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Graduation thesis submitted in partial fulfilment of blah

SOMETHING ABOUT HIGGS+CHARM

my thesis subtitle

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sciences and bioengineering sciences

Abstract

My abstract

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Chapter 1

Introduction

The Standard Model (SM) of particle physics is the theory that best decribes our current understanding of fundamental particles and their interactions. It describes a broad range of phenomena and makes a plethora predictions for these, many of which have been confirmed via measurement to great degrees of accuracy [1]. A noteable feature of the SM is the Brout-Englert-Higgs (BEH) mechanism [2][3], which predicts the existance of a Brout-Englert-Higgs (or often simply Higgs) boson. The EBH mechanism is considered a central part of the SM as it provides a unique mechanism by which SM particles may acquire mass through their interaction with the Higgs boson. As such, the experimental discovery of a Higgs-like scalar boson in 2012 [4][5] was a major milestone in particle physics. Since this discovery, a significant open question in particle physics has been whether this particle indeed behaves entirely in an SM-like way. Measuring the exact properties of the discovered scalar particle has thus been a major feature of LHC experiments such as the CMS collaboration [6]. A significant subset of these properties are the so-called Yukawa interactions between the Higgs boson and massive fermions. As can be seen in Figure 1.1, a number of these have previously been measured and indeed align with the values expected from the SM. However, the measurement of the Yukawa couplings of several of the lighter fermions still remain an open challenge as these couplings decrease in strength with smaller fermion masses.

The next lightest fermion candidate for such a measurement is the charm quark. Consequentially, the study of the Yukawa-coupling between the Higgs boson and the charm quark is of significant interest [7]. Apart from a brief discussion of the SM, this section introduces the charm-Yukawa coupling. Additionally, LHC processes may be targeted to exploit their sensitivity to the Higgs-charm Yukawa coupling with an experiment such as the CMS detector are discussed.

1.1 The Standard Model of particle physics

The SM is formulated as through the formalism of Quantum Field Theory (QFT) [**something here**]. This is a formalism that combines concepts of classical field theory, quantum machanics as well as special relativity into a single, coherent description of fundamental particles as excitations of underlying fields that pervade space-time. In this description, SM particles fall into two categories: fermions and bosons. The former are the massive particles which may make up the matter of the universe while the latter are the force-carrying particles of the strong and electro-weak forces. The distinction between these categories is made based on the spin of the particle, which may be of either half-integer or integer respectively.

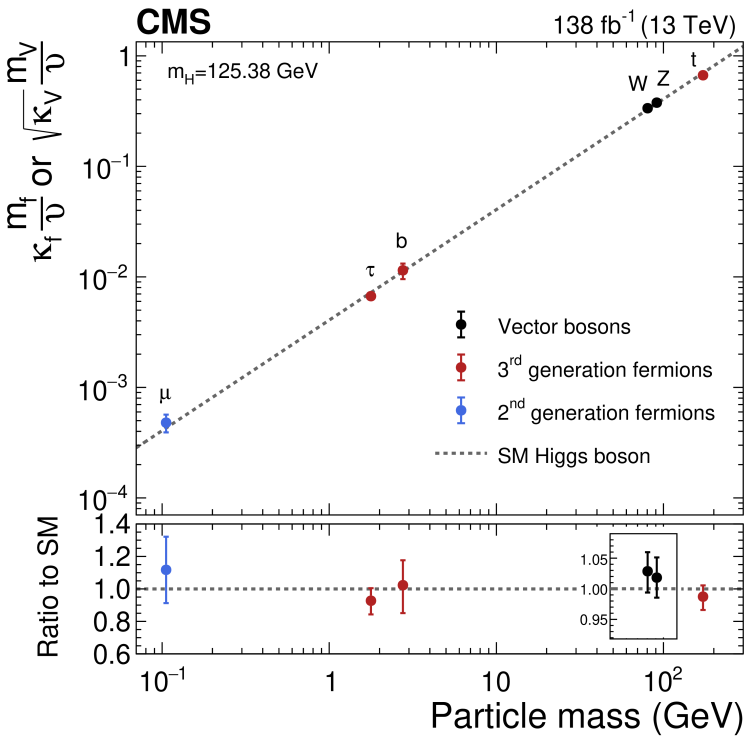

Figure 1.1: The measured coupling modifiers of the coupling between the Higgs boson and fermions as well as heavy gauge bosons as functions of fermion or gauge boson mass $m_{f/V}$, where ν is the vacuum expectation value of the Higgs field. [6] NOTE: coupling modifiers

The fermion content of the SM consists of 12 unique particles. These include six leptons, namely the electron, muon and tau as well as their respective neutrinos as well as six different quarks that are distinguished by their so-called flavour. The different quark flavours include up, down, charm, strange, bottom and top and specifies a quark's mass eigenstate as well as electric charge. These fermions are typically arranged into three generations typically depicted as

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}, \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}. \tag{1.1}$$

However, there are distinct differences between the leptons and quarks. Leptons carry integer (or no) charge while quarks carry fractional charges. More importantly, while both quarks and leptons may interact via the electro-weak force, only the quarks interact via the strong force. Due to the nature of the strong force, quarks almost exlusively form compositive states called hadrons. Lastly, the existence of anti-fermions must be mentioned. These carry the exact opposite quantum numbers (.e.g charge) as their fermion counterparts, though otherwise behave similarly (take the electron and positron for instance). For simplicity, references to a fermion in this work may be understood as referencing both the fermion and anti-fermion counterpart, unless otherwise explicitly indicated. Examples of the latter are e.g. referring explicitly to electrons e^- and positrons e^+ or charm quark c and anti-charm quark $\bar{\mathrm{c}}$ pairs.

There exist 13 unique bosons in the SM. These include the photon γ, $\mathrm{W}^\pm$ and Z which mediate the electro-weak force as well as 8 gluons g that mediate the strong force. The final piece is the Higgs boson. Contrary to the force carriers, which all are spin 1, the Higgs boson is spin 0. By interacting with the Higgs boson, the massive particles of the SM acquire their mass and is thus a central element of the SM.

Considering the introduced particles and forces, the SM has a rich and detailed phenomeology. A great example of a mathematically rigurous delineation of this can be found for example in [8]. Given the focus of this work on the Yukawa coupling between the Higgs boson and charm quark, only this aspect of the SM is discussed in further detail.

1.2 The Higgs-charm Yukawa coupling

The coupling that defines the strength of the interaction between massive fermions and the Higgs boson is the so-called Yukawa coupling. To better understand this and associated concepts, some knowledge of the electro-weak sector of the SM is required. These are discussed in this section while a comprehensive overview may be found in [9].

To understand the origin of the Yukawa-couplings, a brief discussion of Lagrangian densities, gauge transformations and the role of symmetries in the SM is warranted. The Lagrangian density $\mathcal{L}(\phi_i;\, a_i)$ is a quantity dependent on a set of fields ϕ_i and constants a_i from which the equations of motions for the particles associated with these fields may be derived. Commonly, theories of particles and their behaviour in a QFT are thus defined through the formulation of a Lagrangian density. The form of this expression determines the nature of the particles that are included as well as their interactions. A central component to the way in which particle interactions are introduced in the SM is the concept of gauge symmetries. These originate from the fact that the quantum fields in a QFT carry phase information, which may depend on the space-time coordinate of the field. This phase information describes (local) degrees of freedom of the field and should have no effect on the physical obersvables of the system. Thus, $\mathcal{L}$ should remain invariant under arbitary phase transformations. Such transformations are typically referred to as a choice of gauge and such an invariance is accordingly referred to as a *local gauge symmetry*.

In the Lagrangian of the SM, invariance in the presence of local gauge symmetries is insured through the addition of additional fields. These gauge fields couple to the previously existing fields and effectively serve as mediators of phase information between space-time points of the original fields. It is exactly these gauge fields which we identify as the fields force-mediating bosons introduced previously and which are required to maintain local gauge symmetry. A very interesting conclusion from this is that the dynamics of the bosons and the corresponding force are determined entirely by the structure of the local gauge symmetry that must be preserved. For the electro-weak force, the corresponding symmetry is referred to as $\mathbf{SU(2)}_{\mathrm{L}}\,\mathrm{x}\,\mathbf{U(1)}_{Y}$. Here, the L denotes that the associated force only acts on left-handed chiral particles while the Y denotes the charge that is carried by the corresponding bosons and is referred to as the weak hypercharge. There are a total of four boson associated with the electro-weak force. These are the photon γ that mediates the electromagnetic force as well as the electromagnetically charged $\mathrm{W}^{\pm}$ and electromagnetically neutral Z boson that mediate the weak force.

With these concepts in mind the nature of the electro-weak sector's Lagrangian in the SM may be discussed. Naively, the form of this would be given by

$$\mathcal{L}_{\mathrm{EW}} = i\overline{\psi}_L\gamma^\mu D^L_\mu\psi_L + i\overline{\psi}_R\gamma^\mu D^R_\mu\psi_R - \frac{1}{2}\mathrm{Tr}\left(W^a_{\mu\nu}W^{a\mu\nu}\right) - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}\,. \tag{1.2}$$

for a generic combination of a left-handed isospin doublet ψ_L and and right-handed isospin singlet ψ_L. The individual elements of $\mathcal{L}_{\mathrm{EW}}$ are briefly summarised below

g' :	coupling constant of $\mathrm{U}(1)_Y$
g :	coupling constant of $\mathrm{SU}(2)_L$
ψ_L,	left-handed isospin doublet
ψ_R,	right-handed isospin doublet
B_μ :	gauge field of $\mathrm{U}(1)_Y$
W^a_μ :	gauge fields of $\mathrm{SU}(2)_L$, $a = 1, 2, 3$
$W_{\mu\nu}$:	field strength tensor
$B_{\mu\nu}$:	field strength tensor
$t^a = \frac{\sigma^a}{2}$,	SU(2) generators
$Y_L = -1$,	left chiral hypercharge
$Y_R = -2$,	right chiral hypercharge
$D^L_\mu = \partial_\mu + ig'\frac{Y_L}{2}B_\mu + igt^aW^a_\mu$	
$D^R_\mu = \partial_\mu + ig'\frac{Y_R}{2}B_\mu$	

The terms $D_\mu^{L/R}$ are so-called covariant derivates that ensure the local $\mathrm{SU}(2)_\mathrm{L}\,\mathrm{x}\,\mathrm{U}(1)_Y$ gauge symmetry is uphheld for $\mathcal{L}_{EW}$. In this formulation, the observed charged gauge bosons $\mathrm{W}^\pm$ arise from linear combinations of the W_1 and W_2 gauge fields

$$W^\pm = \frac{1}{\sqrt{2}}(W_1 \mp iW_2), \tag{1.3}$$

while the Z boson and photon γ arise from linear combinations of the W_3 and B gauge fields achieved via a rotation

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_\mathrm{W} & \sin\theta_\mathrm{W} \\ -\sin\theta_\mathrm{W} & \cos\theta_\mathrm{W} \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix}. \tag{1.4}$$

with the weak mixing angle θ_W.

The massive natures of of the $\mathrm{W}^\pm$ and Z bosons, as first reported in [10], are however incompatible with such a formulation. This is as naive mass term such as

$$m_W^2 W_\mu^+ W^{-,\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu. \tag{1.5}$$

do not remain invariant under arbitrary $\mathrm{SU}(2)_\mathrm{L}$ gauge transformations. This is as gauge fields A_μ generically transform as

$$A_\mu \to A_\mu^{'} = A_\mu - \frac{1}{g}\partial_\mu \mathcal{V}(x) \tag{1.6}$$

where $\mathcal{V}(x)$ is some arbitrary phase. Substituting Equation 1.6 into Equation 1.5 thus introduces additional terms that do not cancel. The same is true for fermion mass terms in the form of

$$m_\mathrm{f}\overline{\psi}\psi. \tag{1.7}$$

There is however a subtle distinction in this case, as the invariance breaking terms in Equation 1.7 arise from the different transformation behaviour of the ψ_L and ψ_R components of ψ under $\mathrm{SU}(2)_\mathrm{L}\,\mathrm{x}\,\mathrm{U}(1)_Y$ gauge transformations.

1.2.1 The Brout-Englert-Higgs mechanism

The BEH mechanism provides a way to circumvent the gauge symmetry breaking nature of the aforementioned generic mass terms. This is achieved through a porcess referred to as spontaneous symmetry breaking. A spontaneously broken symmetry refers to a symmetry that is upheld in a global view of the system (i.e. the overall Lagrangian density $\mathcal{L}_\mathrm{EW}$ remains invariant under a relevant gauge transformation) while the energetic ground state of the system explicitly breaks this symmetry. This is a process formally described by the Goldstone theorem [11]that states that each broken symmetry in a relativistic QFT generates an additional massless boson. These introduce additional degrees of freedom into the theory and are coined Goldstone bosons. The

BEH mechanism exploits this by adding an additional term

$$\mathcal{L}_{\text{Higgs}} = D_\mu \phi^\dagger D^\mu \phi - V(\phi) \tag{1.8}$$
$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2. \tag{1.9}$$

to $\mathcal{L}_{\text{EW}}$ with the complex field ϕ. This is a $\text{SU}(2)_L$ doublet

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \tag{1.10}$$

with the scalar components ϕ^+ and ϕ^0. Here, $V(\phi)$ corresponds to the potential energy term of the feild. Again, the covariant derivative

$$D_\mu = \partial_\mu + ig' \frac{Y_\phi}{2} B_\mu + igt^a W^a_\mu \tag{1.11}$$

ensures $\mathcal{L}_{\text{Higgs}}$ remains locally gauge invariant under $\text{SU}(2)_\text{L} \,\text{x}\, \text{U}(1)_Y$ transformations. The constants of the potential term Equation 1.9 are chosen in such a way that the ground state of V is non-zero. This can be achieved by choosing them such that $\lambda > 0$ and $\mu^2 > 0$. The result is a ground state of V that is identified as the vacuum expectation

$$v = \sqrt{\frac{\mu^2}{2\lambda}}\,. \tag{1.12}$$

The center of the potential is now an unstable local maximum and the only stable configuration can be found in the non-zero ground state. Through this, the symmetry of the potential is effectively broken. A popular choice of gauge for ϕ is

$$\phi = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix} \tag{1.13}$$

where h is a new scalar field that is used to parametrise radial perturbations of the potential's ground state. This choice is referred to as the unitary gauge and h is identified as the field corresponding to the physical Higgs boson. By expanding Equation 1.8 with this choice of ϕ, a range of terms are introduced to $\mathcal{L}_{\text{EW}}$. These contain a variety of interaction terms between the gauge fields and the Higgs field, as well as newly generated mass terms for the Z and W bosons

$$\left(\frac{g}{2}\right)^2 v^2 W^+_\mu W^{\mu-} = m^2_\text{W} W^+_\mu W^{\mu-} \tag{1.14}$$
$$\left(\frac{\sqrt{g^2 + g'}}{2}\right)^2 v^2 Z_\mu Z^\mu = m^2_\text{Z} Z_\mu Z^\mu\,. \tag{1.15}$$

This can be understood to mean that the electro-weak coupling constants g and g' along with v effectively determine the mass of the Z and $\text{W}^\pm$ bosons. A full description and compilation of all the terms of the electro-weak Lagrangian density of the SM can be found in **??**.

1.2.2 The Yukawa couplings

By including the Higgs contribution in our theory, mass terms for fermions may now be generated by including a term of the form

$$\mathcal{L}_{\text{Yukawa}} = -y_{\text{f}}\overline{\psi}\phi\psi, \tag{1.16}$$
$$= -m_{\text{f}}\overline{\psi}\psi(1 + \frac{1}{v}\frac{h}{\sqrt{2}}) \tag{1.17}$$

which is invariant under $\text{SU}(2)_{\text{L}} \,\text{x}\, \text{U}(1)_Y$ gauge transformations due to the addition of ϕ. Similarly to the W and Z mass terms, the relation

$$m_{\text{f}} = y_{\text{f}}v. \tag{1.18}$$

is obtained. A curious feature of the SM is that the Yukawa-couplings y_{f} are free parameters of the theory with no a priori values. As a result these must be measured experimentally with the measurement of the charm quark Yukawa coupling y_{c} being the goal of this work. As the charm quark mass has previously been determined from experiment to be $m_{\text{c}} = 1.27$ GeV [1], a measurement of y_{c} thus represents an important consistency test of the SM. Another feature that can be read off from Equation 1.17 is that an interaction between fermions and the Higgs field is introduced with an interaction strength proportional to y_{c}. It is exactly this feature that may be exploited by experiments at the LHC to measure y_{c}.

1.3 The cH process

By determining the frequency of occurence of physics processes in which the coupling between the Higgs boson and charm quark appears, y_{c} may be measured indrectly. As such, a suitable process must be found that can be measured by an experiment such as CMS. These fall into two categories. The first consists of processes in which a Higgs boson decays into a charm and anti-charm quark pair ($\text{c}\overline{\text{c}}$) while the second consists of processes in which a Higgs boson is produced in association with a charm quark. The latter category of processes is the focus of this work.

1.3.1 The κ-framework

The κ-framework [12] is a tool to parametrise modifications to couplings between the Higgs boson and other particles with respect to the expected SM values of the couplings. For example, the coupling modifiers for the charm quark Yukawa coupling is introduced as

$$\kappa_{\text{f}} = \frac{y_{\text{f}}}{y_{\text{f}}^{\text{SM}}}. \tag{1.19}$$

where y_{f} is the measured Yukawa-coupling and y_{f}^{SM} is the expected Yukawa-coulpling of the SM, calculated from the known charm quark mass. Thus modifications to the Yukawa-coupling of the charm quark are parametrised in this way as deviations from $\kappa_{\text{c}} = 1$. However, y_{c} is not the quantity that can be measured directly. Instead a rate (or signal strength) measurement μ_{if}, where i represents the production process and f represents the decay process, is made. Thus a measurement of μ_{if} must be converted into an interpretation of κ_{c}. This is a step that contains some finer subtleties.

The rate of a Higgs production and decay process in relation to the expected SM signal may be written as

$$\mu_{if} = \frac{\sigma_i \cdot \mathrm{BR}_f}{(\sigma_i \cdot \mathrm{BR}_f)^{\mathrm{SM}}}, \tag{1.20}$$

where σ_i is the production cross section in a given channel i and BR_f is the decay branching ratio in a given channel f. This can be rewritten as

$$\sigma_i \cdot \mathrm{BR}_f = \kappa_{r,i}\sigma_i^{\mathrm{SM}} \cdot \frac{\kappa_f \Gamma_f^{\mathrm{SM}}}{\Gamma_{\mathrm{H}}} \tag{1.21}$$

to give a general expression in which modifications to the production cross section and partial SM decay width Γ_f^{SF} are introduced via $\kappa_{r,i}$ and κ_f respectively. The denominator Γ_{H} represesents the total decay width which can be written as

$$\Gamma_{\mathrm{H}} = \Gamma_{\mathrm{H}}^{\mathrm{SM}} \sum_f \kappa_f^2 \mathrm{BR}_f^{\mathrm{SM}} \tag{1.22}$$

$$ishouldfullywritethisout := \Gamma_{\mathrm{H}}^{\mathrm{SM}} \kappa_{\mathrm{H}}^2 \tag{1.23}$$

Here, $\Gamma_{\mathrm{H}}^{\mathrm{SM}}$ is the SM total decay width of the Higgs boson and $\mathrm{BR}_f^{\mathrm{SM}}$ are the branching ratios of the possible decay modes (the loop induced coupling of the Higgs boson to gluons and photons are included as independent quantities) where κ_f parametrises modifications thereof. Substituting Equation 1.23 into Equation 1.20, the rate modifier may be written as

$$\mu_{if} = \frac{\kappa_{r,i}^2 \kappa_f^2}{\kappa_{\mathrm{H}}^2}. \tag{1.24}$$

Now, assuming in the production of the Higgs boson only modifications to the charm quark Yukawa coupling plays a role as well as that the decay mode (e.g. $\mathrm{H} \to \mathrm{ZZ} \to 4\mu$) is unmodified, Equation 1.24 becomes

$$\mu_{if} = \frac{\kappa_{\mathrm{c}}^2}{\kappa_{\mathrm{H}}^2} \tag{1.25}$$

Using the flat direction approach discussed in [7] and [13], a simplification of κ_{H} can be introduced. This approach is based on the finding that, when performing fits to existing Higgs production and decay rates, increases in the Yukawa couplings of light quarks including the charm quark could be compensated by increases in the couplings of the gauge bosons and heavy fermions. This is referred to as a "flat direction" in the fit, where observed Higgs production and decay rates can be modeled equally well for any value of κ_{c}. Thus the authors of replace the individual modifiers in the sum of Equation 1.22 with a single modifier κ and thus write

$$\kappa_{\mathrm{H}} = ... \tag{1.26}$$

1.4 SMEFT

Chapter 2

The CMS experiment

Chapter 3

Search for the cH(ZZ$\rightarrow$4μ) process

Chapter 4

An EFT interpretation of the cH(ZZ$\to$4μ) process

Conclusion

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