration is determined with test beam data, radio active sources, and cosmic ray
 1100 measurements. For Run 2, the collision data collected at 7 and 8 TeV was used to refine the
 1101 calibration. The effect of the thresholds in the clustering algorithm are estimated from simulated
 1102 single photons with energies varying from 0.25 to 100 GeV. The photons used for the calibration
 1103 should not have a conversion prior to their entrance to ensure the calibration of single clusters.
 1104 In all ECAL regions and for all energies, the calibrated photon energies agree with the true
 1105 photon energies within 1%.

1106 In contrary to the photons, the hadrons deposit in general energy in both ECAL and HCAL.
 1107 Since the calorimeter responce in the HCAL depends on the fraction of shower energy deposited
 1108 in the ECAL, the ECAL and HCAL cluster energyes are recalibrated together to get an estimate
 1109 of the true hadron energy. Since now the calibration is done for hadrons, single neutral hadrons
 1110 such as K_L^0 are used for determining the calibration constants. The hadrons interactiong with
 1111 the tracker material are rejected for the calibration purposes. This calibration is checked with
 1112 isolated charged hadron selected from early data recorded at $\sqrt{s} = 0.9, 2.2$ and 7 TeV.

1113 4.2 Putting the pieces together

1114 A link algorithm connects the several PF elements from the various CMS subdetectors. It tests
 1115 any pair of elements in an event and is restricted to considering nearest neighbours in the
 1116 $\eta\phi$ -plane. The quality of the link is determined via the distance between the two elements
 1117 and PF blocks of elements are formed from elements with a direct link or indirect link through
 1118 common elements.

1119 The link between a central tracker track and a calorimeter clusters is made by extrapolating
 1120 the tracker track to the two layers of the preshower, the ECAL, and the HCAL. If this extrapolated

²Specifically 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.

1161 **4.3.2 Electrons and isolated photons**

1162 The electrons and photons are reconstructed together as discussed before. An electron candidate
 1163 seeded from a GFS track is considered an electron when the linked ECAL cluster is not linked
 1164 to three or more additional tracks. The photon seeds are ECAL superclusters with transverse
 1165 energies above 10GeV that have no links with a GSF track. After associating photons from
 1166 brehmstrahung with the associated electrons, the remaining energy is associated to the photons
 1167 and the photon direction is taken to be that of the supercluster. The electron direction is
 1168 chosen to be that of the GSF track and its energy is a combination of the ECAL energy with
 1169 the momentum of the GSF track. Photons are retained if they are isolated, while electrons
 1170 should satisfy additional criteria based on a multivariate analysis for isolated and non-isolated
 1171 electrons.

1172 **4.3.3 Hadrons and non-isolated photons**

1173 After muon, electron and isolated photon identification, the remaining particles are hadrons
 1174 from jet fragmentation and hadronisation. These can show up as charged hadrons (e.g. π^\pm ,
 1175 K^\pm , or protons), neutral hadrons (e.g. K_L^0 or neutrons), non isolated photons (e.g. from π^0
 1176 decays), and additional muons from early decays of charged hadrons.

1177 The photons and neutral hadrons are assigned to calorimeter clusters without any link to
 1178 tracks. When the calorimeter clusters between the ECAL and HCAL are linked, the clusters are
 1179 assumed to arise from the same hadron shower. If there is not such a link, HCAL clusters are
 1180 assigned to neutral hadrons, while the ECAL clusters are assigned to photons based on the fact
 1181 that neutral hadrons leave only 3% of their energy in the ECAL. Then the HCAL clusters linked
 1182 with tracks, that are not linked with other HCAL clusters, are assigned to charged hadrons.
 1183 These tracks can be linked with remaining ECAL clusters.

1184 Hadron interactions can result in the creation of extra particles originating from a secondary
 1185 vertex. These extra particles are identified by having a common secondary vertex and replaced
 1186 in the PF list as one single primary charged hadron.

1187 **4.3.4 Post processing**

1188 After identification and reconstruction of all particles as described above. An artificial large
 1189 missing transverse momentum \vec{p}_T^{miss} can be reconstructed. The cause of the \vec{p}_T^{miss} is mostly
 1190 misidentified or misreconstructed high- p_T muons originating from cosmic rays, misconstruction
 1191 of the muon's momentum, or punch-through charged hadrons. A post processing step is applied
 1192 to solve this \vec{p}_T^{miss} . Events with genuine large \vec{p}_T^{miss} due to the presence of neutrino's are
 1193 unaffected by this post processing.

1194 **4.4 Physics object reconstruction and identification**

1195 The particle flow objects are used for building physics objects that are used for analysis. These
 1196 objects are jets, muons, electrons, photons, taus and missing transverse momentum \vec{p}_T^{miss} . They
 1197 are used to compute other quantities such as particle isolation and have extra requirements

that are analysis dependent. In the following section, only the physics objects used throughout this thesis are discussed.

4.4.1 Muons

The muon candidates used for analysis in this thesis correspond to the tight working point. This working point yields the most genuine muons and rejects falsely reconstructed ones. Detail reports on the performance can be found in .

NOTE: Add source

In order to reject objects wrongly reconstructed as muons from hadron showers that reach the muon system (punch-throughs), the global muon fit is required to include at least one valid hit in the muon chambers and for which at least two muon segments in two muon stations is present. Additionally, the muon tracks should have a global fit yielding a goodness-of-fit of $\chi^2/\text{ndof} < 10$. 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 $d_{x,y} < 2 \text{ mm}$ and $d_z < 5 \text{ mm}$. 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 η -dependent scale factors ($\epsilon_{\text{data}}/\epsilon_{\text{MC}}$) to simulated events.

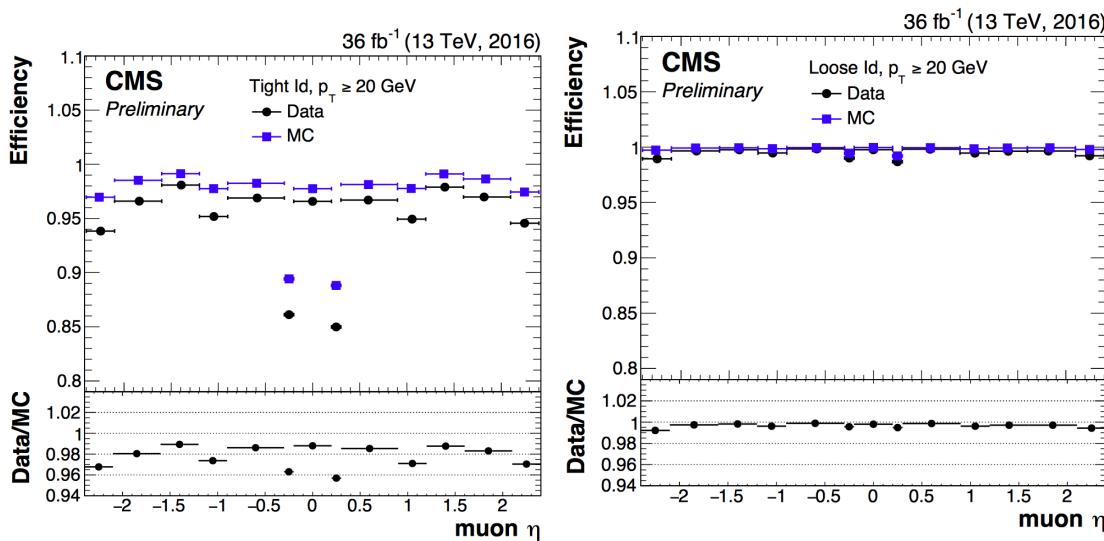


Figure 4.2: Comparison of the muon tight ID (left) and loose ID (right) efficiencies in data and simulation as a function of the pseudorapidity of the muon using the full 2016 dataset. Figure taken from [150].

1218

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

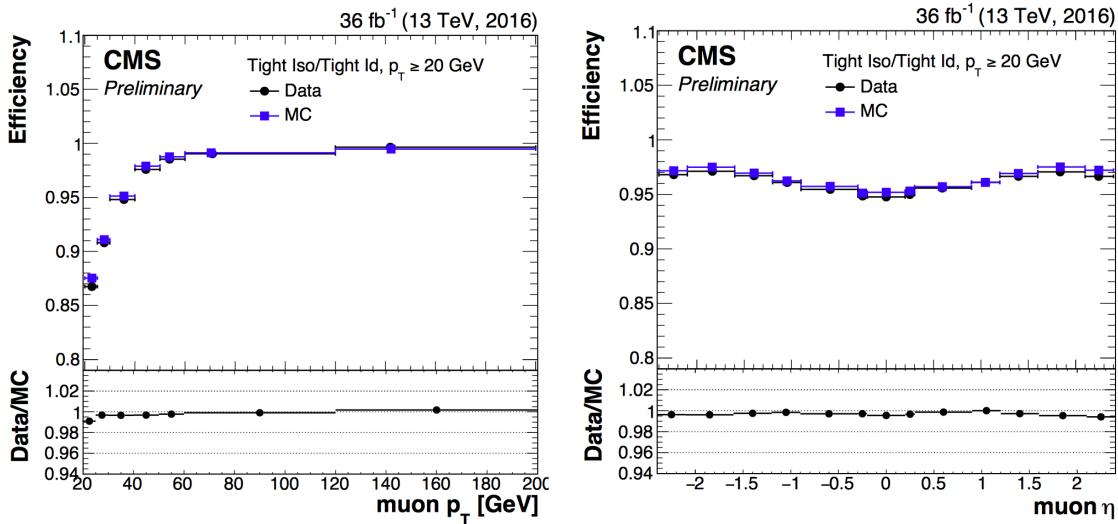


Figure 4.3: Comparison of the muon tight isolation requirement with the muon tight ID efficiencies in data and simulation as a function of the transvers emomentum (left) or pseudorapidity (right) of the muon using the full 2016 dataset. Figure taken from [150].

energy of the particles emitted around the direction of the lepton by defining a cone of radius ΔR in $\eta\phi$ plane around the lepton direction. Then a summed energy is calculated from the charged hadrons (CH), neutral hadrons (NH), photons (γ), excluding the lepton itself. This sum is then corrected to remove the enrgy coming from pile up interactions. The relative isolation for muons \mathcal{I} is defined as

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

where a cone of $\Delta R = 0.4$ is adopted and the pile up mitigation is based on the $\Delta\beta$ correction. The $\Delta\beta$ correction estimates the pile up energy as half of the contribution coming from charged hadrons. For tight ID muons, this relative isolation should $\mathcal{I}_\mu \leq 0.15$, while for loose muons this should be $\mathcal{I}_\mu \leq 0.25$. In Figure 4.3, the isolation efficiencies as a function of the pseudo rapidties using the tag and probe method are shown. 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 apply η - and p_T -dependent scale factors on the simulation.

4.4.2 Jets

Jets are reconstructed using the anti- k_T algorithm . Based on the clustering used by this algorithm, the jets are denoted as

1. PF jets containing all particles reconstructed by the PF algorithm,
2. Calo jets made from the sum of the ECAL and HCAL energy deposits in the calorimeter towers,

1233 3. Ref jets made from all stable particles produced by the event generator with the exclusion
1234 of neutrinos.

1235 **4.4.3 Jets with displaced vertices**

1236 **4.4.4 Electrons**

1237 **4.5 Summary of corrections**

1238 1. Muon ID, Iso see [Section 4.4.1](#)

1239 **4.6 Event selection**

1240 **4.7 Regions and channels**

1241 **4.8 Data driven background simulation**

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

¹²⁴²

5

¹²⁴³ **5.1 Construction of template distributions**

¹²⁴⁴ **5.2 Systematic uncertainties**

¹²⁴⁵ **5.3 Limit setting procedure**

¹²⁴⁶ **5.4 Result and discussion**

Denouement of the top-Z FCNC hunt at 13 TeV

6

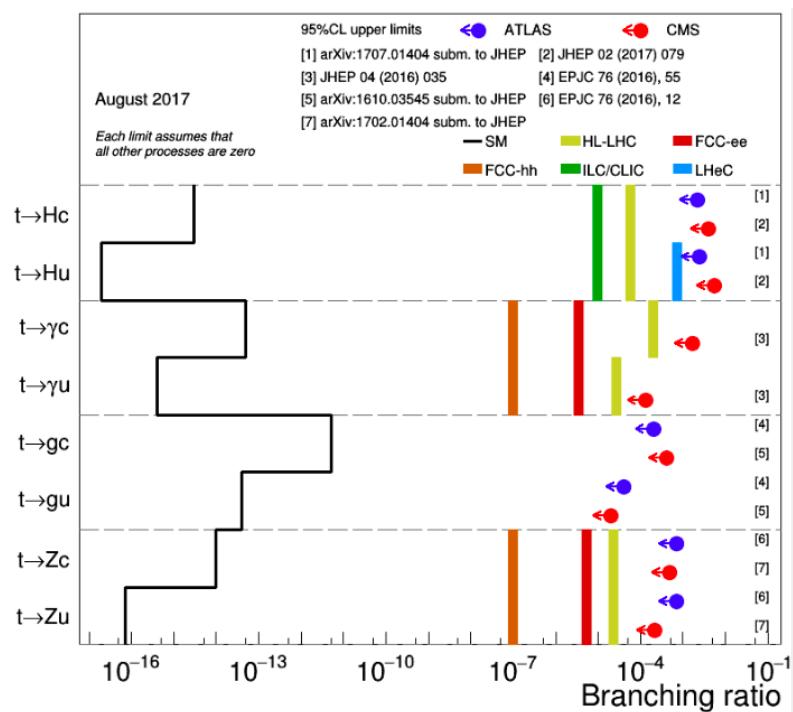


Figure 6.1:

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