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

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Contents

1 Theoretical basis

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

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

1.1 Elementary particles and forces

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

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

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

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

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

Generation	Particle	Mass	Charge
First	e^-	0.511 MeV	$-q_e$
	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

The quarks can also be divided into three generations. Unlike the leptons, they carry colour charge and can interact via the strong interaction. The top quark, discovered in 1995 at the Tevatron [5, 6], is the heaviest SM particle with a mass close to 173.1 ± 0.6 GeV[1] [4]. The quarks and their properties are summarized in Table 1.3. In nature, only colour neutral objects can exist. This has as consequence that quarks are bound through gluons into mesons (quark+anti-quark) and baryons (three quarks). These mesons and baryons are mostly short-lived and unstable particle that rapidly decay through $W^\pm$ and Z bosons, associated with a fermion. The only known stable baryon is the proton, made up of two up quarks and one down quark.

The scalar boson, commonly known as the Higgs boson, is the last piece of the SM and is discovered in 2012 [7, 8]. It is responsible for the masses of the $W^\pm$ and Z boson, and that of the fermions.

1.2 Standard Model Lagrangian

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

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

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

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

coupling. The indices refer to colour C, the left chiral nature of the $\mathrm{SU_L(2)}$ coupling L, and the weak hypercharge Y. Its Lagrangian is constructed such that contains symmetries representing physics conservation laws such as conservation of energy, momentum and angular momentum. The symmetries under local group transformations are sustained by demanding gauge invariance .

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

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

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

The generators T^a satisfy the Lie algebra:

$$\left[T^a, T^b\right] = i\epsilon^{abc}T_c \text{ and} \left[T^a, Y\right] = 0, \tag{1.2}$$

where ϵ^{abc} is an antisymmetric tensor. The gauge fields of $\mathrm{SU_L(2)}$ only couple to left-handed fermions as required by the observed parity violating nature of the weak force. The $\mathrm{SU_C(3)}$ group represents quantum chromodynamics (QCD). It has eight generators corresponding to eight gluon fields $\mathrm{G^{1\ldots8}_\mu}$. Unlike $\mathrm{SU_L(2)\times U_Y(1)}$, $\mathrm{SU_C(3)}$ is not chiral.

Under $\mathrm{SU_C(3)}$ 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:

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

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

$$\mathscr{L}_{\mathrm{SM}} = \mathscr{L}_{\mathrm{gauge}} + \mathscr{L}_{\mathrm{f}} + \mathscr{L}_{\mathrm{Yuk}} + \mathscr{L}_{\phi}, \tag{1.4}$$

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 $\mathrm{U_Y}(1)$ and g for $\mathrm{SU_L}(2)$. The physically observable gauge bosons of this theory are the photon field A_μ, the Z boson field Z^0_μ, and the W field $\mathrm{W}^\pm_\mu$. These are a superposition of the four gauge fields of $\mathrm{SU_L}(2)\times\mathrm{U_Y}(1)$:

$$\mathrm{A}_\mu = \sin\theta_\mathrm{W}\mathrm{W}^1_\mu + \cos\theta_\mathrm{W}\mathrm{B}_\mu,\ \mathrm{Z}^0_\mu = \cos\theta_\mathrm{W}\mathrm{W}^3_\mu - \sin\theta_\mathrm{W}\mathrm{B}_\mu,\ \text{and } \mathrm{W}^\pm_\mu = \sqrt{\frac{1}{2}}\left(\mathrm{W}^1_\mu \mp \mathrm{W}^2_\mu\right), \quad (1.5)$$

where θ_W represents the weak mixing angle defined as $\tan\theta_\mathrm{W} = \frac{g'}{g}$.

The coupling constant representing the strength of the QCD interactions is denoted as g_s. In QCD their 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.

Electroweak symmetry breaking

In $\mathscr{L}_\mathrm{gauge}$ and $\mathscr{L}_\mathrm{f}$ are no mass terms for fermions present because only singlets under $\mathrm{SU_C}(3)\times\mathrm{SU_L}(2)\times\mathrm{U_Y}(1)$ 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 $\mathscr{L}_\phi$ is introduced.

The scalar doublet is introduced in the SM as

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

NOTE: check if I need to add constants here

Its field potential is of the form

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

with $\mu^2 < 0$ and 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 ($\cancel{\mathrm{EW}}$):

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

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:

$$m_{\mathrm{W}} = \frac{1}{2} v |g| \quad \text{and} \quad m_{\mathrm{Z}} = \frac{1}{2} v \sqrt{g'^2 + g^2}. \tag{1.9}$$

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

1.3 Flavour changing currents in the SM

Flavour changing charged currents are introduced in 1963 by Nicola Cabibbo [9]. 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 $\mathrm{d}_{\mathrm{weak}}$, where $\mathrm{d}_{\mathrm{weak}}$ is a linear combination of the down and strange quarks, $\mathrm{d}_{\mathrm{weak}} = \cos\theta_c \mathrm{d} + \sin\theta_c \mathrm{s}$. This linear combination is a direct consequence of the chosen rotation

$$\begin{pmatrix} \mathrm{d}_{\mathrm{weak}} \\ \mathrm{s}_{\mathrm{weak}} \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} \mathrm{d} \\ \mathrm{s} \end{pmatrix} = \mathscr{R} \begin{pmatrix} \mathrm{d} \\ \mathrm{s} \end{pmatrix}, \tag{1.10}$$

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,

$$J_\mu = \bar{\mu} \gamma_\mu (1 + \gamma_5) \mathrm{d}_{\mathrm{weak}}. \tag{1.11}$$

A consequence of Cabibbo's approach is that the $\mathrm{s}_{\mathrm{weak}}$ is left uncoupled, leading to Glashow, Iliopoulos and Maiani (GIM) [10–12] to require the existence of a fourth quark with charge $\frac{2}{3}\mathrm{q_e}$. This quark, known as the charm quark, couples to $\mathrm{s}_{\mathrm{weak}}$ and a new definition of the charged weak current is modified to

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

The neutral weak current is defined as

$$J_3 = \bar{U} \gamma_\mu (1 + \gamma_5) \left[\mathscr{R}, \mathscr{R}^\dagger \right] D, \tag{1.13}$$

and is diagonal in flavour space. This has as consequence that no flavour changing neutral currents occur at tree-level Feynmann diagrams[2] .

NOTE: should I explain feynmann diagrams?

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

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

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

$$\begin{pmatrix} \mathrm{d}_{\mathrm{weak}} \\ \mathrm{s}_{\mathrm{weak}} \\ \mathrm{b}_{\mathrm{weak}} \end{pmatrix} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} \begin{pmatrix} \mathrm{d} \\ \mathrm{s} \\ \mathrm{b} \end{pmatrix} = \mathcal{V}_{\mathrm{CKM}} \begin{pmatrix} \mathrm{d} \\ \mathrm{s} \\ \mathrm{b} \end{pmatrix}. \tag{1.14}$$

The unitarity of the matrix ($\mathcal{V}^{\dagger}_{\mathrm{CKM}}\mathcal{V}_{\mathrm{CKM}} = \mathbb{1}$). 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 fives 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 [13]. Each element V_{ij} of $\mathcal{V}_{\mathrm{CKM}}$ represents the transition probability of a quark i going to a quark j, and is experimentally determined to be [4]

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

From Equation 1.15 follows that top quarks predominantly decay via charged weak currents to bottom quarks, with a probability consist with unity. In the SM, FCNC can only occur via higher loop Feynmann diagrams which are highly suppressed. The expected transition probabilities for a top quark decaying via a FCNC interaction in the SM are given in Table 1.4, where it is clear 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 [14]

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

1.4 Top quark physics in the SM

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

$$\mathcal{L}_{\mathrm{top-Yukawa}} = -\frac{\lambda_t v}{\sqrt{2}}\bar{\mathrm{t}}_{\mathrm{L}}\mathrm{t}_{\mathrm{R}} - \frac{\lambda_{\mathrm{t}}}{\sqrt{2}}\mathrm{H}\bar{\mathrm{t}}_{\mathrm{L}}\mathrm{t}_{\mathrm{R}} + \mathrm{h.c.}, \tag{1.16}$$

yielding a Yukawa coupling of

$$\lambda_{\mathrm{t}} = \frac{\sqrt{2}m_{\mathrm{t}}}{v} = 0.991 \pm 0.003, \tag{1.17}$$

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 ir 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 $1/\Gamma_\mathrm{t} \approx 5\,10^{-25}$ sleading 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 $1/\Lambda_\mathrm{QCD} \approx 10^{-23}$ 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.

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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→t$\bar{\mathrm{t}}$) or quark fusion (q$\bar{\mathrm{q}}$→ t$\bar{\mathrm{t}}$). 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 the LHC compared to quark fusion at Tevatron. The gg→t$\bar{\mathrm{t}}$ 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.

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	$m_\mathrm{t} = 173.3$ GeV	$\sqrt{s} = 1.96$ TeV	$\sigma_{\mathrm{t\bar{t}}} = 7.16^{+0.11+0.17}_{-0.20-0.12}$
LHC	$m_\mathrm{t} = 173.2$ GeV	$\sqrt{s} = 7$ TeV	$\sigma_{\mathrm{t\bar{t}}} = 173.6^{+4.5+8.9}_{-5.9-8.9}$
LHC	$m_\mathrm{t} = 173.2$ GeV	$\sqrt{s} = 8$ TeV	$\sigma_{\mathrm{t\bar{t}}} = 247.7^{+6.3+11.5}_{-8.5-11.5}$
LHC	$m_\mathrm{t} = 173.2$ GeV	$\sqrt{s} = 13$ TeV	$\sigma_{\mathrm{t\bar{t}}} = 816.0^{+19.4+34.4}_{-28.6-34.4}$

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

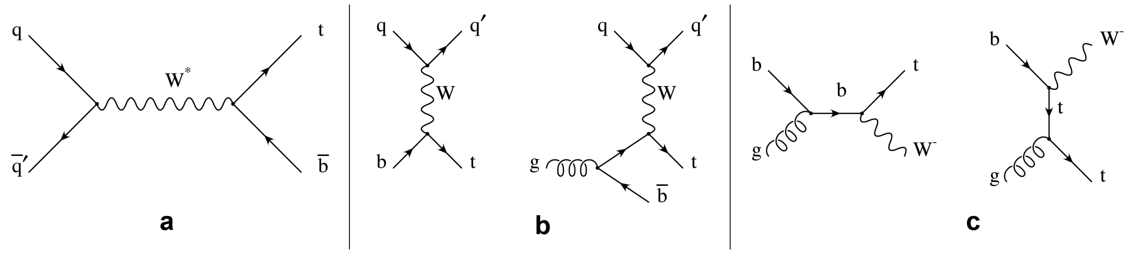

Figure 1.2: Leading order Feynman diagrams of the electroweak production of single top quarks in the s-channel (left), t-channel (middle), and for the tW associated production. Figure taken from [15].

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

1.5 Experimental results on the SM top quark

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

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 $\bar{\mathrm{t}}$ 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 $m_{\mathrm{t}} = 172.5$ GeV [4, 16].

Experiment	Centre-of-mass energy	Cross section $\sigma_{\mathrm{t}+\bar{\mathrm{t}}}$ (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	$216.99^{+9.04}_{-7.71}$	$10.32^{+0.40}_{-0.36}$	$71.7^{+1.80+3.40}_{-1.80-3.40}$

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

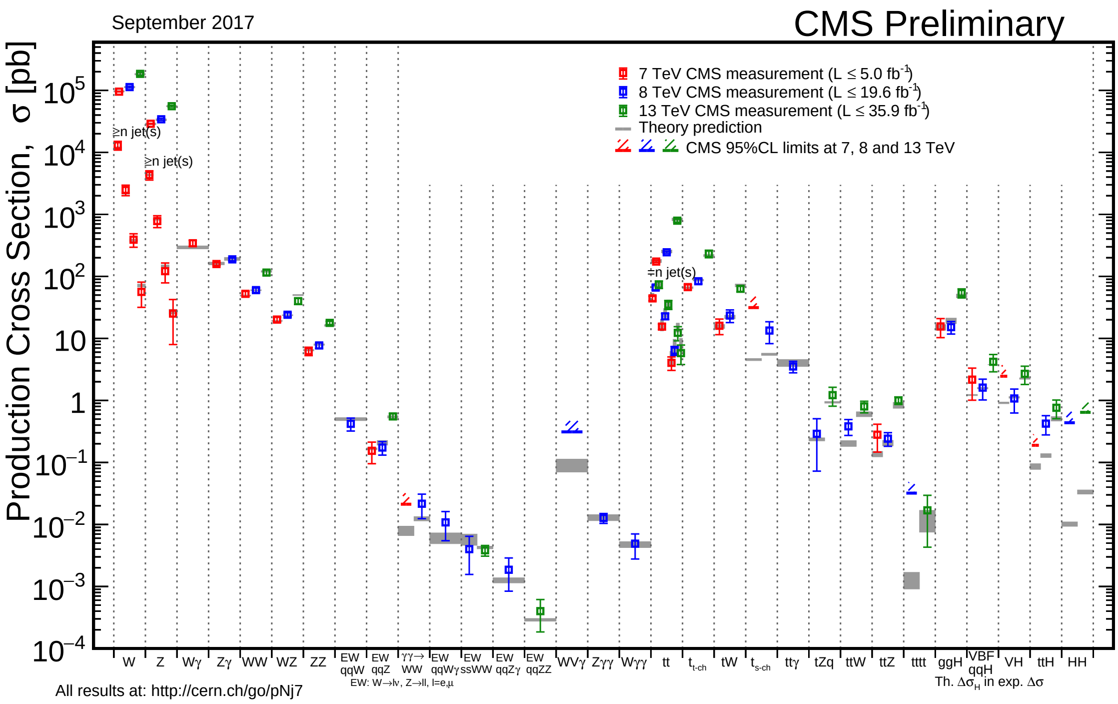

Figure 1.3: Summary of the SM cross section measurements performed by the CMS collaboration. Figure taken from [17]

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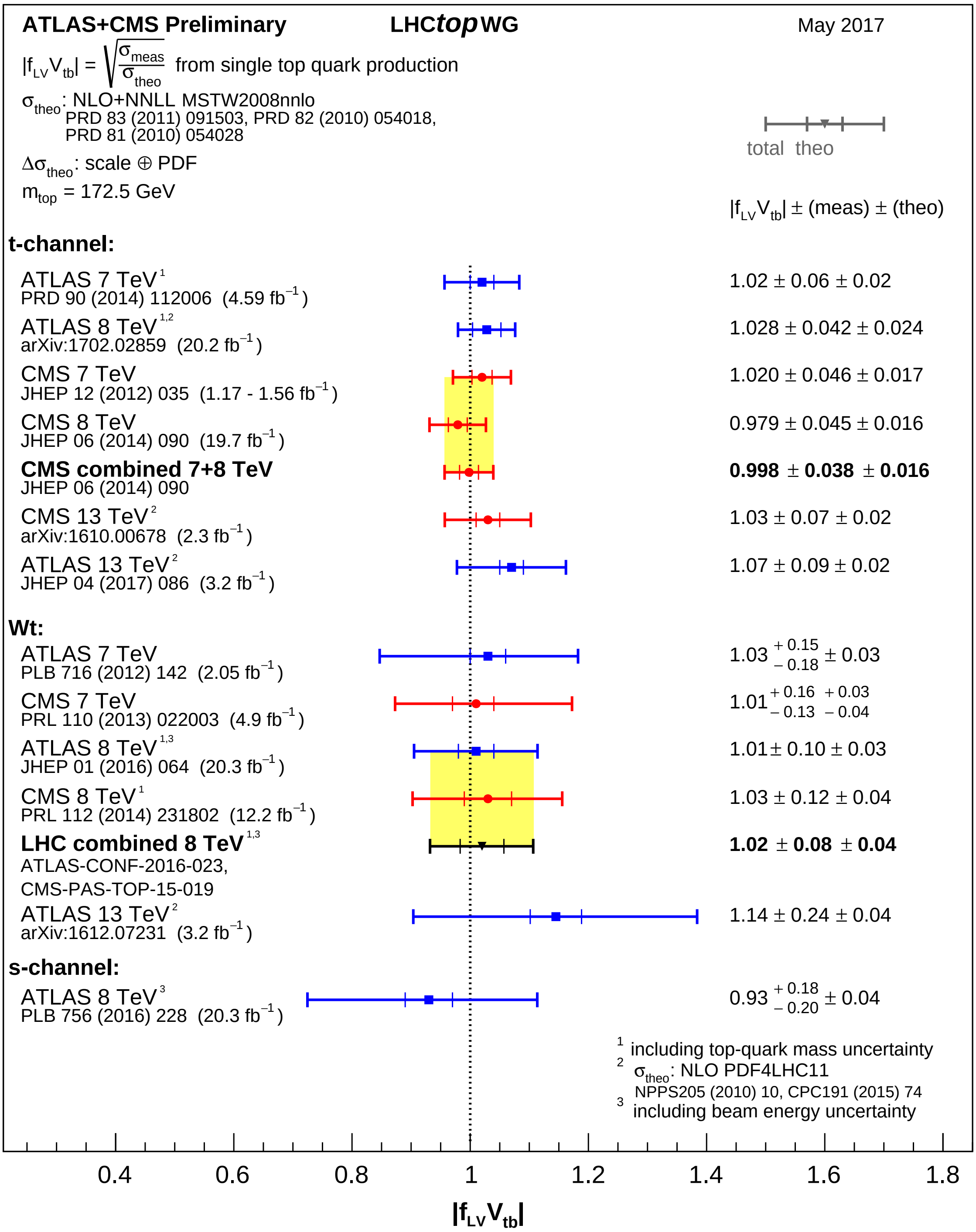

Figure 1.4: Estimations of the SM V_{tb} CKM element from single top cross section measurements. Figure taken from [18].

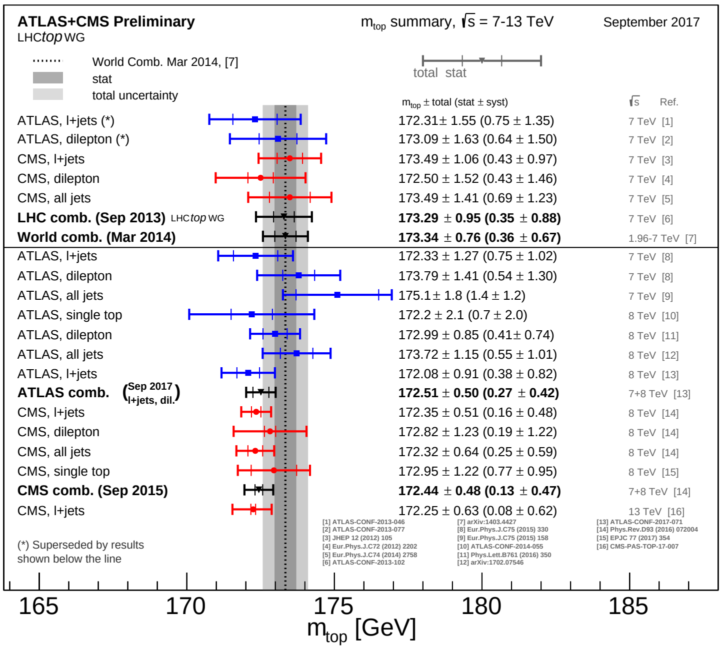

Figure 1.5: Summary of the top mass direct measurements performed by CMS and ATLAS, and compared with the LHC and LHC+Tevatron combinations. The results below the line are produced after the LHC and LHC+Tevatron combinations. Figure taken from [18].

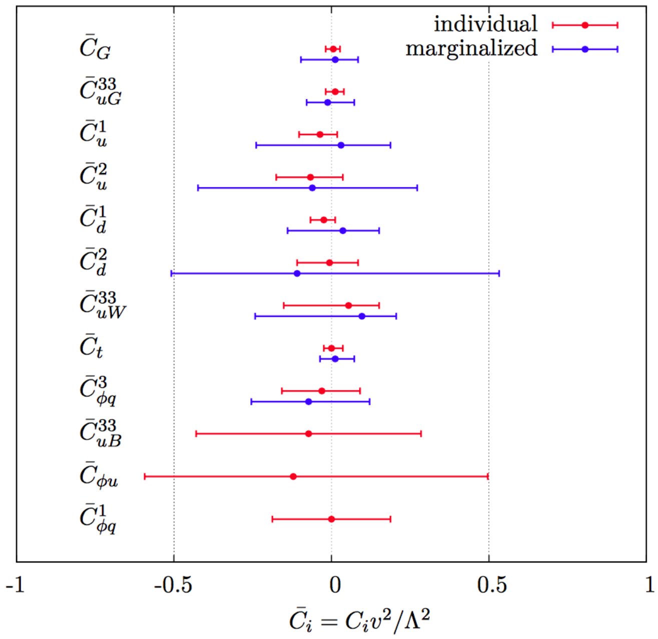

Figure 1.6: Global fit results of top quark effective field theory to experimental data including all constrainable operators at dimension six. For the operators, the Warsaw basis of [19]is used. The bounds are set on the Wilson coëfficients of various operators contributing to top quark production and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

1.6 Motivations for new physics

Many high energy experiments confirm the success of the SM. In particular the scalar boson, the cornerstone of the SM, has consecrated the theory. Unfortunately there are also strong indications that the SM ought to be a lower energy expression of a more global theory. The existence of physics beyond the SM (BSM) [21] is strongly motivated. These motivations are based on direct evidence from observation such as the existence of neutrino masses, the existence of dark matter and dark energy, or the matter-antimatter asymmetry, and also from theoretical problems such as the hierarchy problem, the coupling unification or the large numbers of free parameters in the SM.

In the SM, the neutrino is assumed to be massless, whilst experiments with solar, atmospheric, reactor and accelerator neutrinos have established that neutrinos can oscillate and change flavour during flight [22, 23]. These oscillations are only possible when neutrino's have masses. The flavour neutrinos (ν_e, ν_μ, ν_τ) are then linear expressions of the fields of at least three mass eigenstate neutrinos ν_1, ν_2, and ν_3.

The ordinary or baryonic matter described by the SM describes only 5% of the mass (energy) content of the universe. Astrophysical evidence indicated that dark matter is contributing to approximately 27%, and dark energy to 68% of the content of the universe. From the measurements of the temperature and polarizations anisotropies of the cosmic microwave background by the Planck experiment [24], the density of cold non baryonic matter is determined. Cold dark matter is assumed to be only sensitive to the weak and gravitational force, leading to only one possible SM candidate: the neutrino. However, these are too light to account for the vast amount of dark matter and other models are needed. Dark energy is assumed to be responsible for the acceleration in the expansion of the universe [25].

At the Big Bang matter and antimatter is assumed to be produced in equal quantities. However, it is clear that we are surrounded by matter. So where did all the antimatter go? In 1967, Sakharov identified three mechanisms that are necessary to obtain a global matter antimatter asymmetry [26]. These mechanisms are those of baryon and lepton number violation, that at a given moment in time there was a thermal imbalance for the interactions in the universe, and there is charge C and charge parity CP violation[3].

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

The hierarchy problem [27] is related to the huge difference in energy between the weak scale and the Planck scale. The vev of the Brout-Englert-Higgs field determines the weak scale that is approximately 246 GeV. The radiative corrections to the scalar boson squared mass m_{H}^2, coming from its self couplings and couplings to fermions and gauge bosons, are quadratically

[3] The rate of a process $i \to f$ can be different from the CP-conjugate process: $\tilde{i} \to \tilde{f}$. 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.

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

$$\Delta m_{\mathrm{H}}^2 = -\frac{|\lambda_{\mathrm{f}}|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2, \tag{1.18}$$

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 $-\lambda_{mathrmS}|\phi|^2|\mathrm{S}|^2$ is

$$\Delta m_{\mathrm{H}}^2 = -\frac{|\lambda_{\mathrm{S}}|^2}{16\pi^2}\left(\Lambda_{\mathrm{UV}}^2 - 2m_{\mathrm{S}}^2\ln\left(\frac{\Lambda_{\mathrm{UV}}}{m_{\mathrm{S}}}\right) + \ldots\right). \tag{1.19}$$

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

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

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

The closeness of the top mass to the electroweak scale led physicist to believe that it is a sensitive probe for new physics. Its property study is therefore an important topic of the experimental program at the LHC. Several extensions of the SM enhance the FCNC branching ratios and can be probed at the LHC [14], from which some of them are shown in Table 1.7. Previous searches have been performed at the Fermilab Tevatron by the CDF [28] and D0 [29] collaborations, and at the LHC by the ATLAS [30–33] and CMS [34–38] collaborations.

The impact of BSM models can written in a model independent way by means of an effective field theory valid up to an energy scale Λ. The leading effects are parametrized by a set of fully gauge symmetric dimension-6 operators that are added to the SM Lagrangian and can be reduced to a minimal set of operators as discussed in [39, 40]. The full Lagrangian, neglecting neutrino physics, in the fully gauge symmetric case is given by

$$\mathscr{L}_{\mathrm{SM+EFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{\mathrm{i}} \frac{\bar{c}_{\mathrm{i}}}{\Lambda^2}\mathscr{O}_{\mathrm{i}} + \mathscr{O}\left(\frac{1}{\Lambda^3}\right), \tag{1.20}$$

Table 1.7: The predicted branching ratios $\mathscr{B}$ for FCNC interactions involving the top quark in some BSM models [14]: 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
$t \to uZ$	$\leq 1.1\ 10^{-4}$	$-$	$\leq 2\ 10^{-6}$	$t \to cZ$	$\leq 1.1\ 10^{-4}$	$\leq 10^{-7}$	$\leq 2\ 10^{-6}$
$t \to u\gamma$	$\leq 7.5\ 10^{-9}$	$-$	$\leq 2\ 10^{-6}$	$t \to c\gamma$	$\leq 7.5\ 10^{-9}$	$\leq 10^{-6}$	$\leq 2\ 10^{-6}$
$t \to ug$	$\leq 1.5\ 10^{-7}$	$-$	$\leq 8\ 10^{-5}$	$t \to cg$	$\leq 1.5\ 10^{-7}$	$\leq 10^{-4}$	$\leq 8\ 10^{-5}$
$t \to uH$	$\leq 4.1\ 10^{-5}$	$\leq 5.5\ 10^{-6}$	$\leq 10^{-5}$	$t \to cH$	$\leq 4.1\ 10^{-5}$	$\leq 10^{-3}$	$\leq 10^{-5}$

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 [14, 41] 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

$$\mathscr{L}^{t}_{\mathrm{EFT}} = \frac{\sqrt{2}}{2} \sum_{q=u,c} \Big[g' \frac{\kappa_{t\gamma q}}{\Lambda} A_{\mu\nu} \bar{t} \sigma^{\mu\nu} \left(f^{L}_{\gamma q} P_L + f^{R}_{\gamma q} P_R \right) q \tag{1.21}$$

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

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

$$+ g_S \frac{\kappa_{gqt}}{\Lambda} Z_{\mu\nu} \bar{t} \sigma^{\mu\nu} \left(f^{L}_{gq} P_L + f^{R}_{gq} P_R \right) q G^{a}_{\mu\nu} \tag{1.24}$$

$$+ \eta_{Hqt} \bar{t} \left(\hat{f}^{L}_{q} P_L + \hat{f}^{R}_{q} P_R \right) q H + \mathrm{h.c.} \Big], \tag{1.25}$$

where the 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 $|f^{L}_{xq}|^2 + |f^{R}_{xq}|^2 = 1$, $|\tilde{f}^{L}_{q}|^2 + |\tilde{f}^{R}_{q}|^2 = 1$, and $|\hat{f}^{L}_{q}|^2 + |\hat{f}^{R}_{q}|^2 = 1$. In the expression for $\mathscr{L}^{t}_{\mathrm{EFT}}$, 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 $G^{1\ldots8}_{\mu}$, and the Z boson Z^0_μ are defined as

$$A_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu,\ Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu, \text{ and } G_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_S f^a_{bc} G^b_\mu G^c_\nu. \tag{1.26}$$

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

NOTE: should I explain cov. der?

1.8 Experimental constraints on top-FCNC

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

$$\mathscr{B}(t \to qX) = \frac{\delta^2_{tXq}\Gamma_{t\to qX}}{\Gamma_t}, \tag{1.27}$$

where $\Gamma_{t\to qX}$ represents the FCNC decay width[4] for a coupling strength $\delta^2_{tXq} = 1$, and Γ_t the full decay width of the top quark. In the SM, supposing a top quark mass of 172.5 GeV, the full width becomes $\Gamma_t^{SM} = 1.32$ GeV [42].

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

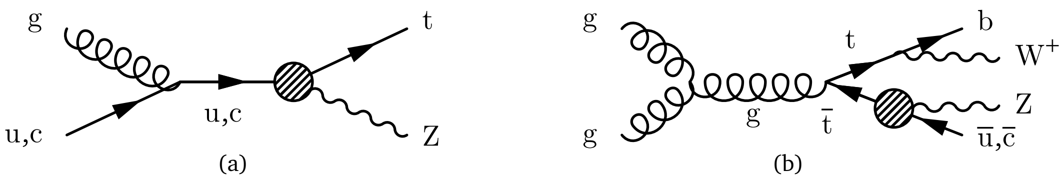

Figure 1.7: Feynman diagrams for the tZq FCNC interaction, where the FCNC interaction is indicated with the shaded dot. (a) Single top production through an FCNC interaction. (b) Top pair production with an FCNC induced decay.

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

NOTE: Check atlas result for tZq from top2017 proceedings when they appear

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

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

Process	Search mode	Observed $\mathcal{B}$	Expected $\mathcal{B}$	Experiment	
$\mathrm{t} \rightarrow \mathrm{uZ}$	top pair decay and single top production	2.2 10^{-4}	2.7 10^{-4}	CMS	[34]
$\mathrm{t} \rightarrow \mathrm{u}\gamma$	single top production	1.3 10^{-4}	1.9 10^{-4}	CMS	[36]
$\mathrm{t} \rightarrow \mathrm{ug}$	single top production	4.0 10^{-5}	3.5 10^{-5}	ATLAS	[31]
$\mathrm{t} \rightarrow \mathrm{uH}$	top pair decay	2.4 10^{-3}	1.7 10^{-3}	ATLAS	[33]
$\mathrm{t} \rightarrow \mathrm{cZ}$	top pair decay and single top production	4.9 10^{-4}	12 10^{-4}	CMS	[34]
$\mathrm{t} \rightarrow \mathrm{c}\gamma$	single top production	2.0 10^{-3}	1.7 10^{-3}	CMS	[36]
$\mathrm{t} \rightarrow \mathrm{cg}$	single top production	2.0 10^{-4}	1.8 10^{-4}	ATLAS	[31]
$\mathrm{t} \rightarrow \mathrm{cH}$	top pair decay	2.2 10^{-3}	1.6 10^{-3}	CMS	[33]

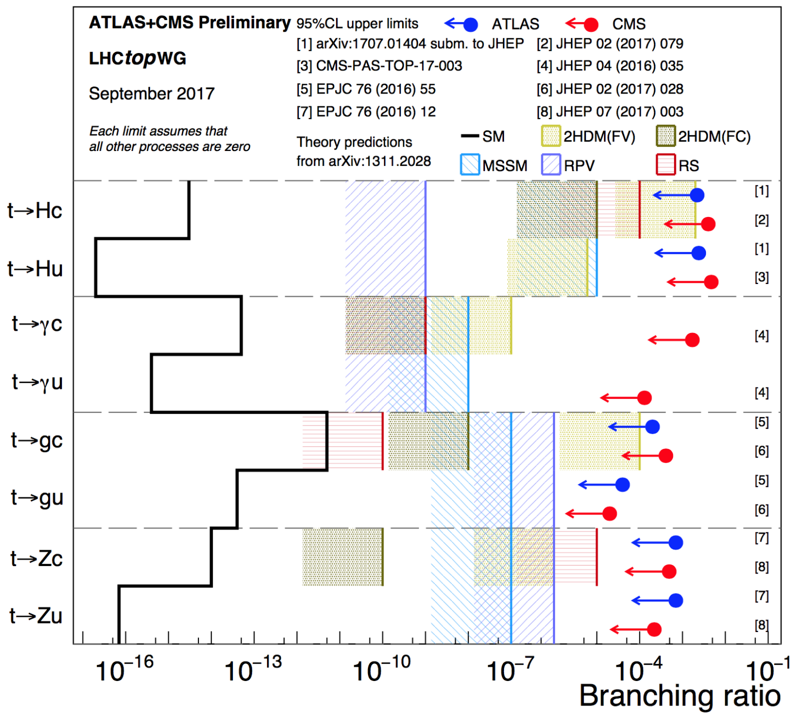

Figure 1.8: Current best limits set by CMS and ATLAS for top-FCNC interactions.

2 Experimental set-up

The main objective of the Large Hadron Collider (LHC) was the search for the Brout-Englert-Higgs boson. The Large Electron Positron (LEP) [43] and Tevatron [44] experiments had established that the mass of the scalar boson has to be larger than 114 GeV [45, 46], and smaller than approximate 1 TeV due to unitarity and perturbativity constraints [47]. On top of this, the search for new physics such as supersymmetry or the understanding of dark matter were part of the motivation for building the LHC. Since the start of its operation, the LHC is pushing the boundaries of the Standard Model, putting the most stringent limits on physics beyond the Standard Model as well as precision measurements of the parameters of the Standard Model. A milestone of the LHC is the discovery the scalar boson in 2012 by the two largest experiments at the LHC [7, 8].

This chapter is dedicated to the experimental set up of the LHC and the Compact Muon Solenoid (CMS) experiment. Section 2.1 describes the LHC and its acceleration process for protons to reach their design energies. The CMS experiment and its components are presented in Section 2.2.

2.1 The Large Hadron Collider

The LHC has started its era of cutting edge science on 10 September 2008 [48] after approval by the European Organisation of Nuclear Research (CERN) in 1995 [49]. Installed in the previous LEP tunnels, the LHC consists of a 26.7 km ring, that is installed between 45 and 170 m under the French-Swiss border amidst Cessy (France) and Meyrin (Switzerland). Built to study rare physics phenomena at high energies, the LHC can accelerate two type of particles, protons or ions Pb^{45+}, and provides collisions at four interaction points, where the particle bunches are crossing. Experiments for studying the collisions are installed on each interaction point.

As can be seen in Figure 2.1, the LHC is last element in a chain that creates, injects and accelerates protons. The starting point is the ionisation of hydrogen, creating protons that are injected in a linear accelerator (LINAC 2). Here, the protons obtain an energy of 50 MeV. They continue to the proton synchrotron booster (PSB or Booster), where the packs of protons are accelerated to 1.4 GeV and each pack is split up in twelve bunches with 25 ns spacing for Run 2 (50 ns for Run 1). The proton synchrotron (PS) then increases their energy to 25 GeV before the super proton synchrotron (SPS) increases the proton energy up to 450 GeV. Each accelerator ring expands in radius in order to reduce the energy loss of the protons by synchrotron radiation[1] Furthermore, the magnets responsible for the bending of the proton trajectories have to be strong enough to sustain to higher proton energy. Ultimately, the protons are injected into opposite directions into the LHC, where they are accelerated to 3.5 TeV (in 2010 and 2011), 4 TeV (in 2012 and 2013) or 6.5 TeV (in 2015 and 2016) [50]. Before the start of the LHC in 2010, the previous energy record was held by the Tevatron collider at Fermilab, colliding 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).

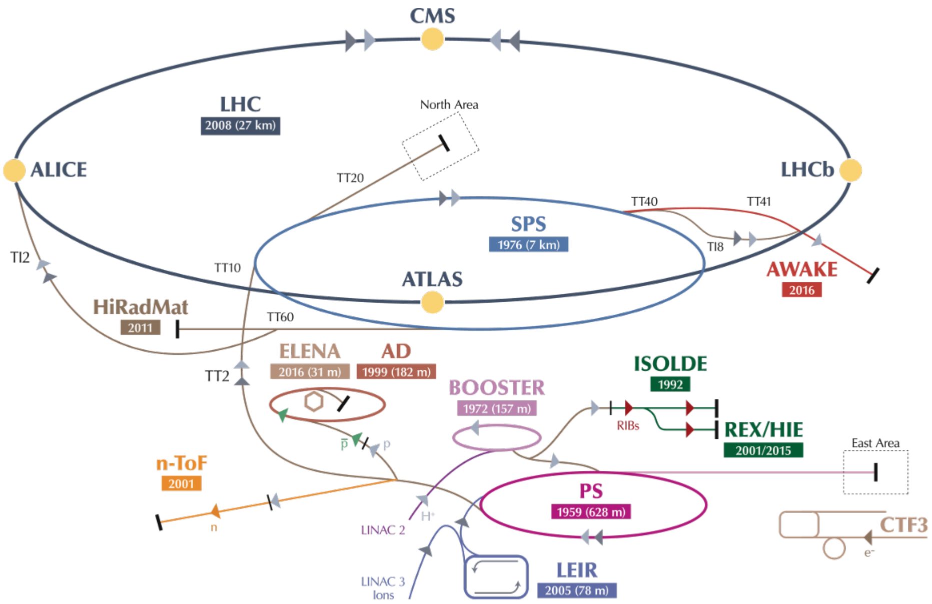

Figure 2.1: Schematic representation of the accelerator complex at CERN [51]. The LHC (dark blue) is the last element in chain of accelerators. Protons are successively accelerated by LINAC 2, the Booster, the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) before entering the LHC.

Inside the LHC ring [52], the protons are accelerated by the means of radio frequency cavities, while 1232 dipole magnets of approximately 15 m long, each weighing 35 t ensure the deflection of the beams. The two proton beams circulate in opposite direction in separate pipes inside of the magnet. Through the use of a strong electric current in the coils around the beam pipe, magnetic fields are generated and cause the protons to bend in the required orbits. In order to get the coil to become superconducting and able to produce - with the aid of an iron return yoke - a strong magnetic field of 8.3 T, the magnet structure is surrounded by a vessel. This vessel is filled with liquid Helium making it possible to cool down the magnet to 1.9 K. In order to get more focussed and stabilised proton beams, additional higher-order multipole and corrector magnets are placed along the LHC beam line.

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

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

- A Toroidal LHC ApparatuS (ATLAS) [53] and the Compact Muon Solenoid (CMS) [54] experiments are the two general purpose detectors at the LHC. They both have a hermetic, cylindrical structure and were designed to search for new physics phenomena along with precision measurements of the Standard Model. The existence of two distinct experiments allows cross-confirmation of any discovery.
- A Large Ion Collider Experiment (ALICE) [55] and the LHC Beauty (LHCb) [56] experiments are focusing on specific phenomena. ALICE studies strongly interacting matter at extreme energy densities where a quark-gluon plasma forms in heavy ion collisions (Pb-Pb or p-Pb). LHCb searches for differences between matter and antimatter with the focus on b physics..
- The forward LHC (LHCf) [57] and the TOTal cross section, Elastic scattering and diffraction dissociation Measurement (TOTEM) [58] experiments are two smaller experiments that focus on head on collisions. LHCf consists of two parts placed before and after ATLAS and studies particles created at very small angles. TOTEM is placed in the same cavern as CMS and measures the total proton-proton cross section and studies elastic and diffractive scattering.
- The Monopoles and Exotics Detector At the LHC (MoEDAL) [59] experiment is situated near LHCb and tries to find magnetic monopoles.

For the enhancement of the exploration of rare events and thus enhancing the number of collisions, high beam energies as well as high beam intensities are required. The luminosity [60] 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

$$N_{\mathrm{event}} = L\sigma_{\mathrm{event}}, \tag{2.1}$$

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

$$L = \frac{1}{4\pi} N_{\mathrm{b}} n_{\mathrm{b}} f_{rev} \frac{N_{\mathrm{b}}}{\epsilon_n} \left(1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2\right)^{\frac{-1}{2}} \frac{\gamma_{\mathrm{r}}}{\beta^*}. \tag{2.2}$$

The number of particles per bunch is expressed by N_{b}, while n_{b} is the number of bunches per beam, f_{rev} the revolution frequency, γ_{r} the relativistic gamma factor, ϵ_n the normalized transverse beam emittance - a quality for the confinement of the beam , β^* the beta function at the collision point - a measurement for the width of the beam, θ_c the angle between two beams at the interaction point, σ_z the mean length of one bunch, and σ^* the mean height of one bunch. In Equation 2.2, the blue part represents the stream of particles, the red part the brilliance, and the green part the geometric reduction factor due to the crossing angle at the interaction point.

The peak design luminosity for the LHC reached in 2016 is $10^{34}\,\mathrm{m^{-2}s^{-1}}$, which leads to about 1 billion proton interactions per second. In 2016, the LHC was around 10% above this design luminosity [61]. The luminosity is not a constant in time since it diminishes due to collisions between the beams, and the interaction of the protons and the particle gas that is trapped in the centre of the vacuum tubes due to the magnetic field. The diffusion of the beam degrades the emittance and therefore also the luminosity. For this reason, the mean lifetime of a beam inside the LHC is around 15 h. The integrated luminosity - the luminosity provided in a certain time range - recorded by CMS and ATLAS over the year 2016 is given in Figure 2.2. In Run 2, the peak luminosity is 13-17 $10^{33}\ \mathrm{cm^{-2}s^{-1}}$ compared to 7.7 $10^{33}\ \mathrm{cm^{-2}s^{-1}}$ in Run 1.

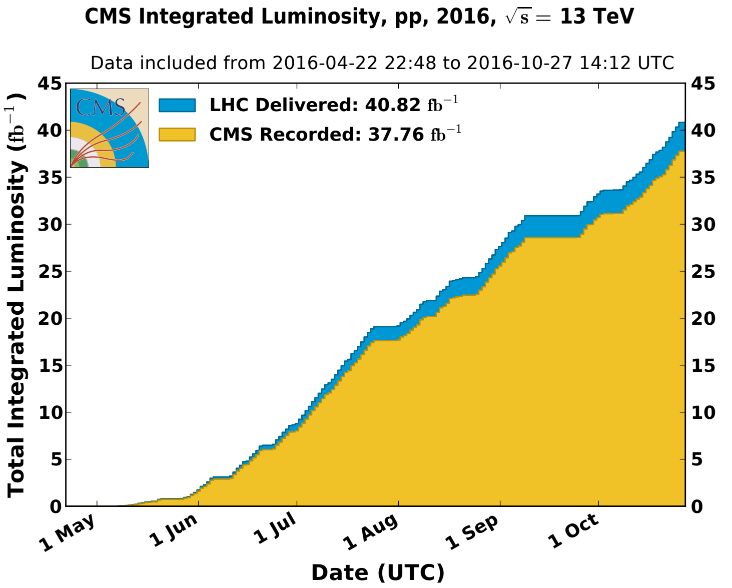

Figure 2.2: Cumulative offline luminosity measured versus day delivered to (blue), and recorded by CMS (orange) during stable beams and for proton collisions at 13 TeV centre-of-mass energy in 2016. The delivered luminosity accounts for the luminosity delivered from the start of stable beams until the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

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

2.2 The Compact Muon Solenoid

At one of the collision points of the LHC, the CMS detector[62–64] is placed. Weighing 14 000 t, This cylindrical detector is about 28.7 m long and 15 m in diameter, weighing around 14 000 t. It has an onion like structure of several specialised detectors and contains a superconducting solenoid with a magnetic field of 3.8 T. The CMS detector is designed in a way that it can address the needs of physics coming from the LHC. 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 muon, electrons and photons is one of the main goals of the CMS detector. Further it provides a good charged particle momentum resolution and reconstruction efficiency in the inner tracker such that for example jets coming from b quarks or tau particles can be identified. Also the electromagnetic resolution for an efficient photon and lepton isolation as well as a good hadronic calorimeter for the missing transverse energy were kept into account while designing CMS. In Figure 2.3, an overview of the CMS detector is given.

The LHC provides many collisions in a short amount of time. In order to discriminate between consecutive collisions - known as out of time pile up events - , CMS has to complete the full data acquisition for one collision event before the next one happens (around 25 ns in Run II and around 50 ns in Run I [65]). Furthermore, since the photons are in packets, around 21 in Run I and approximately 40 in Run II inelastic collisions happen every beam crossing . This creates a great amount of background processes in the detector called in time pile up events. Due to this difficult conditions, the detector has a high granularity which on its turn creates a need for huge number of synchronized electronic channels. Furthermore, due to to high flux of particles in the regions close to the beam, the electronics have to be able to endure high radiation.

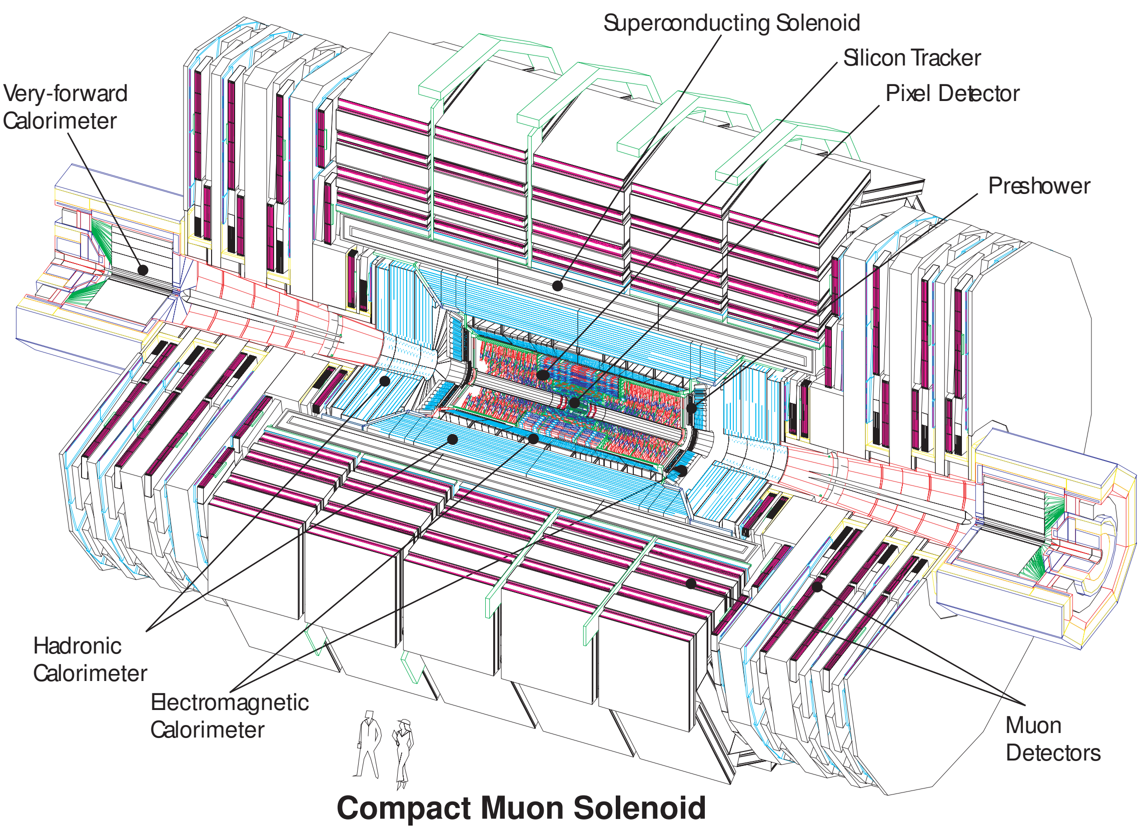

Figure 2.3: Mechanical layout of the CMS detector[66].

Before the start of taking collision data for 13 TeV operations on 3 June, CMS had a long shutdown (LS1)[67]. During this shut down several upgrades were performed. The innermost part of detection material in CMS (pixel) is made of three concentric cylindrical layers in run I. At the end of 2016 it is upgraded by adding a fourth layer, enhancing the particle tracking capabilities of CMS. In order to be able to incorporate this new layer, the section of the beryllium beam pipe within CMS was replaced by a narrower one during LS1. For this, the pixel was removed and reinserted into CMS. In order to avoid long damage caused by the intense particle flux at the heart of CMS, the tracker is been made ready to operate at much lower temperature than before. During Run I, a small problem was detected in the electromagnetic calorimeter preshower system. For this, the preshower discs were removed, repaired and reinstalled successfully inside CMS in 2014. To help the discrimination between interesting low momentum muons coming from collisions and muons caused by backgrounds, a fourth triggering and measurement station for muons was added in each of the end caps. CMS measures the collision rate within the detector and monitors beam related backgrounds. For this, several new detectors were installed into CMS during LS1.

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 to describe the momentum $\vec{p}$: the distance ρ, the azimuthal angle $\phi \in [-\pi, \pi]$ - the angle between the x-axis and the projection in the transverse plane of $\vec{p}$ ($\vec{p}_T$) - , the pseudo-rapidity η - expressed by the polar angle θ between the direction of $\vec{p}$ and the beam - :

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

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

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

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

2.2.2 Towards the heart of CMS

The CMS detector consists of two parts; a central barrel around the beam pipe ($|\eta| < 1.4$) and two plugs to ensure the hermeticity of the detector. In Figure 2.3 and Figure 2.5 the onion like structure of the CMS detector is visible. The choice of a solenoid of 12.9 m long and 5.9 m diameter gives the advantage of bending the particle trajectories in the transverse plane. The hadronic calorimeter, the electromagnetic calorimeter and the tracker are within the solenoid, while the muon chambers are placed outside the solenoid.

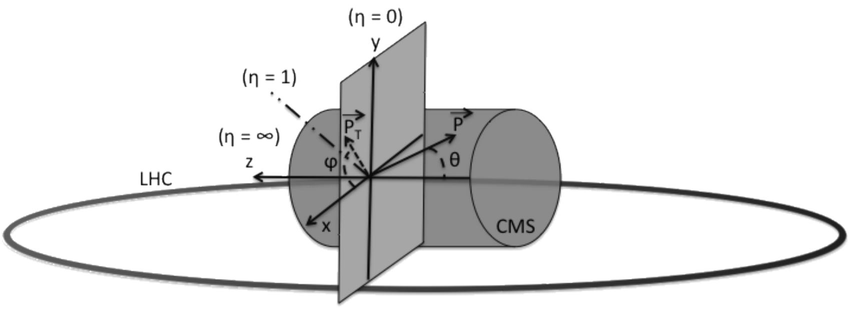

Figure 2.4: Representation of the coordinate system used by CMS. The point of origin is put at the collision point. The x-axis points towards the centre of the LHC ring such that the z-axis lies tangent to the beam axis.

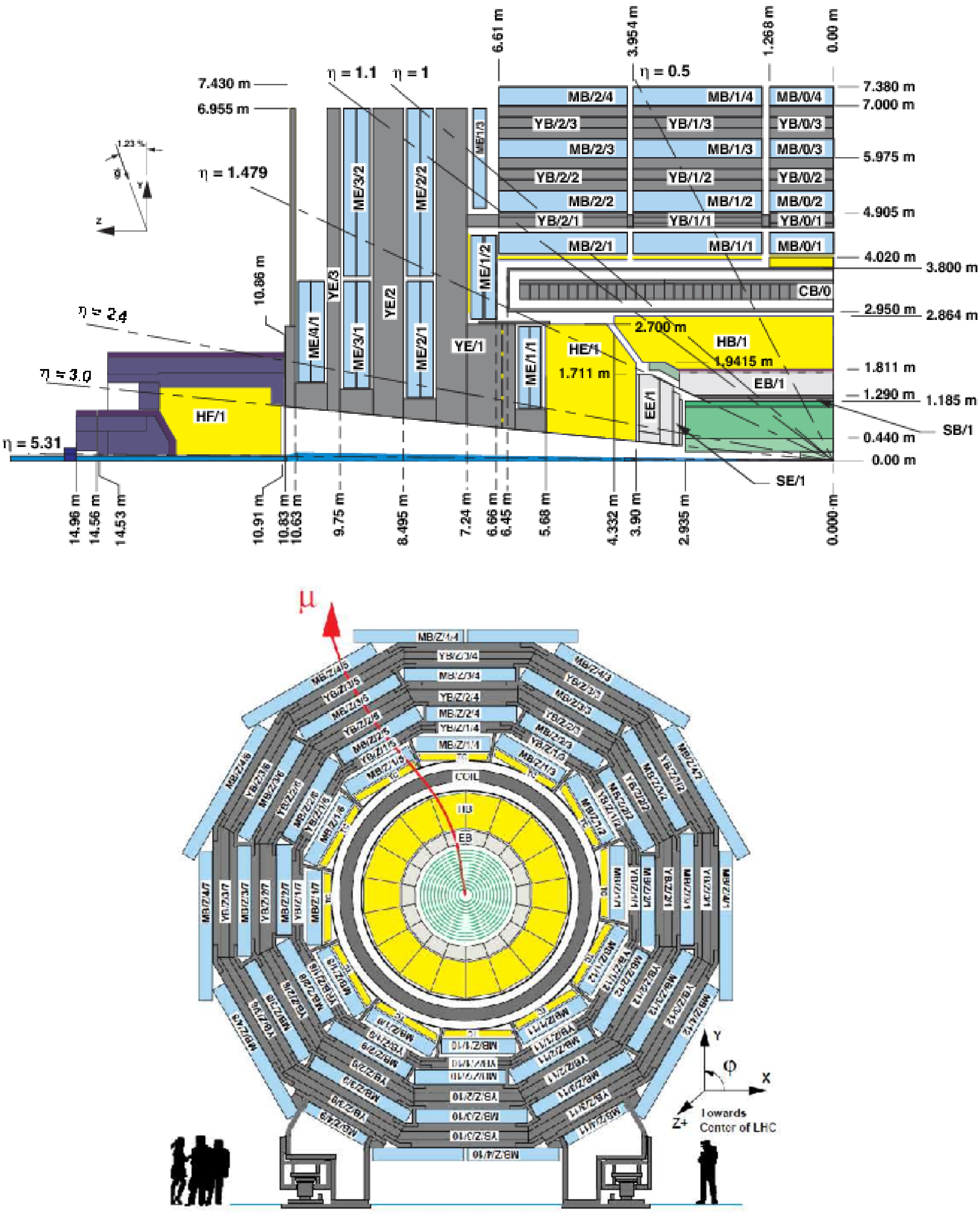

Figure 2.5: Schematic view of the CMS detector in the Run I configuration. (LEFT) Longitudinal view of one quarter of the detector. (RIGHT) Transversal view of one quarter of the detector. The muon system barrel elements are denoted as MBZ/N/S, where z= −2... + 2 is the barrel wheel number, n= 1...4 the station number and S= 1...12 the sector number. Similary, 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 electromagnet calorimeter as EE(end cap)/EB (barrel). The green part represents the tracking system[68]

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2.2.2.1 Muon system

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

The muon system is divided into three parts, shown in Figure 2.6[68]. The muon rate and neutron induced backgrounds are small and the magnetic field is very low for the barrel, thus CMS can use drift tube (DT) chambers. For the end caps however, the muon and background flux is much higher and there is a need to use cathode strip chambers (CSC) which are able to provide a faster response, higher granularity and have a better resistance against radiation. In order to form a redundant trigger system, resistive plate chambers (RPC) are added. This makes a total of 250 DT chambers, 540 CSC and 610 RPC. In Figure 2.5 the arrangement is shown.

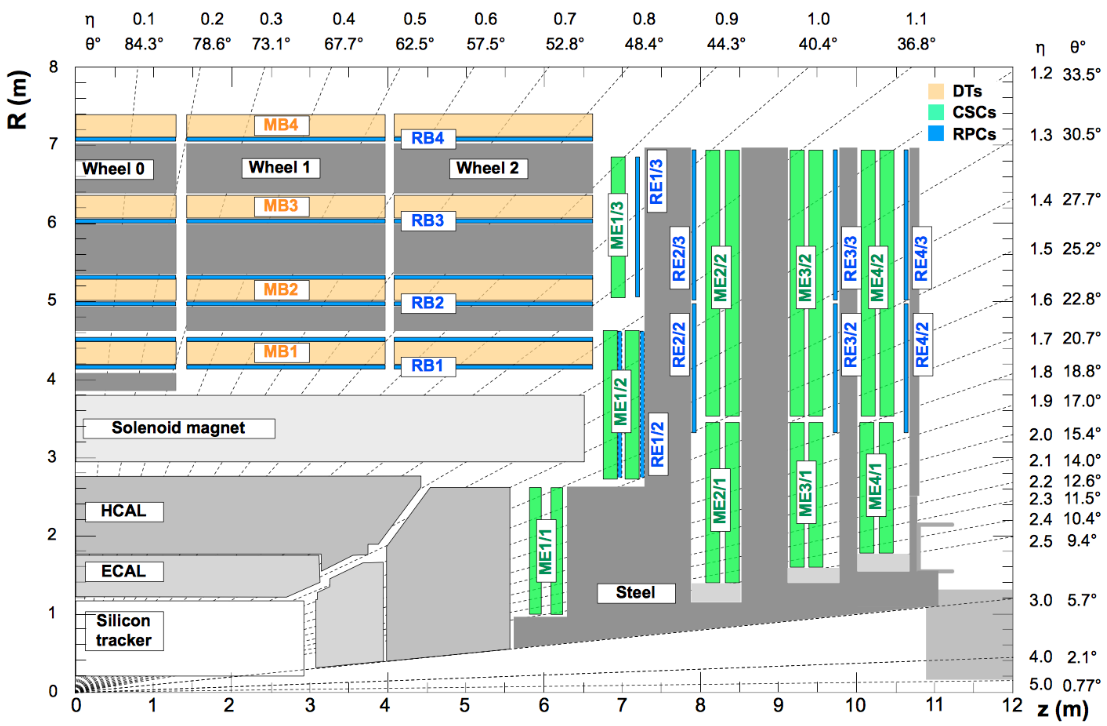

Figure 2.6: Schematic view of one quarter of the CMS muon system in the Run I configuration. [68]

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Providing a measurement for $|\eta| < 1.2$. The DT chambers in the barrel are on average 2×2.5 m in size and consist of 12 layers of DT cells - 4 cm wide gas tubes with positively charged stretched wire inside - arranged in three groups of four. The $r\phi$ coordinate is provided by the two outside groups, while the middle group measures the z coordinate. For each ϕ sector, the DT chamber is mixed with the flux return yoke. For the outer muon station, the DT chamber contains only 8 layers of DT cells, providing a muon position in th $r\phi$ plane. There are four CSC stations in each end cap, providing muon measurements for $0.9 < |\eta| < 2.4$ (Run I configuration). These CSC are multi-wired proportional chambers that consist of 6 anode wire planes crossed by 7 copper strips cathode panels in a gas volume. The r coordinate is provided by the copper strips, while ϕ coordinate comes from the anode wires, giving a two dimensional position measurement. There are six layers of RPC in the barrel muon system and one layer into each of the first three stations of the end cap. They are made from two high resistive plastic plates with an applied voltage and separated by a gas volume. Read out strips mounted on top of the plastic plates detect the signal generated by a muon passing through the gas volume. The RPC provides a fast response with a time resolution of 1 ns and covers a range of $|\eta| < 1.8$ (Run I configuration).

During the LS1, the muon system underwent major upgrades [69, 70]. In the fourth station of each end cap, the outermost rings of CSC and RPC chambers were completed, providing an angular region of $1.2 < |\eta| < 1.8$ for Run II, increasing the system redundancy, and allowing tighter cuts on the trigger quality. In order te reduce the environmental noise, outer yoke discs have been placed on both sides for the end caps. At the innermost rings of the first station, the CSC has been upgraded by refurbishing the readout electronics to make use of the full detector granularity instead of groups of three (Run I).

The muon system provides triggering on muons, identifying muons and improves the momentum measurement and charge determination of high p_T muons. On top of the muon system, the muon energy is deposited in the electromagnetic calorimeter, the hadronic calorimeter, and outer calorimeter. The high magnetic field enables an efficient first level trigger and allows a 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 (FIXME). There is an efficient muon measurement up to $|\eta| < 2.4$.

Muon reconstruction

The muon reconstruction[71] has three subdivision: local reconstruction, regional reconstruction and global reconstruction. The local reconstruction is performed on individual detector elements such as strip and pixel hits in the inner tracking system, and muon hits and/or segments on the muon chambers. Independent tracks are reconstructed in the inner tracker - called tracker track - and in the muon system, called standalone tracks. Based on these tracks, two reconstructions are considered. The outside-in approach is referred to as Global Muon reconstruction. For each standalone track, a tracker track is found by comparing the parameters of the two tracks propagated onto a common surface. Combining the hits from the tracker track and the standalone track, gives a fit via the Kalman filter technique [72, 73] for a global muon track. The second approach is an inside-out reconstruction, creating tracker muons. All candidate tracker tracks are extrapolated to the muon system taking into account the magnetic field, the average expected energy losses, and multiple Coulomb scattering in the detector material. When at least one muon segment - DT or CSC hits - matches the extrapolated track, the corresponding tracker track is indicated as a tracker muon.

For low transverse momenta ($p_T \lesssim 5$ GeV), the tracker muon reconstruction is more efficient than the global muon approach. This is due to the fact that tracker muons only require a single muon segment in muon system, while the global muon approach requires typically segments in at least two muon stations. The global muon approach typically improves the tracker reconstruction for $p_T \gtrsim 200$ GeV.

2.2.2.2 Solenoid

Making use of the knowledge of previous experiments of ALEPH and DELPHI at LEP and H1 at HERA, CMS choose for a large super conducting solenoid with a a length of 12.9 m and a 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 large bending power can be obtained for a modestly-sized solenoid. In order to ensure a good momentum resolution in the forward regions, a favourable length/radius was necessary. In Figure 2.7, a photo of the CMS solenoid is given.

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

2.2.2.3 Hadronic calorimeter

The hadronic calorimeter (HCAL) is dedicated to precisely measure the energy of charged and neutral hadrons via a succession of absorbers and scintillators. This makes it crucial for physics analyses with hadronic jets or missing transverse energy. The HCAL extends between $1.77 < r < 2.95$ m where r is the radius in the transverse plane with respect to the beam. Due to space limitations, the HCAL needs to be as small as possible and is made from materials with short interaction lengths - the length needed for absorbing 36.7% of the hadrons. The quality of the energy measurements is dependant on the fraction of the hadronic shower that can be detected. Therefore, the HCAL barrel (HB) inside the solenoid is reinforced by an outer hadronic calorimeter between the solenoid and muon detectors (HO, see Figure 2.8), using the solenoid as extra absorber. This increases the thickness to 12 interaction lengths. Furthermore, it should be as hermetic as possible and extend to large pseudo rapidity values. The HB and HO provide measurements for $\left|\eta\right| < 1.3$, while an end cap on each side (HE,$1.3 < \left|\eta\right| < 3$) and a forward calorimeter (HF, $\left|\eta\right| < 5.2$) extend the pseudo rapidity range.

The HB is made of 16 absorber plates where most of them are built from brass and others are made from stainless steal and is about five to ten intercation lengths thick. The HE is also composed of brass absorber plates and has a thickness corresponding to approximately ten interaction lengths. The HF experiences intense particle fluxes with an energy of 760 GeV deposited on average in a proton interaction at a center 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 I, it became clear that the glass windows of the PMTs had to be replaced which was done during LS1 [74]

2.2.2.4 Electromagnetic calorimeter

The electromagnetic calorimeter (ECAL) is designed to measure the energy of photons and electrons and covers $\left|\eta\right| < 3$. It is an hermetic, homogeneous detector and consists of 75 848

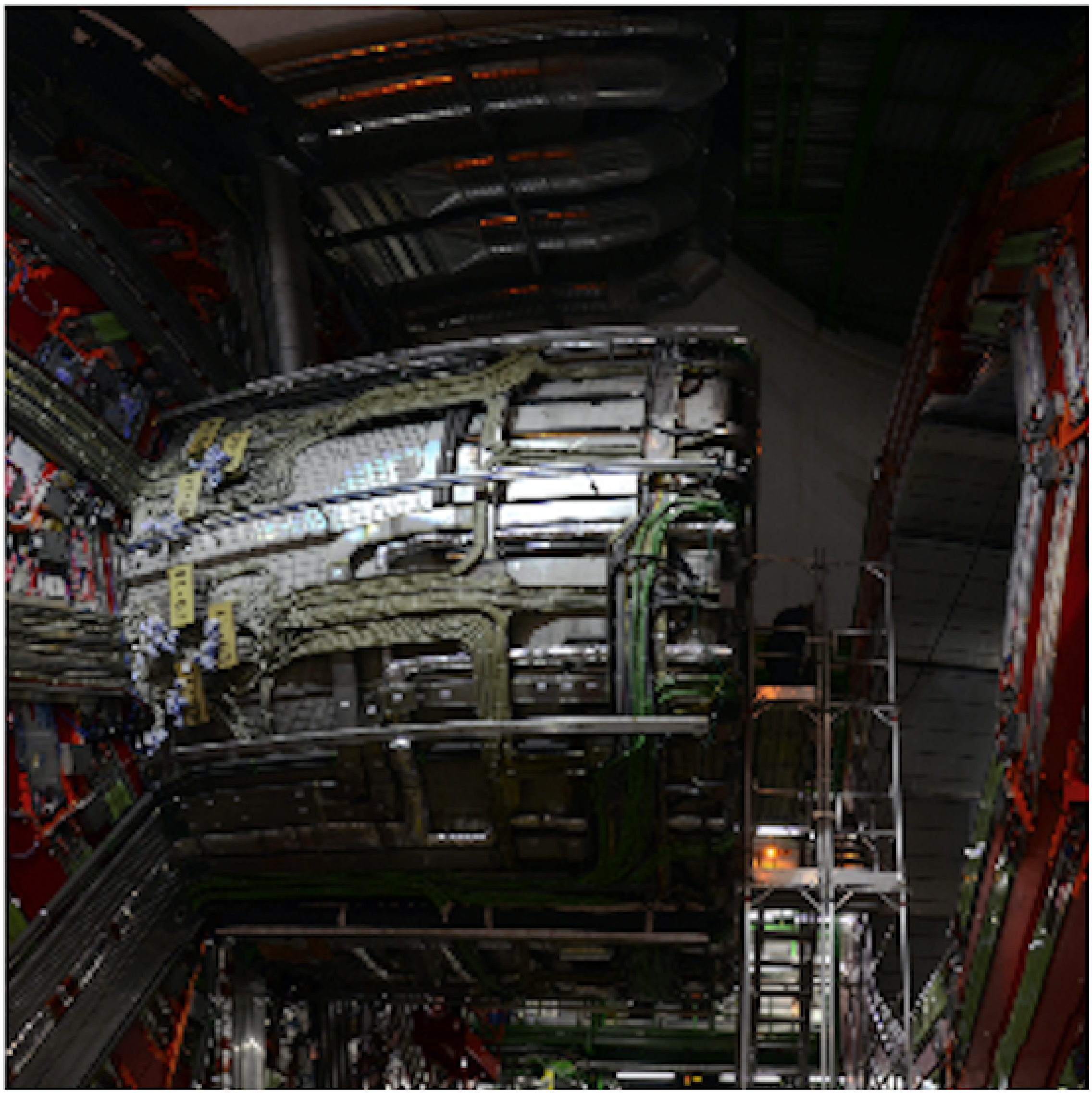

Figure 2.7: CMS solenoid during the long shutdown in 2013.

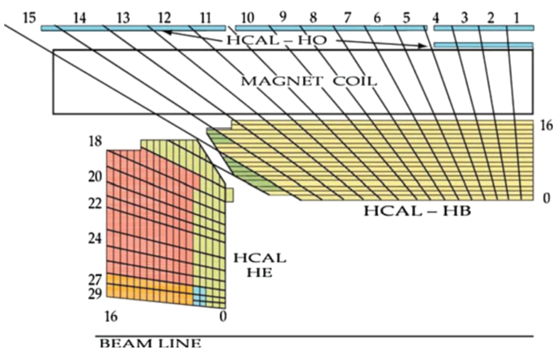

Figure 2.8: Tower segmentation for one quarter of the HCAL displayed in the rz plane[54].

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.

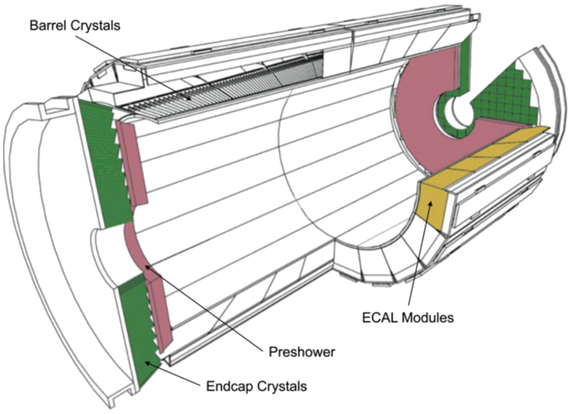

Figure 2.9: Schematic cross section of the electromagnetic calorimeter[54].

There are three regions: a central barrel (EB), a 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 $1.479 < |\eta| < 3.0$, are the EE. They consist of semi-circular aluminium plates from which structural units of 5×5 crystals (super crystals) are supported. The ES is placed in front of the crystal calorimeter over the end cap pseudo rapidity range with two planes of silicon strip detectors as 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[75] 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 super cluster algorithm, taking into account energy radiated via bremsstrahlung or conversion:

$$E_{e/\gamma} = GF_{e/\gamma} \sum_{i \in cluster} S_i(t) V C_i A_i, \tag{2.5}$$

where G is the absolute energy scale in GeV/ADC, F the energy containment corrections (depends on type of particle, its energy and pseudo rapidity, eg shower leakage and bremsstrahlung losses for electrons), $S(t)$ the relative channel variation with time, C the relative channel response and A the amplitude in ADC counts. The energy resolution is given by

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E(GeV)} \oplus 0.3\%, \tag{2.6}$$

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

In Run I, the energy reconstruction happened via a weighted sum of the digitized samples[76]. For Run II however, the reconstruction had to be made more resistant for out of time pile up and a multi-fit approach has been set in to place. In this approach, the pulse shape is modelled as a sum of one in-time pulse plus the out of time pulses [75]. The energy resolution is less than 2% in the central barrel region and 2-5 % elsewhere.

2.2.2.5 Inner tracking system and operations

The tracking system (tracker) [77] is the detecting unit closest to the point of interaction. Responsible for the reconstruction of trajectories from charged particles with $|\eta| < 2.5$ that are bent by the magnetic field, it provides a measurement of the momentum. The tracker is also responsible for the determination of the interaction point or vertex. It should be able to provide high granularity as well as speed, and be able to endure high radiation. For this reason, the CMS collaboration choose silicon detector technology.

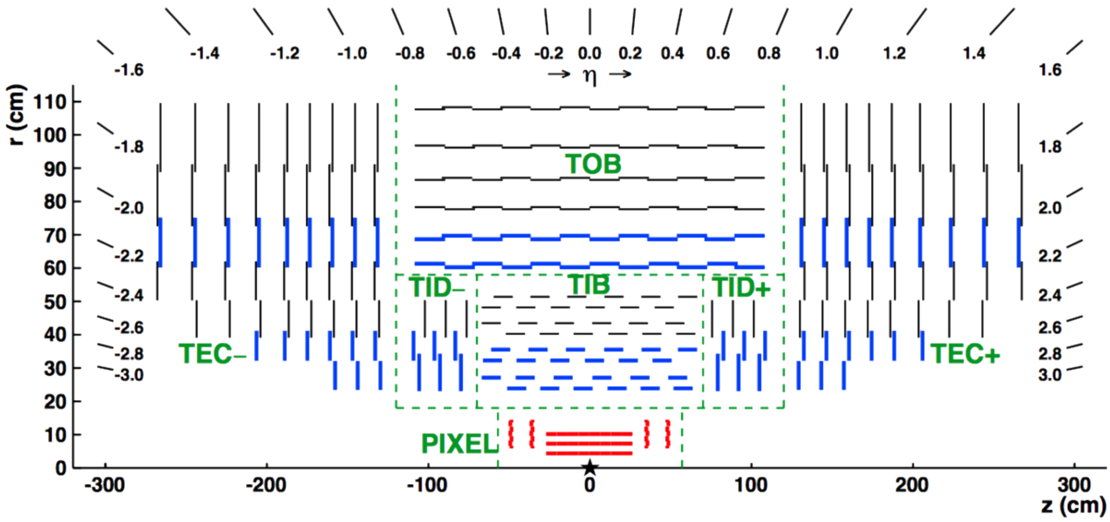

Figure 2.10: Schematic cross section of the top half of the CMS tracking system in the rz plane. The centre of tracker is shown with a star and corresponds to the approximate position of the proton collision point. The green dashed lines are an indication for each named tracker subsystem. The strip tracker modules that provide two-dimensional hits are shown by thin, black lines, while those able to reconstruct three-dimensional hit positions are shown by thick, blue lines. The pixel modules, shown in red, also provide three-dimensional hits. [63]

The tracking system consists of a cylinder of 5.8 m long and 2.5 m in diameter. It is immersed in a co-axial magnetic field of 3.8 T due to the solenoid. As shown Figure 2.10, the tracker is built up from a large silicon strip tracker with a small silicon pixel inside. The inner region, pixel ($4.4 < r < 10.2$ cm), gets the highest flux of particles. Therefore, pixel silicon sensors of 100×150 μm aree used. It consists of three cylindrical barrels that are complemented by two discs of pixel modules at each side. The silicon strip tracker ($20 < r < 116$ cm) has three subdivisions. The Tracker Inner Barrel and Discs (TIB, TID, see Figure 2.12) are composed of four barrel layers accompanied by three discs at each end. The outer part of the tracker - Tracker Outer Barrel (TOB) - consists of 6 barrel layers. In the outer discs, there are nine discs of silicon sensors, referred to as Tracker End Caps (TEC).

The pixel, shown in Figure 2.11 has 1440 modules that cover an area of about 1 m^2 and have 66 million pixels. It provides a three-dimensional position measurement of the hits arising from the interaction from charged particles with the sensors. In transverse coordinate ($r\phi$), the hit position resolution is about 10 µm, while 20-40 µm is obtained in the longitudinal coordinate (z). The sensor plane position provides the third coordinate. The silicon strip trackers consists of 15 148 single sided modules placed in the TIB, TID and the first four rings of the TEC. They provide 9.3 million readout channels. In the TOB and the outer three rings of the TEC, double sided modules are used. These modules are constructed from two back-to-back single sided modules, where one module is rotated through a stereo angle. This covers an active area of about 198 m^2. The TIB and TID provide position measurements in $r\phi$ with a resolution of approximately 13-38 µm, while the TOB provides a resolution of about 18-47 µm. The resolution in the z direction is approximately 230 µm in the TIB/TID and 530 µm in the TOB. To allow overlay and avoid gaps in acceptance, each module is shifted slightly in r or z with respect to its neighbouring modules within a layer. With this detector lay out, at least nine points per charged particle trajectory can be measured in an $|\eta|$ range up to 2.4.

Figure 2.11: The pixel barrel being re-installed after the Long Shutdown in 2015, around the beam pipe at CMS [78]

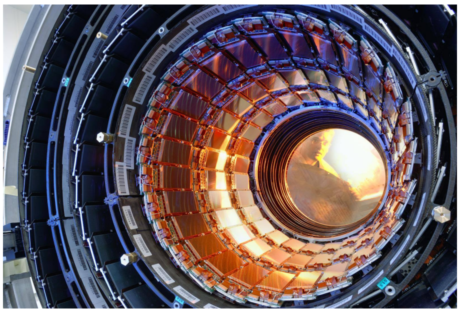

Figure 2.12: First half of the inner tracker barrel, consisting of three layers of silicon modules [79].

During the first data taking period of the LHC (2010 to 2013), the tracker operated at +4°C. With the higher LHC beam intensities from 2015 onwards, the tracker needs to be operated at much lower temperatures. This is due to the fact 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:

$$I \propto T^2 e^{-\frac{E_g}{2kT}}, \tag{2.7}$$

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

During the LS1, the CMS cooling plant was refurbished[80](Figure 2.14) and the fluorocarbon cooling system overhauled. To help to suppress the humidity inside the tracker, new methods for vapour sealing and insulation were applied (Figure 2.13. Furthermore, several hundred high-precision sensors are used to monitor the humidity and temperature. In order to get as dry air as possible, a new dry-gas plant provides eight times more dry gas (air or nitrogen) than during the first run, and allows regulation if the flow. As final addition, the cooling bundles outside the tracker are equipped with heater wires and temperature sensors in order to maintain safe operations above the cavern dew point For the data taking in 2015-2016, the tracker operated at −15°C.

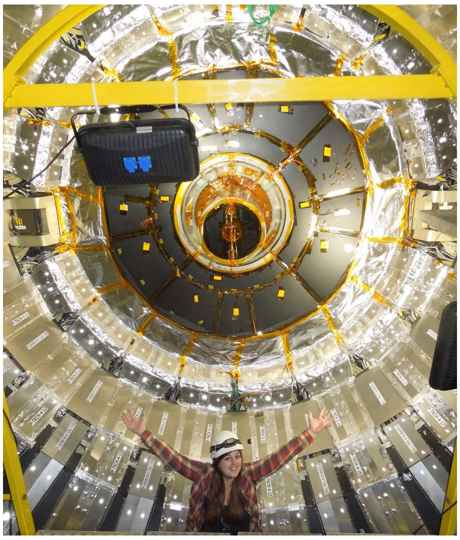

Figure 2.13: Tracker bulkhead being put into closed state with insulation pieces installed during an early trial in fall 2013

Figure 2.14: New Tracker high-capacity dry-gas plant with membrane separation system [67].

Track reconstruction

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

The seed generation is the first step. It consists of finding reconstructed hits that are usable for seeding the subsequent track-finding algorithm. They are identified from a group of at least three reconstructed hits in the tracker, or from a pair of hits while requiring the origin of the track segment to be compatible with the nominal beam-collision point. Since the pixel has a higher granularity compared to the strip tracker, its seed generation efficiency is higher. The overall efficiency exceeds 99%. The second step of each iteration, the pattern recognition algorithm, uses the seeds as a starting point for a Kalman filter method [72, 73]. This algorithm extrapolates the seed trajectory towards the next tracker layer taking into account the magnetic field and multiple scattering effects. The track parameters are updated when a compatible hit in the next layer is found. This procedure continues until the outermost layer us reached. Since the Kalman filter method can result in multiple tracks associated to the same seed, or different tracks sharing the same hits, a removal of ambiguities is necessary. This ambiguity resolving is done by removing tracks that are sharing too many hits from the list of track candidates. The tracks with highest number of hits or with the lowest χ^2 if the track fit is kept. The updated track parameters are then refitted using the Kalman filter method, where all hits found in the pattern recognition step are taken into account. The fit is done twice - once outwards from the beam line towards the calorimeters, and inwards from the outermost track hit to the beam line -, improving the estimation of the track parameters.

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

Primary vertex reconstruction

The primary vertex reconstruction should be able to meausre the location of all proton interaction vertices in each event: the signal vertex an all vertices from pile up events. It consists of a vertex finding and a vertex fitting algorithm and happens in three steps. Tracks are selected to be consistent with being produced promptly in the primary interaction by imposing requirements on the track parameters[77] By grouping reconstructed tracks according to the z coordinate of their closest approach to the beam line, vertices for all interaction in the same beam crossing are found, at CMS this is done by a deterministic annealing algorithm [81] . On top of this, a vertex fitting algorithm like the Adaptive Vertex fitter [82], is performed. This creates the three-dimensional primary-vertex position. With this fit, the contribution from long-lived hadron decays is reduced by down weighting the tracks with a larger distance to the vertex. The primary vertex corresponding to the highest sum of squared track transverse momenta is noted as the point of the main interaction. The resolution on the primary vertex is about 14 µm in $r\phi$ and about 19 µm in the z direction for primary vertices with the sum of the track $p_T > 100$ GeV for 2016 data taking.

2.2.3 Data acquisition

At a design luminosity of 10^{34} $1/(\mathrm{m}^2\,\mathrm{s})$, the proton interaction rate exceeds 1 GHz. This makes it impossible for the CMS experiment to store all the data generated. For this, a two level trigger system has been put in place. The first level (Level-1) is a custom hardware system, while a second level (HLT) is software based running on a large farm of computers. In run II, with the increase in centre of mass energy and a higher luminosity, a larger number of simultaneous inelastic collisions per crossing is expected with respect to run I. For this, the CMS Level-1 has been upgraded [83].

CMS Level-1 trigger

The Level-1 trigger has to be a flexible, maintainable system, capable of adapting to the evolving physics programme of CMS [84]. Its output rate is restricted to 100 kHz imposed by the CMS readout electronics. It is implemented by custom hardware and selects events containing candidate objects - eg ionization deposits consistent with a muon, or energy clusters corresponding to an electron / photon / tau lepton / missing transverse energy / jet. Collisions with large momenta can be selected by using scalar sum of the transverse momenta of the jets.

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

For run II, all hardware, software, databases and the timing control system have been replaced. The main changes are that the muon system now uses the redundancy of three muon detector system earlier to make a high resolution muon trigger. Other upgrades are that the calorimeter system isn't bound any more for streaming data the data and the global trigger has more level-1 trigger algorithms.

CMS HLT trigger

The HLT is an array of commercially available computers with programmable menu that has output rate of on average 400 Hz for off-line event storage. The data processing is based on a HLT path. This is a set of algorithmic steps to reconstruct objects and make selections on them. Here, the information of all sub detectors can be used to perform algorithms on higher level reconstructed objects.

2.2.4 CMS computing model

The selected data is stored, processed and dispersed via the Worldwide Large Hadron Collider GRID (WLCG)[85, 86]. This has a tiered structure that function as a single, coherent system:.

At CERN, a single Tier-0 is located. The raw data collected by CMS is archived here, and a first reconstruction of the data is done. This data is then already in a file format usable for physics analysis. Furthermore, it is able to reprocess data when new calibrations are made available. The Tier-0 site distributes this data to a total of seven Tier-1 centres. They carry out data reprocessing and store real data as well as simulated data. The Tier-1 further distribute the data to over 50 Tier-2 centres. These make the data accessible for physics analysis and are also being used for the production of simulated data. The data is made accessible for physicists around the world.

3 Analysis techniques

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3.1 Hadron collisions at high energies

In hadron collisions at as 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 expresses as a fraction of the hadron momentum

$$\vec{p}_{\mathrm{parton}} = x\vec{p}_{\mathrm{hadron}}, \tag{3.1}$$

where x is referred to as the Björken scaling variable. The interaction $\mathrm{p_A p_B} \to \mathrm{X}$ can then be factorised in terms of partonic cross sections $\hat{\sigma}_{\mathrm{ij}\to\mathrm{X}}$ [87]

$$\sigma_{\mathrm{p_A p_B}\to\mathrm{X}} = \sum_{\mathrm{ij}} \iint dx_1 dx_2\, f_{\mathrm{i}}^{\mathrm{A}}(x_1, Q^2) f_{\mathrm{j}}^{\mathrm{B}}(x_2, Q^2) d\hat{\sigma}_{\mathrm{ij}\to\mathrm{X}}, \tag{3.2}$$

where i and j are the partons resolved from protons A and B, $f_{\mathrm{i}}(x_{\mathrm{i}}, Q^2)$ the parton density functions (PDF), and Q^2 the factorisation scale more commonly denoted as μ_{F}. The factorisation scale is the scale at which the hadronic interaction can be expressed as a product of the partonic cross section and the process independent PDF. In Figure 3.1, the kinematic regions in x and μ_{F} are shown for fixed target and collider experiments.

The parton density functions (PDF) [88–90] give the momentum distribution of the proton amongst its partons at an energy scale μ_{F}. These function can not be determined from first principles and have to obtained from global fits to data. The PDFs are obtained from measurements on deep inelastic scattering using lepton-proton collision by the HERA collider [91], supplemented with proton-antiproton collisions from Tevatron at Fermi lab [92], and proton collision data from the ATLAS, CMS and LHCb collaborations at the LHC (Run 1) [93]. These measurements are included in global PDF sets known as the `PDF4LHC` recommendation [90]. From their measurement at scale μ_{F} these PDFs can be extrapolated using the DGLAP equations . The PDFs are used to calculate the cross section of a certain process and are therefore used as input for the Monte Carlo generators used to make the simulated data samples at the LHC. In the framework of this thesis, the NLO `PDF4LHC15_100` set is used. This set is an envelope

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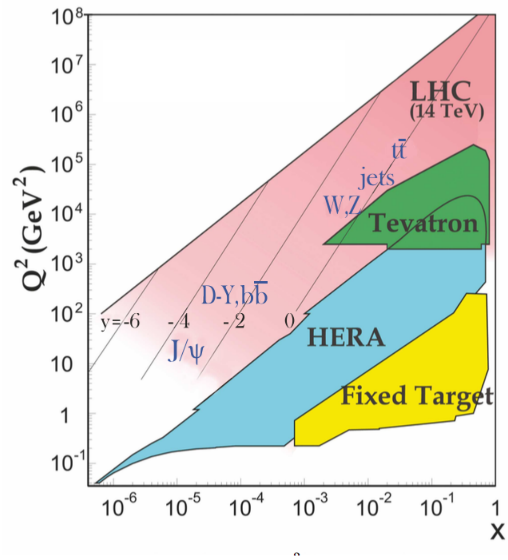

Figure 3.1: Kinematic regions in momentum fraction x and factorisation scale Q^2 probed by fixed-target and collider experiments. Some of the final states accessible at the LHC are indicated in the appropriate regions, where y is the rapidity. In this figure, the incoming partons have $x_{1,2} = (M/14\text{TeV})e^{\pm y}$ 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].

of three sets, CT14, MMHT2014 and NNPDF3.0 [90]. In Figure 3.2 the dependency of the PDFs on the momentum fraction x is shown for the NNPDF3.0 set on hadronic scale ($\mu_F^2 = (10\text{GeV})^2$ and LHC scale ($\mu_F^2 = (10^4\text{GeV})^2$. For most values of the momentum fraction, the gluon density dominates, meaning that it is easier to probe muons than the quarks. For x close to one, the parton densities of the up and down quarks (the valence quarks of the proton) dominate over the gluon density. The charm, anti-up, and anti-down quarks have lower densities in general since those are sea quarks which originate in the proton only through gluon splitting. The resolution scale Q^2 is typically taken to be the energy scale of the collision. For the top quark pair production a scale of $Q^2 = (350\,\text{GeV})^2$ is chosen, meaning that the centre-of-mass energy of the hard interaction is about twice the top quark mass. The uncertainty on the parton distributions is evaluated using the Hessian technique [94], where a matrix with a dimension identical to the number of free parameters needs to be diagonalised. In the case of PDF4LHC15_100 set, this translates into 100 orthonormal eigenvectors and 200 variations of the PDF parameters in the plus and minus direction.

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

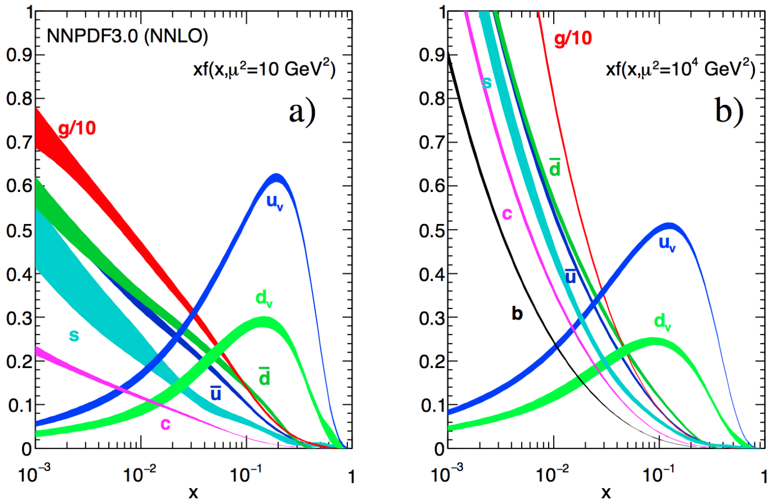

Figure 3.2: The momentum fraction x times the parton distribution functions $f(x)$, where $f = \mathrm{u_v}, \mathrm{d_v}, \overline{\mathrm{u}}, \overline{\mathrm{d}}, \mathrm{s}, \mathrm{c}$, or g as function of the momentum fraction obtained in the NNLO `NNPDF3.0` global analysis at factorisation scales $\mu^2 = 10\,\mathrm{GeV}^2$ (left) and $\mu^2 = 10^4\,\mathrm{GeV}^2$ (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].

particular the running behaviour of the strong coupling constant[1] α_S is found to be

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

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 $\alpha_S(\mu_F = m_Z) = 0.1181 \pm 0.0011$ [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 $\Lambda_{QCD} \approx 200\,\mathrm{MeV}$ is found for which α_S becomes larger than one. Under this limit, the perturbative calculations of observables can no longer be done.

Cross sections be written in terms of interacting vertices contributing to the matrix element (ME) originating from elements of a perturbative series [95], allowing them to be expanded as a power series of the coupling constant α

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

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

[1]The strong coupling constant is defined as $\alpha_S = \frac{g_S^2}{4\pi}$.

3.2 Event generation

In order to compare reconstructed data with theoretical predictions, collision events are generated and passed through a simulation of the CMS detector and an emulation of its readout. For the detector simulation, a so-called Full Simulation package [96, 97] based on the `Geant4` toolkit [98] is employed. It allows a detailed simulation of the interactions of the particles with the detector material.

3.2.1 Fundamentals of simulating a proton collision

The procedure of to generate $\mathrm{pp} \rightarrow \mathrm{X}$ events can be subdivided into sequential steps [99–101], as shown in Figure 3.3.

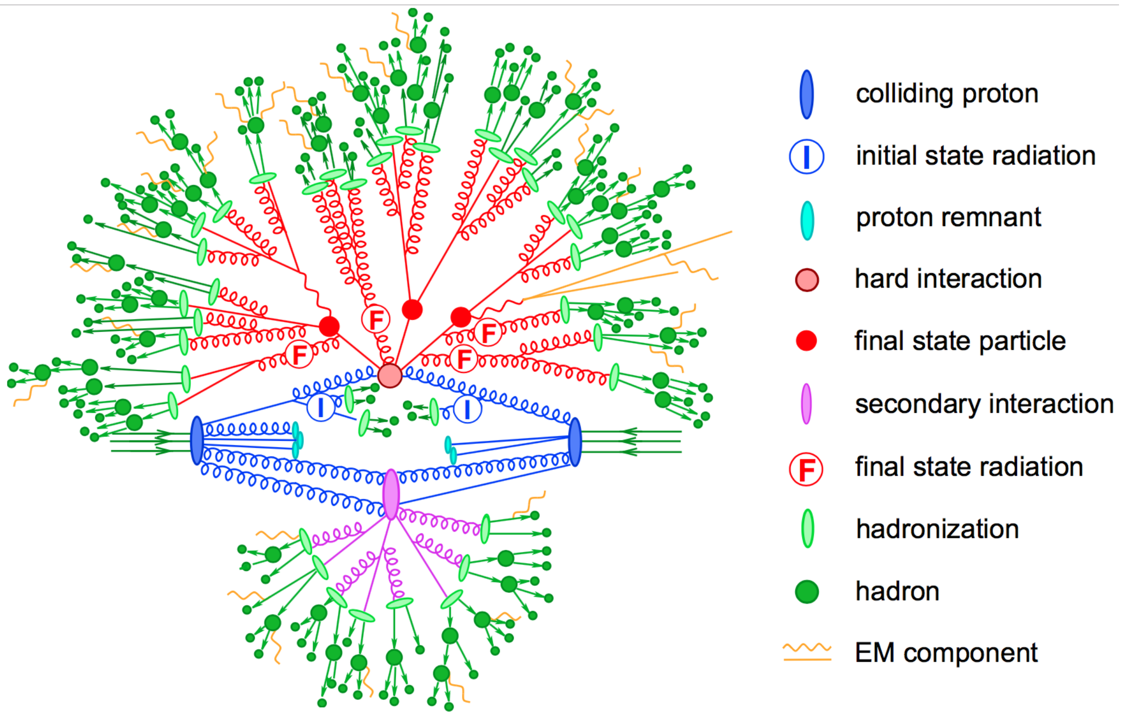

Figure 3.3: Sketch of a hadron collision as simulated by a Monte-Carlo event generator. The red blob in the centre represents the hard collision, surrounded by a tree-like structure representing Bremsstrahlung as simulated by parton showers. The purple blob indicates a secondary hard scattering event. 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 [101].

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

NOTE: Should I add more details?

3.2.2 Programs for event generation

The FEYNRULES package [102] allows the calculation of the Feynman rules in momentum space for any quantum field theory model. By use of a Lagrangian, the set of Feynman rules associated with this Lagrangian are calculated. Via the `Universal Feynrules Output` (UFO) [103] the results are then passed to matrix element generators.

The `MadGraph` program [104] is used to interpret the physics model and calculate the corresponding Feynman diagrams and matrix elements. After this, `MadEvent` [105] is used to calculate the corresponding partons. These generated parton configurations are then merged with `Pythia` [106–108] parton showers using the MLM merging scheme [109].

The `MadGraph5_aMC@NLO` program [110] combines the LO `MadGraph` [104] and the `aMC@NLO` program into a common framework. This combination supports the generation of samples at LO or next to NLO together with a dedicated matching to parton showers using the MLM [109] or FXFX [111] schemes respectively. The FXFX scheme produces a certain fraction of events with negative weights originating from the subtraction of amplitudes that contain additional emissions from the NLO matrix element to prevent double-counting.

The `POWHEG` box (versions 1,2) [112–117] contains predefined implementations of various processes at NLO. It applies the `POWHEG` method for ME- to PS- matching, where the hardest radiation generated from the ME has priority over subsequent PS emission to remove the overlap with the PS simulation.

The `JHU` generator (version 7.02) [118–121] is used to generate the parton level information including full spin and polarization correlations. It is commonly used for studying the spin an parity properties of new resonances such as $ab \to X \to VV$, where $V = Z, W, \gamma$).

The generation of events from processes involving the production and decay of resonances creates a computational heavy load, especially at NLO. The narrow width approximation the resonant particle is assumed to be on-shell. This makes the production and decay amplitude factorize, allowing to perform the simulation of the production and decay of heavy resonances like top quarks or Higgs bosons to be performed in separate steps. The `MadSpin` program [122] extends this approach and accounts for off-shell effects through a partial reweighting of the events. Additionally, spin correlation effects between production and decay products are taken into account.

The `Pythia` program (versions 6,8) [106–108] generates events of various processes at LO. Usually in the analysis, it is however only used for its PS simulation and it is interfaced with other LO and NLO event generators to perform subsequent parton showering, hadronisation, and simulation of the underlying event. In this thesis the underlying event tunes [123] are the CUETP8M2T4, CUETP8M1 and CUETP8M2.

The detector response is simulated via the `Geant4` [98] program. This program tracks the particles through the detector material via a detailed description of the detector and generates several hits throughout several sensitive layers. In addition, the response of the detector electronics to these hits are simulated.

3.2.3 Generating FCNC top-Z interactions

The FCNC processes are generated by interfacing the Lagrangian in Equation 1.25 with `MadGraph5_aMC@NLO` by means of the `FeynRules` package and its `Universal Feynrules Output` format. The complex chiral parameters are arbitrary chosen to be $f^{L}_{Xq} = 0$ and $f^{R}_{Xq} = 1$.

NOTE: Why LH and not RH?

The signal rates are estimated by use of the `MadGraph5_aMC@NLO` program for estimating the partial widths. The anomalous couplings are left free to float for this estimation, and only one coupling allowed to be non-vanishing at a time. The results are presented in Table 3.1. The

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	$3.665220\ 10^{5}$	$\left(\kappa_{tgu}/\Lambda\right)^2$
	t g c	$3.664620\ 10^{5}$	$\left(\kappa_{tgc}/\Lambda\right)^2$
$\kappa_{t\gamma q}/\Lambda$	t γ u	$1.989066\ 10^{4}$	$\left(\kappa_{t\gamma u}/\Lambda\right)^2$
	t γ c	$1.988904\ 10^{4}$	$\left(\kappa_{t\gamma c}/\Lambda\right)^2$
κ_{tZq}/Λ	t Z u	$1.637005\ 10^{4}$	$\left(\kappa_{tZu}/\Lambda\right)^2$
	t Z c	$1.636554\ 10^{4}$	$\left(\kappa_{tZc}/\Lambda\right)^2$
ζ_{tZq}	t Z u	$1.685134\ 10^{-1}$	$\left(\zeta_{tZu}\right)^2$
	t Z c	$1.684904\ 10^{-1}$	$\left(\zeta_{tZc}\right)^2$
η_{tHq}	t H u	$1.904399\ 10^{-1}$	$\left(\eta_{tHu}\right)^2$
	t H c	$1.904065\ 10^{-1}$	$\left(\eta_{tHc}\right)^2$

anomalous single top cross sections are calculated by convolution of the hard scattering matrix elements with the LO order set of `CTEQ6` partons densities [124]. The NLO effects are modelled by multiplying each LO cross section by a global k-factor. The LO single top production cross section and the global k-factors for the top-Z production are shown in Table 3.2. The hard scattering events are then matched to parton showers to `Pythia` to account for the simulation 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 ($\sigma_{t\bar{t}} = 6.741\ 10^{2}$pb), and considering the decay $t\bar{t} \rightarrow (bW^{\pm})(Xqt)$. The branching ratio

Table 3.2: Leading order single top production cross section for $\mathrm{pp} \to \mathrm{tZ}$ or $\bar{\mathrm{t}}\mathrm{Z}$, where the new physics scale is given in GeV. The NLO *k*−factors [125] are given in the last column.

Anomalous coupling	Cross section (pb)	NLO k−factor
$\kappa_{\mathrm{tgu}}/\Lambda$	$3.272\ 10^{7}\ \left(\kappa_{\mathrm{tgu}}/\Lambda\right)^2$	1.00
$\kappa_{\mathrm{tgc}}/\Lambda$	$3.021\ 10^{6}\ \left(\kappa_{\mathrm{tgc}}/\Lambda\right)^2$	1.00
$\kappa_{\mathrm{t\gamma u}}/\Lambda$	$2.260\ 10^{5}\ \left(\kappa_{\mathrm{t\gamma u}}/\Lambda\right)^2$	1.00
$\kappa_{\mathrm{t\gamma c}}/\Lambda$	$2.654\ 10^{4}\ \left(\kappa_{\mathrm{t\gamma c}}/\Lambda\right)^2$	1.00
$\kappa_{\mathrm{tZu}}/\Lambda$	$1.728\ 10^{6}\ \left(\kappa_{\mathrm{tZu}}/\Lambda\right)^2$	1.40
$\kappa_{\mathrm{tZc}}/\Lambda$	$2.040\ 10^{5}\ \left(\kappa_{\mathrm{tZc}}/\Lambda\right)^2$	1.40
ζ_{tZu}	$7.484\ \left(\zeta_{\mathrm{tZu}}\right)^2$	1.40
ζ_{tZc}	$1.038\ \left(\zeta_{\mathrm{tZc}}\right)^2$	1.40

$\mathscr{B}(\mathrm{t} \to \mathrm{bW}^{\pm})$ is assumed to be equal to one and the FCNC branching ratio is calculated as

$$\mathscr{B}(\mathrm{t} \to \mathrm{qX}) = \frac{\Gamma_{\mathrm{t}\to\mathrm{qX}}}{\Gamma_{\mathrm{t}}^{\mathrm{SM}} + \Gamma_{\mathrm{t}}^{\mathrm{FCNC}}} \approx \frac{\Gamma_{\mathrm{t}\to\mathrm{qX}}}{\Gamma_{\mathrm{t}}^{\mathrm{SM}}}, \tag{3.5}$$

where $\Gamma_{\mathrm{t}\to\mathrm{qX}}$ is given in Table 3.1, and the assumption $\Gamma_{\mathrm{t}}^{\mathrm{FCNC}} \ll \Gamma_{\mathrm{t}}^{\mathrm{SM}}$ is made . In Table 3.3 the resulting NLO cross sections for the top-Z FCNC interactions are given.

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

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

Anomalous coupling	Process	Cross section (pb)
$\kappa_{\mathrm{tZu}}/\Lambda$	$\mathrm{t\bar{t}} \to (\mathrm{b}\ell^+\nu)(\bar{\mathrm{u}}\ell^+\ell^-)$	$2.727008\ 10^{5}\ \left(\kappa_{\mathrm{tZu}}/\Lambda\right)^2$
	$\mathrm{t\bar{t}} \to (\bar{\mathrm{b}}\ell^-\bar{\nu})(\mathrm{u}\ell^+\ell^-)$	$2.727008\ 10^{5}\ \left(\kappa_{\mathrm{tZu}}/\Lambda\right)^2$
$\kappa_{\mathrm{tZc}}/\Lambda$	$\mathrm{t\bar{t}} \to (\mathrm{b}\ell^+\nu)(\bar{\mathrm{c}}\ell^+\ell^-)$	$2.72625710^{5}\ \left(\kappa_{\mathrm{tZc}}/\Lambda\right)^2$
	$\mathrm{t\bar{t}} \to (\bar{\mathrm{b}}\ell^-\bar{\nu})(\mathrm{c}\ell^+\ell^-)$	$2.726257\ 10^{5}\ \left(\kappa_{\mathrm{tZc}}/\Lambda\right)^2$
ζ_{tZu}	$\mathrm{t\bar{t}} \to (\mathrm{b}\ell^+\nu)(\bar{\mathrm{u}}\ell^+\ell^-)$	$2.827184\ \left(\zeta_{\mathrm{tZu}}\right)^2$
	$\mathrm{t\bar{t}} \to (\bar{\mathrm{b}}\ell^-\bar{\nu})(\mathrm{u}\ell^+\ell^-)$	$2.827184\ \left(\zeta_{\mathrm{tZu}}\right)^2$
ζ_{tZc}	$\mathrm{t\bar{t}} \to (\mathrm{b}\ell^+\nu)(\bar{\mathrm{c}}\ell^+\ell^-)$	$2.806801\ \left(\zeta_{\mathrm{tZc}}\right)^2$
	$\mathrm{t\bar{t}} \to (\bar{\mathrm{b}}\ell^-\bar{\nu})(\mathrm{c}\ell^+\ell^-)$	$2.806801\ \left(\zeta_{\mathrm{tZc}}\right)^2$

3.2.4 Generating SM background events

The SM tZqevents were generated using the `MadGraph5_aMC@NLO` generator, interfaced with `Pythia` version 8.2 [108] for parton showering and hadronisation. The WZ+jets, $\mathrm{t\bar{t}Z}$, tZq, and $t\bar{t}W$ samples are produced using the `MadGraph5_aMC@NLO`(version 5.222) [110], which includes up to one hadronic jet at next to leading order (NLO) QCD accuracy. Other minor background (e.g. WW, ZZ, tWZ and $t\bar{t}H$) are simulated using different generators such as `MadGraph` [104],`MadSpin` [122] and `JHU` [118–121]. 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

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

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
$WZ \to 3\ell\nu$	MadGraph5_aMC@NLO+Pythia	5.26	1.61
tZq with $Z \to \ell^+\ell^-$	MadGraph5_aMC@NLO+Pythia	0.0758	3.77
tqH with $H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$	JHU+Pythia	$8.80\ 10^{-6}$	-
$t\bar{t}W$+jets with $W \to \ell\nu$	MadGraph5_aMC@NLO+MadSpin+Pythia	0.2043 ± 0.0020	1.94
$t\bar{t}Z \to 2\ell + 2\nu +$ other, with $m_{\ell\ell} > 10$ GeV	MadGraph5_aMC@NLO+Pythia	0.2529 ± 0.0004	2.15
$t\bar{t}H$,no $b\bar{b}$ decays	POWHEG+Pythia	0.2151	-
$t\bar{t}H$, $b\bar{b}$ decays	POWHEG+Pythia	0.2934	-
$WW \to 2\ell 2\nu$	POWHEG+Pythia	12.178	-
$ZZ \to 4\ell$	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 $Z_\mu \to \ell^+\ell^-$	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 ± 0.90 (scale) ± 1.70 (PDF)	-
single top tW	POWHEG+Pythia	35.85 ± 0.90 (scale) ± 1.70 (PDF)	-
$t\bar{t}$	POWHEG+Pythia	$831.76\ ^{+19.77+35.06}_{-29.20-35.06}$	-
$Z/\gamma^* +$ jets, with $m_{\ell\ell} >$ 50GeV	MadGraph5_aMC@NLO+Pythia	$3 \times (\ 1921.8 \pm 0.6 \pm 33.2\ )$	1.49
$Z/\gamma^* +$ jets, with 10 GeV $< m_{\ell\ell} <$ 50 GeV	MadGraph+Pythia	18610	-

3.3 Multivariate analysis techniques: Boosted Decision Trees

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

There are many software tools that exist for MVA. In this thesis the `Tool for Multivariate Analysis` (TMVA) [126] is used. This software is an open source project included into `ROOT` [127]. All multivariate techniques in TMVA belong to supervised learning algorithms. By training on events for which the outcome is known, a mapping function is determined that describes a classification or an approximation of the underlying behaviour defining the target value (regression).

In this thesis boosted decision trees (BDT) are employed for the classification of events as implemented in the `TMVA` framework [126]. This multivariate techniques is based on a set of decision trees where each yields a binary output depending on the fact that an event is signal- or background-like. The advantage of such a multivariate technique is that several discriminating variables can be combined into a powerful one-dimensional discriminant D.

In Figure 3.4 a schematic view of de 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 $x_{\mathrm{i}} > C_{\mathrm{i}}$ is found by maximizing the separation gain between nodes

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

with the gain computed using the Gini index

$$\mathrm{gain(cell)} \approx p(1-p), \tag{3.8}$$

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

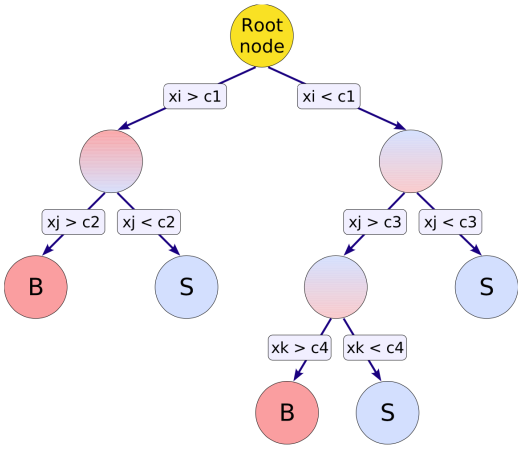

Figure 3.4: Schematic view of a decision tree. Figure taken from [126].

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 i = 3, which improves the robustness against overtraining. Examples of such boosting algorithms are Adaptive Boosting (AdaBoost) and Gradient Boosting [128]. 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

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

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 $\beta \leqslant 0.5$ 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.

In this thesis, the Gradient boost is used in combination with bagging, so-called stochastic gradient boosting. Bagging is a resampling technique draws a subset of events is 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 [129]. 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 the same parent distribution, albeit statistically fluctuated. Bagging smears over the statistical fluctuations in the training data, making it suitable for stabilising the response of the classifier and increasing the performance by eliminating overtraining. In stochastic gradient boosting the bagging resampling procedure uses random sub-samples of the training events for growing the trees.

The discriminating power of a BDT is assessed by analysing the receiver operating statistics (ROC) curve. This curves show the background rejection over the signal efficiency of the remaining sample. By looking at the area under the curve with respect to random guessing (AUC), the best classifier can be identified. This follows the Neyman-Pearson lemma that the best ROC curve is given by the likelihood ratio $\mathfrak{L}(x|\text{Signal})/\mathfrak{L}(x|\text{Background})$ [129]. No 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.

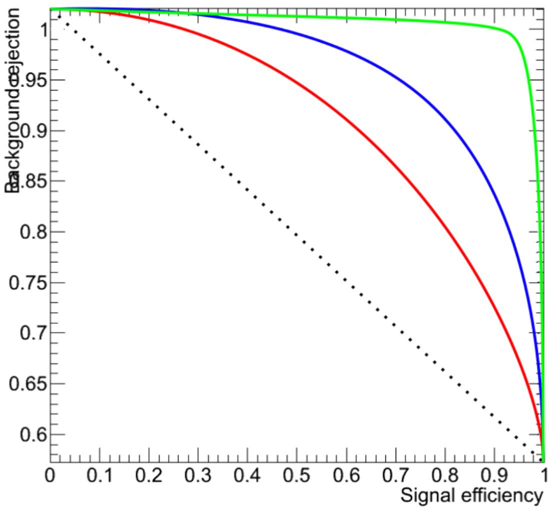

Figure 3.5: Example of ROC curves. In this example, the green method is better than the red one, which is better than the blue one. The dashed line represents a case where there is no separation. Figure taken from [130].

3.4 Statistical methodology

The search performed in the framework of this thesis requires the simultaneous analysis of data from different decay channels. The statistical methodology used for this search is developped by the ATLAS and CMS collaborations in the context of the LHC Higgs Combination group. The description of the methodology can be found in Refs. [131–134]. The `Higgs Combined Tool` [135] is a `RooStats` [136] framework which runs different statistical methods. In this section, only the statistical tools necessary for the performed search are described. The results presented in this thesis are obtained using the asymptotic formulae [137].

In general the event yields of signal and background processes are denoted as s and b respectively. These represent event counts in multiple bins or for 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 is 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 ($\sigma \times \mathscr{B}$) or on the signal cross section times branching ratio times detector acceptance ($\sigma \times \mathscr{B} \times \mathfrak{A}$). In order to test various theories, the latter is not useful unless the acceptance $\mathfrak{A}$ is provided. However, many analysis are not able to present result in a from of limits on $\sigma \times \mathscr{B}(\times\mathfrak{A})$, 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. sections.

In this thesis, the modified frequentist approach confidence levels are used [138, 139]. 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 $\mathfrak{L}(\text{data}|\,\mu,\theta)$ is constructed as

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

The probability density function (pdf) $p(\tilde{\theta}|\theta)$ describes all sources of uncertainty and is described in Section 3.4.1.1. 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

$$\text{Poisson}(\text{data}|\,\mu s(\theta) + b(\theta)) = \prod_\mathrm{i} \frac{(\mu s_\mathrm{i}(\theta) + b_\mathrm{i}(\theta))^{n_\mathrm{i}}}{n_\mathrm{i}!} e^{-\mu s_\mathrm{i}(\theta) - b_\mathrm{i}(\theta)}. \tag{3.11}$$

At the LHC, the test statistic is defined as

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

where the likelihood is maximised in the numerator 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 $\hat{\mu} \leq \mu$ 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[2].

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

$$\mathrm{CL} = \frac{\mathrm{P}\left(q_\mu \geq q_\mu^{\mathrm{obs}} | \, \mu s + b\right)}{\mathrm{P}\left(q_\mu \geq q_\mu^{\mathrm{obs}} | \, b\right)} \leq \alpha. \tag{3.13}$$

These probabilities are defined as

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

where p_μ and p_b are called the p-values associated to the two hypothesis, and $f(q_\mu | \mu, \hat{\theta}_\mu^{\mathrm{obs}})$ and $f(q_\mu | \, \mu = 0, \hat{\theta}_{\mu=0}^{\mathrm{obs}})$ 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 $\hat{\theta}_{\mu=0}^{\mathrm{obs}}$ and $\hat{\theta}_\mu^{\mathrm{obs}}$. These values of the nuisance parameters for the background only $\hat{\theta}_{\mu=0}^{\mathrm{obs}}$ and signal plus background $\hat{\theta}_\mu^{\mathrm{obs}}$ 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 CL$= 0.05$

The expected median upper limit and the $\pm 1\sigma$ and $\pm 2\sigma$ bands for a hypothesis is generated by a large set of pseudo data and calculate the CLs and the value of μ at 95% CL for each of them. A cumulative probability distribution can be build by starting the integration from the side corresponding to low event yields. The median expected value is where the cumulative distribution function crosses the 50% quantile. The $\pm 1\sigma$ (68%) and $\pm 2\sigma$ (95%) bands are defined by the crossings of the 16% and 84%, and 2.5% and 97.5% quantiles.

3.4.1.1 Adding sources of uncertainty

3.4.2 Extracting the signal model parameters

From a scan of the profile likelihood ratio,

$$q(a) = -2 \ln \frac{\mathfrak{L}(\mathrm{obs} | \, s(a) + b, \hat{\theta}_a)}{\mathfrak{L}(\mathrm{obs} | \, s(\hat{a}) + b, \hat{\theta})}, \tag{3.15}$$

[2]The signal hypothesis is data with a signal with strength μ.

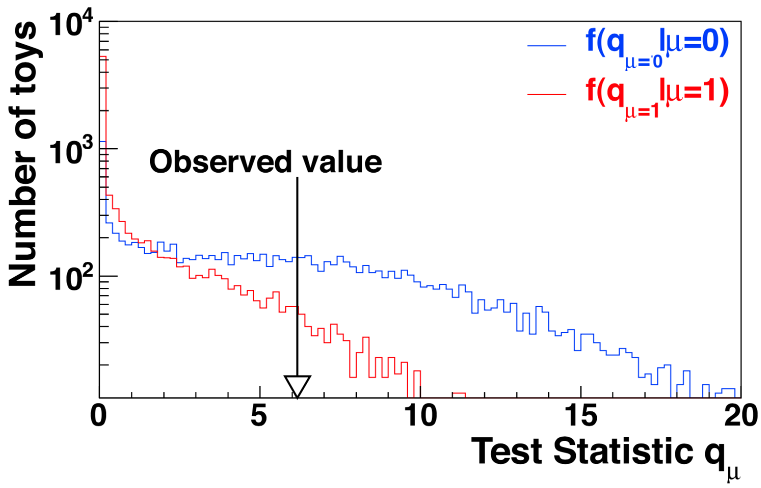

Figure 3.6: Test statistic distributions for pseudo data generated for the signal plus background ($\mu = 1$) and background only ($\mu = 0$) hypothesis. Figure taken from [134].

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

$$\mathfrak{L}_{\text{max}} = \mathfrak{L}(\text{obs}|\, s(\hat{a}) + b, \hat{\theta}) \tag{3.16}$$

is called the best-fit set.

The 68% and 95% CL on a given parameter of interest a_i is then evaluated from $q(a_i) = 1$ or $q(a_i) = 3.84$ respectively, where all other unconstrained model parameters are treated in the same way as the nuisance parameters [133].

4 Event reconstruction and selection

After the detector simulation described in Section **??**, the simulated data has the exact same format as the real collision data recorded at the CMS experiment. Therefore the same software can be used for the reconstruction of both simulation and real data. In this Chapter, the event reconstruction for physics analysis is shown.

4.1 Event reconstruction

4.2 Event selection

4.3 Regions and channels

4.4 Data driven background simulation

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

5.1 Construction of template distributions

5.2 Systematic uncertainties

5.3 Limit setting procedure

5.4 Result and discussion

Conclusion and outlook 6

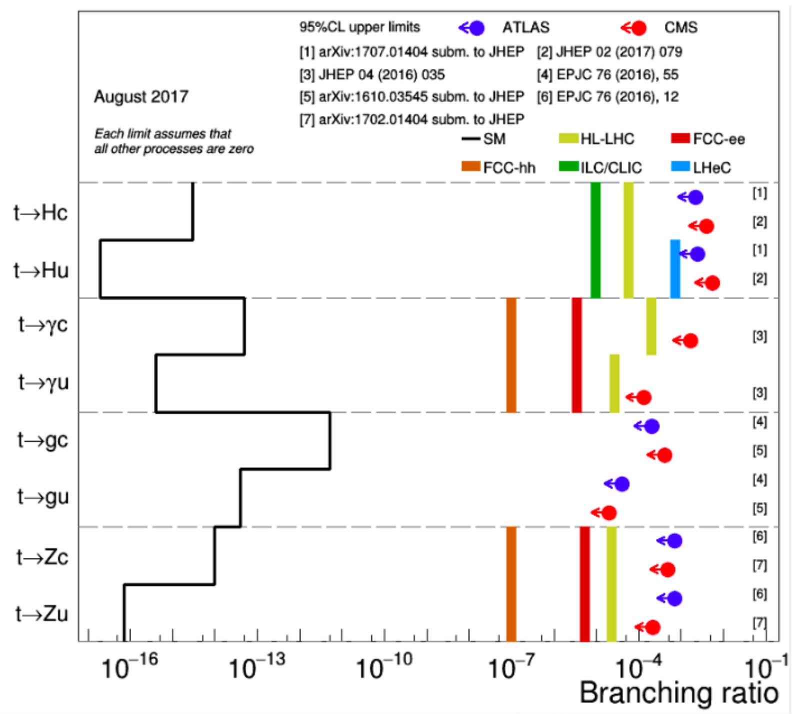

Figure 6.1:

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