Observation of the Higgs boson decaying to photons with the CMS detector using p-p collisions at 13 TeV

Louie Dartmoor Corpe
of Imperial College London

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Abstract

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Declaration

Louie Dartmoor Corpe

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Chapter 1

Introduction and theory

1.1 The Standard Model of particle physics

1.1.1 Introduction

The standard model (SM) of particle physics was put together during the second half of the 20$^{\text{th}}$ century. It has been an immensely successful theory, accurately describing all known processes in high energy physics encountered thus far [1]. The SM is a quantum field theory (QFT), in particular a renormalisable gauge theory. In this model, the fundamental elements of matter, as well as the forces which govern their interaction, can be represented as relativistic quantum fields, the excitations of which are manifested as particles (see Section 1.1.2). The SM places all the forces except for gravity in the same framework, and unites the electromagnetic and weak forces into the electroweak force (see Section 1.1.3). The Higgs mechanism explains the manifest breaking of the underlying symmetry between these forces and leads to the prediction of an observable particle, the Higgs boson (see Section 1.1.4).

1.1.2 Particles and Forces

In the SM, matter is made up of spin-1/2 particles, called *fermions*. Fermions come in two types: those which interact exclusively via the electroweak force, the *leptons*, and those which can also interact via the strong nuclear force, the *quarks*. The fermions can be arranged into three *generations*, which are identical copies of each other, aside from the masses of the constituent particles. Each of the particles mentioned in the table has a corresponding *antiparticle*, with the same mass and opposite charges. The SM fermions and their properties are displayed in Table 1.1.

type	Generation I		Generation II		Generation III	
leptons	e electron	$m = 0.511\,\mathrm{MeV}$ $q = -1$	μ muon	$m = 105\,\mathrm{MeV}$ $q = -1$	τ tau	$m = 1777\,\mathrm{MeV}$ $q = -1$
	ν_e electron neutrino	$m \sim 0\,\mathrm{MeV}$ $q = 0$	ν_μ muon neutrino	$m \sim 0\,\mathrm{MeV}$ $q = 0$	ν_τ tau neutrino	$m \sim 0\,\mathrm{MeV}$ $q = 0$
quarks	u up	$m = 2.3\,\mathrm{MeV}$ $q = +\frac{2}{3}$	c charm	$m = 1.275\,\mathrm{GeV}$ $q = +\frac{2}{3}$	t top or truth	$m = 173\,\mathrm{GeV}$ $q = +\frac{2}{3}$
	d down	$m = 4.8\,\mathrm{MeV}$ $q = -\frac{1}{3}$	s strange	$m = 95\,\mathrm{MeV}$ $q = -\frac{1}{3}$	b bottom or beauty	$m = 4.18\,\mathrm{GeV}$ $q = -\frac{1}{3}$

Table 1.1: The fundamental SM particles which constitute all matter in the universe are presented. The mass m and electric charge q are indicated for each particle [1]. The uncertainties on the masses have been omitted, although these can sometimes be large.

The matter particles interact via the fundamental forces. There are four known fundamental forces in the universe: the electromagnetic force, the weak nuclear force, the strong nuclear force and the gravitational force. The gravitational force is many orders of magnitude weaker than any of the other forces, and therefore has a negligible effect on the interactions of the SM particles. Furthermore, no adequate quantum theory of gravity currently exists, therefore it cannot be easily included in the SM. Consequently, the SM describes only with the strong, weak and electromagnetic forces. In the SM, the fundamental forces, are represented by the exchange of spin-1 *mediator particles*, the *vector bosons*. The forces described by the SM are listed in Table 1.2.

Force	Indicative Strength	Mediator	Mass
strong	1	gluons g (8)	0
electromagnetic	10^{-3}	photon γ	0
weak	10^{-8}	W-boson $\mathrm{W}^{\pm}$ Z-boson Z^0	80.4 GeV 91.2 GeV

Table 1.2: The three fundamental forces described by the SM are presented. For each force, the approximate strength relative to the strong force is shown, assuming two fundamental particles separated by a distance of $10^{-15}\,\mathrm{m}$. The mediator particle of each force is indicated along with its measured mass, where the uncertainties have been omitted. [1, 2]

The γ and g are massless, in contrast to the $\mathrm{W}^{\pm}$ and Z^0, which are massive. This difference is explained by the process of *electroweak symmetry breaking* via the Brout-

Englert-Higgs mechanism [3–8] described in Section 1.1.4. This mechanism introduces an additional scalar field, which implies the existence of a massive spin-0 particle, the Higgs boson.

1.1.3 Gauge groups of the SM Lagrangian

The Lagrangian $\mathcal{L}_{\mathrm{QFT}}$ of a QFT codifies the dynamics and interactions of its particles. It is constructed by considering the nature of the particles involved in the QFT and imposing the symmetries which the theory ought to display. Nöther's Theorem [9] states that for every symmetry in a Lagrangian, there is an associated conservation law. For example, if a QFT is invariant in time or space, this directly implies that the theory respects conservation of energy or momentum respectively. This illustrates that imposing a symmetry in a Lagrangian places requirements on how the particles in the theory are allowed to propagate and interact.

A gauge theory is a particular type of QFT where local gauge transformations are a symmetry of the Lagrangian. Such gauge symmetries are of principal importance in particle physics, as they lead to the introduction of gauge fields, which generate the mediator particles. For this reason, the mediators of the forces are sometimes referred to as *gauge bosons*. Typically, a gauge transformation takes the form of shifting the quantum mechanical phase of all wavefunctions. It is reasonable to require such transformations to leave the dynamics of the theory intact, since the phase of a wavefunction is never manifest in any physical observable. Thus the Lagrangian of any realistic theory should be *gauge invariant*, i.e. symmetric under phase transformation operations.

Quantum Electrodynamics

A simple example of a gauge theory is quantum electrodynamics (QED). This theory must incorporate fermions, which are described by the Dirac Lagrangian [10]:

$$\mathcal{L}_{\mathrm{fermion}} = i\overline{\psi}\gamma^{\alpha}\partial_{\alpha}\psi - m\overline{\psi}\psi, \tag{1.1}$$

where i is the imaginary unit, ψ is a Dirac spinor and $\overline{\psi}$ is its adjoint, m is the mass of the fermion, γ^{α} represents the Dirac gamma matrices and ∂_{α} is the 4-gradient.

Requiring *local gauge invariance* means that the Lagrangian should be invariant under a phase transformation such as $\psi \rightarrow \psi' = \psi e^{i\theta(\vec{x},t)}$, where $\theta(\vec{x},t)$ is some arbitrary differentiable function. Applying the transformation to Equation 1.1 gives:

$$\mathcal{L}_{\text{fermion}} \rightarrow \mathcal{L}'_{\text{fermion}} = \mathcal{L}_{\text{fermion}} - \overline{\psi}\gamma^{\alpha}\psi(\partial_{\alpha}\theta(\vec{x},t)). \tag{1.2}$$

Evidently $\mathcal{L}_{\text{fermion}}$ is not gauge invariant. This is remedied by introducing an additional field A_{α}. An extra term, $-g_{\text{EM}}\overline{\psi}\gamma^{\alpha}\psi A_{\alpha}$, is added to the Lagrangian to account for the interaction of the fermion with A_{α}, where g_{EM} is the strength of the interaction. Local gauge invariance is restored so long as A_{α} changes in the following way [10]:

$$A_{\alpha} \rightarrow A_{\alpha} - \frac{1}{g_{\text{EM}}}\partial_{\alpha}\theta(\vec{x},t), \tag{1.3}$$

The Lagrangian can also accommodate a term for A_{α} propagating freely through space. Since A_{α} is a 4-vector, it is described by the Proca equation for spin-1 bosons [10]:

$$\mathcal{L}_{\text{boson}} = -\frac{1}{16\pi}F^{\alpha\beta}F_{\alpha\beta} + \frac{1}{8\pi}m_{\text{boson}}A^{\alpha}A_{\alpha}, \tag{1.4}$$

where $F^{\alpha\beta} = (\partial^{\alpha}A^{\beta} - \partial^{\beta}A^{\alpha})$ and m_{boson} is the mass of the spin-1 boson. Equation 1.4 is locally gauge invariant so long as $m_{\text{boson}} = 0$, i.e. the boson is required to be massless.

It is convenient to define the *covariant derivative*, incorporating the interaction term:

$$D_{\alpha} = \partial_{\alpha} + ig_{\text{EM}}A_{\alpha}, \tag{1.5}$$

so that $\mathcal{L}_{\text{QED}}$ can be written compactly as :

$$\mathcal{L}_{\text{QED}} = i\overline{\psi}\gamma^{\alpha}D_{\alpha}\psi - m\overline{\psi}\psi - \frac{1}{16\pi}F^{\alpha\beta}F_{\alpha\beta}. \tag{1.6}$$

The full Lagrangian for QED describes a free fermion, a free spin-1 boson and a term for interactions between the boson and the fermion. The boson is identified as the photon. The factor multiplying g_{EM} is interpreted as the electric charge of the fermion.

The local gauge transformation is equivalent to applying a unitary 1×1 matrix to the wavefunction. The group of all such transformations is $U(1)$. It is a general principle that the number of degrees of freedom in the underlying symmetry group dictates the number of additional bosons needed to keep the theory locally gauge invariant [10].

Quantum Chromodynamics

The strategy described in Section 1.1.3 can be used to derive the Lagrangian for quantum chromodynamics (QCD), which codifies the dynamics of the strong force [10]. The situation is more complicated because the underlying group is not $U(1)$ but $SU(3)$, which has eight degrees of freedom. This leads to eight massless gluons. In QED, the interaction between the boson and the fermion is dictated by electric charge; the analogue for QCD is *colour charge*. However, colour charge cannot be represented by a single real number. Colours charges are instead linear combinations of *red, antired, green, antigreen, blue, antiblue*. Each SM quark has three identical copies with different colour charge. Another important difference is that $U(1)$ is abelian while $SU(3)$ is not. The consequence of this is that unlike the QED photon, which carries no electric charge, the QCD gluons do carry colour charge. Gluons can therefore feel the strong force and self-interact. This fact leads QCD to display unusual properties such as confinement of quarks and asymptotic freedom [11, 12]. The gauge group for QCD, $SU(3)_{\mathrm{C}}$, is generally written with a subscript to indicate that it generates colour charge.

Electroweak unification

A major achievement of 20$^{\text{th}}$ century science was the unification of the electromagnetic and weak forces by Glashow, Weinberg and Salam [13–15]. Their electroweak theory (EWT) considers the gauge group $SU(2)_{\mathrm{L}} \times U(1)_{\mathrm{Y}}$. The $SU(2)_{\mathrm{L}}$ group has three degrees of freedom, so three gauge bosons and three types of charge are obtained from imposing local gauge invariance. The charges are called *weak isospin*, and labelled i_1, i_2, i_3. The subscript in $SU(2)_{\mathrm{L}}$ indicates that only left-handed particles carry nonzero weak isospin charge. The $U(1)_{\mathrm{Y}}$ group behaves as in QED, but generates *weak hypercharge* y. The electric charge q is related to weak isospin and weak hypercharge by the relation $q = y/2 + i_3$. The subscript in $U(1)_\mathrm{Y}$ refers to the fact hypercharge is the generated charge.

Right- and left-handed fermions are considered separately in EWT. It is helpful to think of the right-handed fermion spinors as *singlets*, or column vectors of one spinor. For example, this is labelled e_R, for the right-handed electron singlet. The left-handed fermions come in *doublets* (a column vector of two fermion spinors), e.g.:

$$L_\mathrm{L} = \begin{pmatrix} \nu_\mathrm{e} \\ \mathrm{e} \end{pmatrix}_\mathrm{L},$$

which is the left-handed lepton doublet containing the left-handed electron and electron neutrino. No right-handed neutrinos are included in this scheme.

Imposing gauge invariance leads to the introduction of gauge fields: $W^1_\alpha, W^2_\alpha, W^3_\alpha$ and B_α, for $SU(2)_\mathrm{L}$ and $U(1)_\mathrm{Y}$ respectively. The physical states observed in nature are mixtures of the underlying weak isospin and weak hypercharge gauge bosons:

$$\mathrm{W}^{\pm}{}_\alpha = \sqrt{\frac{1}{2}}(W^1_\alpha \mp W^2_\alpha), \tag{1.7}$$

$$\mathrm{Z}^0{}_\alpha = \cos\theta_W W^3_\alpha - \sin\theta_W B_\alpha, \tag{1.8}$$

$$A_\alpha = \sin\theta_W W^3_\alpha + \cos\theta_W B_\alpha, \tag{1.9}$$

where θ_W is the Weinberg angle, which relates strengths of the electromagnetic (g_EM) and weak (g_W) forces via the relation $\tan\theta_W = g_\mathrm{W}/g_\mathrm{EM}$.

Quarks are also accommodated in this framework. For example, for the first generation of quarks, two right-handed quark singlets u_R and d_R and one left-handed quark doublet Q_L are introduced. The full SM, incorporating the electroweak and strong forces, is described by the gauge group $SU(3)_\mathrm{C} \times SU(2)_\mathrm{L} \times U(1)_\mathrm{Y}$.

An issue arises when considering masses of particles. The left- and right-handed components of the fermions transform as doublets and singlets respectively, so the usual fermion mass term is no longer gauge invariant. Furthermore, the gauge bosons should be massless to preserve the gauge symmetry. This is the case for the photon and gluons, but the $\mathrm{W}^\pm$ and Z^0 have experimentally measured masses of the order of 90 GeV [1]. A mechanism is needed to account for the masses of these particles.

1.1.4 Electroweak Symmetry Breaking and the Higgs Mechanism

The process which allows the $W^{\pm}$ and Z^0 to acquire a mass is *electroweak symmetry breaking*. This occurs in the SM via the Brout-Englert-Higgs mechanism [3–8]. In this scheme, an additional complex scalar $SU(2)_{\mathrm{L}}$ doublet ϕ is introduced. The Lagrangian for ϕ is gauge invariant but the ground state is not:

$$\begin{aligned}\mathcal{L}_\phi =& \frac{1}{2}(D_\alpha\phi)^*(D^\alpha\phi) \text{ (kinetic term)} \\ &+ \frac{1}{2}\mu^2(\phi^*\phi) - \frac{1}{4}\lambda^2(\phi^*\phi)^2 \text{ (potential term)} ,\end{aligned} \tag{1.10}$$

where μ and λ are constants. The covariant derivative D_α defined in Equation 1.5 has been used here to ensure gauge invariance. In this case, D^α also accounts for the interactions with the $W^{\pm}, Z^0$ and gluons in addition to the photon. The first term of the Lagrangian corresponds to the kinetic part, while the second and third correspond to a potential. The term $\frac{1}{2}\mu^2(\phi^*\phi)$ resembles a mass term, but it is not: the sign needs to be negative. If $\mu^2 < 0$, the potential has a non-zero vacuum expectation value (VEV), and the ground state is represented by a circle of minima. In order to re-write the Lagrangian in terms of physical particles, an expansion around one of the minima is required. Since they are all equivalent, an arbitrary minimum is chosen:

$$\phi_0 = \text{VEV} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}, \tag{1.11}$$

where $v = \sqrt{-\mu^2/\lambda}$. At this stage, any of the minima lying upon the circle of ground states could have been chosen, but a particular choice had to be made. This step breaks the manifest symmetry in the physical states while preserving it in the Lagrangian.

To obtain the physical states from this Lagrangian, a small perturbation field, H, around the VEV is introduced:

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+H\end{pmatrix}, \tag{1.12}$$

which can be substituted back into Equation 1.1.4. Expanding out the implicit interactions with the gauge bosons from the covariant derivative, the equation becomes:

$$\begin{aligned}\mathcal{L}_\phi = &\frac{1}{2}(\partial_\alpha H)(\partial^\alpha H) - \frac{1}{2}\mu^2 H^2 \\ &+ \frac{v^2}{8}(g_{\mathrm{W}}\mathrm{W^+}_\alpha \mathrm{W}^{+\alpha} + g_{\mathrm{W}}\mathrm{W^-}_\alpha \mathrm{W}^{-\alpha} + (g^2_{\mathrm{W}} + g^2_{\mathrm{EM}})\mathrm{Z^0}_\alpha \mathrm{Z}^{0\alpha}) + ...\end{aligned} \tag{1.13}$$

where terms which are not mass-like have been omitted. The first two terms can be identified as the Klein-Gordon equation for a massive scalar boson of mass $\sqrt{2}\mu$: this is the Higgs boson. The other terms represent the great success of the Brout-Englert-Higgs mechanism: the $\mathrm{W}^\pm$ and Z^0 bosons have acquired masses. The absence of equivalent terms for the photon and gluons means that they do not acquire masses, which is in accordance with experimental expectations.

Furthermore, it is possible to add additional gauge invariant terms involving the scalar field. These are known as the Yukawa interactions. For example, in the case of the first generation leptons:

$$\begin{aligned}\mathcal{L}_{\mathrm{Yukawa}} &= \kappa_e(\overline{L}\phi e_R + \overline{e_R}\phi^\dagger L) \\ &= \kappa_e v(\overline{e_L}e_R + \overline{e_R}e_L) + \kappa_e(\overline{e_L}He_R + \overline{e_R}He_L),\end{aligned} \tag{1.14}$$

where κ_e is a real constant. The first term gives a mass to the electron and the second represents the interaction between the electron and the Higgs boson. By construction, the strength of the interaction is directly proportional to the mass of the particle which is considered. Furthermore, the neutrino does not acquire any mass via this mechanism. The scheme described above does not *prescribe* the masses of the Higgs boson or fermions: these are free parameters and must be specified from experimental measurements.

To summarise, the Brout-Englert-Higgs mechanism adds gauge-invariant terms to the SM Lagrangian which permit the $\mathrm{W}^\pm$ and Z^0 bosons and the fermions to acquire masses while leaving the gluons and the photon massless. The outcome is one additional spin-0 particle, the Higgs boson, the mass of which is not directly predicted by the theory.

1.2 Higgs boson phenomenology

1.2.1 History of Higgs boson searches

Since the Higgs boson was postulated in the 1960s, there have been many efforts to try to detect it. Theoretical considerations precluded large Higgs boson masses above the order of 1 TeV [16]. Experiments conducted before the start of the Large Electron-Positron Collider (LEP) operation excluded a Higgs boson of mass below the order of 10 GeV [17]. Direct searches at LEP and the Tevatron excluded a Higgs boson mass below 114 GeV [18, 19], and precision measurements of the electroweak parameters suggested that the Higgs boson mass should be below 200 GeV [20]. The search for the Higgs boson prompted the construction of the the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN). Two multi-purpose detectors, A Toroidal LHC Apparatus (ATLAS) and Compact Muon Solenoid (CMS), were designed with the Higgs observation as one of their main physics goals. In 2012, the two experiments jointly announced the observation of a Higgs-like particle, ending a 50-year interval between postulation and discovery [21, 22]. The most precise measurement of the Higgs boson's mass to date is $m_{\mathrm{H}} = 125.09 \pm 0.24$ [23].

1.2.2 Higgs boson production at the LHC

According to SM (see Equation 1.14), the Higgs boson interacts with particles proportional to their masses. Five production modes can lead to the production of a Higgs boson in p-p collisions at the LHC. The Feynman diagrams for these processes can be seen in Figure 1.1. The most likely production mode for $m_{\mathrm{H}} = 125.09$ GeV is gluon-gluon fusion (ggH) via a loop of top quarks, which has a cross section of approximately 49 pb at 13 TeV. The other production modes are vector boson fusion (VBF) at 3.8 pb, W boson associated production (WH) at 1.4 pb, Z boson associated production (ZH) at 0.9 pb, and top quark fusion and associated production (ttH) at 0.5 pb [24]. The WH and ZH modes are often considered collectively as vector boson associated production (VH).

1.2.3 Higgs boson decays

The SM Higgs boson can decay either directly to pairs of particles, or via virtual loops. In direct decays to pairs of particles, the branching ratios are proportional to the mass

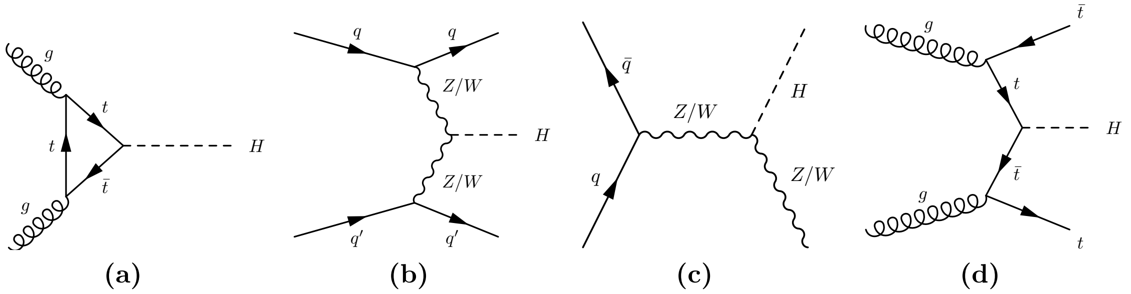

Figure 1.1: Higgs production modes at the LHC: (a) gluon-gluon fusion, via a loop of top quarks, (b) vector boson fusion, with associated quark production, (c) associated vector boson production with either the Z^0 or W boson and (d) top quark fusion with associated top quark production.

of the decay product. The most likely direct decay modes to massive particles for a SM Higgs boson with $m_{\mathrm{H}} = 125.09\,\mathrm{GeV}$ are $\mathrm{H} \rightarrow \mathrm{bb}$ (58.2%), $\mathrm{H} \rightarrow \mathrm{WW}^*$ (21.4%), $\mathrm{H} \rightarrow \tau\tau$ (6.3%), $\mathrm{H} \rightarrow \mathrm{ZZ}^*$ (2.6%) [24]. The production of a pair of t quarks is not kinematically allowed. The Higgs coupling to electrons, muons, neutrinos, up quarks, down quarks and strange quarks is very small due to the mass of the decay products. In addition, Higgs boson decays can occur via a loop of virtual massive particles to a pair of gluons (8.2%), to a pair of photons (0.23%) or to $\mathrm{Z}^0\gamma$ (0.02%) [24].

Despite the low branching fraction, the decay $\mathrm{H} \rightarrow \gamma\gamma$ played a key role in the discovery of the Higgs boson. This is because it has a very clean signature of two highly energetic photons in the detector, with an irreducible but controllable SM background. This is in contrast with some of the other more frequent decay modes, where difficulties in reconstructing the decay products or excessive noise from the LHC p-p collisions drastically reduce the experimental sensitivity. The leading order Feynman diagrams for the $\mathrm{H} \rightarrow \gamma\gamma$ decay can be seen in Figure. 1.2.

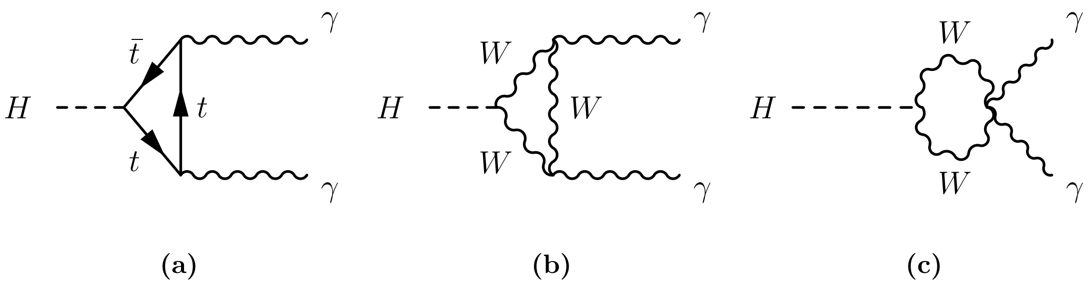

Figure 1.2: A Higgs boson decaying to photons via a loop of top quarks (a) or via loops of W bosons (b, c).

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List of Acronyms

VBF vector boson fusion

ggH gluon-gluon fusion

VH vector boson associated production

ttH top quark fusion and associated production

ZH Z boson associated production

WH W boson associated production

VEV vacuum expectation value

CERN the European Organization for Nuclear Research

LHC the Large Hadron Collider

CMS Compact Muon Solenoid

ATLAS A Toroidal LHC Apparatus

LEP the Large Electron-Positron Collider

SM standard model

QFT quantum field theory

EWT electroweak theory

QED quantum electrodynamics

QCD quantum chromodynamics