SEARCH FOR Z’ PRODUCTION IN 4 B-TAGGED JET FINAL STATES IN PROTON-PROTON COLLISIONS

A Dissertation

by

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ABSTRACT

The LHCb experiment has reported slight discrepancies in the ratio in which B mesons decay to muons and electrons. some of these theories attempting to explain these anomalies theorize the existence of new particles beyond the standard model. This study performs a search for a heavy neutral gauge boson at the LHC with the CMS experiment. This Z' boson is assumed to couple mostly to third generation fermions, specifically b-quarks. The main production channel is b-quark fusion. Furthermore, since the b-quark PDF's are at least 10 times lower when compared to the gluon PDF's, we take advantage of the large contribution of bottom quarks coming from gluon-splitting to Z' production. In short, a study for Z'$\rightarrow b\bar{b}$ decays is proposed. The final state consists of 4 b jets, with the two extra jets coming from the initial gluon splitting. Results are correspond to 27.27 fb^{-1} of proton-proton collision data recorded by the CMS detector at the LHC with a center-of-mass-energy of 13 TeV during 2016.

DEDICATION

To Elvis, Simon, and Alice

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NOMENCLATURE

BFF	Bottom Fermion Fusion
EW	Electroweak
QCD	Quantum Chromodynamics
QFT	Quantum Field Theory
SM	Standard Model of particle physics
VBF	Vector Boson Fusion

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1. INTRODUCTION

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2. THEORETICAL FRAMEWORK

2.1 The Standard Model

Particle physics is the study of the fundamental constituents of matter and the forces between them. For more than 40 years these have been described by the so-called standard model of particle physics (SM), which provides, at least in principle, a basis for understanding most particle interactions, with the only exception of gravity.

The SM can be understood as a gauge theory combining the theory of electroweak interactions(EW) and quantum chromodynamics(QCD), or $SU(3) \times SU(2) \times U(1)$. Several experiments have validated this theory to a great accuracy. However, we know the SM to be incomplete as it does not provide answers to questions like the origin of neutrino masses, the existence of dark matter, or that of dark energy.

2.2 Structure and Particle Content

In this section, the particle content of the SM will be intriduced, along with the various force carriers. In the following section, the specifics of particle-particle interactions will be explained in detail.

Elementary particles have an associated quantum number call spin, which allows for particle classification in terms of this quantity as fermions and bosons.

2.2.1 Fermions

Fermions are elementary particles with half-integer spin. They constitute the matter content of the SM, which accounts for 12 named fermions, which interact via the weak and electromagnetic force (with the exception of neutrinos). Also, they obey Fermi-Dirac statistics and the Pauli exclusion principle, meaning that no two fermions may be described by the same quantum numbers. Each fermion has its own anti-particle with the same mass but opposite quantum numbers.

The particle content of the SM can be divided into two additional categories of six fermions each, i.e. quarks and gluons. the quarks, which must bind together due to their strong force interaction and the leptons, which can exist independently. Quarks are known to bind into triplets and doublets, called baryons and mesons, respectively. Leptons come into three flavors, each one corresponding to a doublet where the electron, muon and tau are paired with a neutrino.

Moreover, fermions are grouped into 3 families or generations of 4 particles (2 quarks and 2 leptons), according to their masses. Each subsequent generation being a heavier version of the previous generation, with the same quantum numbers (neutrinos may have a different mass order). Therefore, the particle formed from Generation I particles are usually more stable and long-lived than those made from Generation III particles. Protons and neutrins themselves are made up of up and down quarks.

2.2.2 Bosons

The SM bosons are the mediators of the interaction between the matter content of the SM, but also within themselves. They have integral spin quantum number and follow Bose-Einstein statistics. There are 5 named bosons, the gluons, photons, and W and Z with spin 1 since they go with vector fields, and the Higgs boson which corresponds to a scalar field and therefore has spin 0.

2.3 Particle Interactions

The interactions of the particles described in the previous section can be described in the mathematical framework of gauge field theory. Three of the four fundamental forces of nature are described in the SM (electromagnetism, the strong and the weak force). To each of these forces belongs a physical theory, its corresponding charge, (i.e. electric charge, color or flavor) and an associated boson as mediator.

Modern theories describe these forces in terms of Quantum fields, namely QED, QCD and the unified electroweak quantum field theory. One feature all these theories have in commmon is that they are all gauge invariant. This is important because this is a fundamental requirement from which the detailed properties of the interaction are deduced.

To describe each of the three SM interactions or forces, we will start with a Lagrangian that describes the dynamics of a given system of particles. Then we will take a look at the invariance of the Lagrangian after performing a local gauge transformation that will then require the introduction of gauge fields and their corresponding covariant derivatives. Finally, we will take a look at the conservation laws arising from the symmetry of the gauge invariance.

2.3.1 Quantum Electrodynamics

Quantum Electrodynamics (QED) describes the dynamics of the electromagnetic interaction between fermions and the boson mediating the interaction, the photon. QED corresponds to the U_{EM} group and it was the first discovered example of gauge symmetry.

In QFT, particles are represented by fields, which are in turn represented mathematically by Lagrangian densities $\mathcal{L}$. QED is described by the Dirac Lagrangian density

$$\mathcal{L} = \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi \tag{2.1}$$

where γ^{μ} are the gamma matrices, ϕ is a four-component column vector representing the wave function of a spin 1/2 particle (or Dirac spinor), $\bar{\psi} = \psi^{\dagger}\gamma^{0}$, and m is the mass of the particle. The Lagrangian is invariant under a global U(1) transformation

$$\psi \rightarrow \psi' = e^{-i\alpha}\psi \tag{2.2}$$

while the parameter α is kept a constant. If instead, α is allowed to vary as a function of space-time, then equation (transformation) becomes a local U(1) transformation and the Lagrangian density becomes

$$\mathcal{L} \rightarrow \mathcal{L}' = \mathcal{L} + \bar{\psi}\gamma^{\mu}(\partial_{\mu}\alpha(x))\psi \tag{2.3}$$

which is not invariant under the local transformation as is.

In order to restore local gauge invariance, a gauge field A_{μ} representing the photon and the covariant derivative

$$D_\mu = \partial_\mu + iqA_\mu \tag{2.4}$$

, where $q = -e$ (electric charge) are introduced. The new gauge field transforms as

$$A_\mu \rightarrow A'_\mu = A_\mu + \partial_\mu \chi(x) \tag{2.5}$$

, where $\chi(x)$ is an arbitrary function of space-time. The covariant derivative has the same transformation properties as ψ and is chosen to replace ∂_μ.

After introducing these modifications, the Lagrangian takes the form:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \tag{2.6}$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field strength tensor.

An interesting result is that the Lagrangian does not contain a mass term for the newly-introduced photon field (i.e. no term $m^2 A_\mu A^\mu$), which explains the infinite range of the electromagnetic interaction.

The final form of the Lagrangian includes lepton-photon interactions, those in the form of $l^+l^-\gamma$ and a quatric term in the field strngth tensor which is the photon kinetic energy. It can also be generalized to include all leptons by taking the form

$$\mathcal{L} = \sum_i \bar{\psi}_i(i\gamma^\mu D_\mu - m_i)\psi_i - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \tag{2.7}$$

where $i = e, \mu, \tau, u, d, c, s, t, b$.

2.3.2 Electroweak Interaction

The electroweak interaction is based on a local $SU(2)_L \times U(1)_Y$ gauge symmetry where $L$and Y are the generators of the symmetry. As a result, electromagnetic and weak interactions are unified into a single non-abelian gauge theory. Also, just like in Section, the requirement of local gauge invariance leads to the introduction of gauge fields and determined the interactions mediated by those fields.

In order to understand this unification, we will first work with a fermionic doublet representing an $SU(2)$ symmetry

$$\psi = \begin{pmatrix} \psi_1(x) \\ \psi_2(x) \end{pmatrix}, u_R, d_R \tag{2.8}$$

which transforms under the three dimensional rotation

$$\psi \rightarrow exp < i\alpha^i \frac{\sigma_i}{2} > \psi \tag{2.9}$$

which is the three dimensional version of eq. and σ^i are the Pauli sigma matrices.

Just like in the previous section, we allow the parameter α to vary as a function of space-time and thus

$$\psi(x) \rightarrow V(x)\psi(x) \tag{2.10}$$

, where $V(x) = exp(i\alpha^i(x)\frac{\sigma^i}{2})$.

In order to keep the Lagrangian invariant under this transformation, we introduce three vector fields $A^i_\mu(x)$ and the covariant derivative

$$D_\mu = \partial_\mu - igA^i_\mu \frac{\sigma^i}{2} \tag{2.11}$$

and therefore

$$A^i_\mu(x)\frac{\sigma^i}{2} \rightarrow V(x)(A^i_\mu(x)\frac{\sigma^i}{2} + \frac{i}{g}\partial_\mu)V^\dagger(x) \tag{2.12}$$

To simplify this calculation, we can expand $V(x)$ to first order in α

$$A^i_\mu \frac{\sigma^i}{2} \rightarrow A^i_\mu \frac{\sigma^i}{2} + \frac{1}{g}(\partial_\mu \alpha^i)\frac{\sigma^i}{2} + i[\alpha^i \frac{\sigma^i}{2}, A^i_\mu \frac{\sigma^i}{2}] + ... \tag{2.13}$$

The covariant derivative will have the form

$$D_\mu\psi \to (1 + i\alpha^i\frac{\sigma^i}{2})D_\mu\psi \tag{2.14}$$

and the field strength tensor will be

$$F^i_{\mu\nu} = \partial_\mu A^i_\nu - \partial_\nu A^i_\mu + g\epsilon^{ijk}A^j_\mu A^k_\nu \tag{2.15}$$

and the Yang-Mills Lagrangian becomes

$$\mathcal{L} = -\frac{1}{4}(F^i_{\mu\nu})^2 + \bar{\psi}(i\gamma^\mu\partial_\mu - igA^i_\mu\frac{\sigma^i}{2})\psi \tag{2.16}$$

Now we can obtain the interaction by following the same procedure as in the previous section, i.e., requiring local gauge invariance in the Lagrangian and introducing new gauge fields and covariant derivatives.

First we should note that the SM fermions possess a fundamental property called chirality, which describes how a given particle's wave function behaves under rotation. In the SM, the left-handed components of the electron neutrino and electron are grouped into an SU(2) doublet. Since the right-handed component of the electron is invariant under SU(2), it is placed in a singlet, i.e.:

$$L_e = \begin{pmatrix} \nu_e \\ e_L \end{pmatrix}, e_R \tag{2.17}$$

And so on for the heavier generations of leptons. So far, there is no evidence of right-handed neutrinos in the SM.

The kinetic energy term of the electroweak Lagrangian for first generation leptons can be represented by:

$$\mathcal{L}^e_{KE} = L^\dagger_e\tilde{\sigma}^\mu i\partial_\mu L_e + e^\dagger_R\sigma^\mu i\partial_\mu e_R \tag{2.18}$$

where $\sigma = (\sigma^0, \sigma^1, \sigma^2, \sigma^3)$, $\tilde{\sigma} = (\sigma^0, -\sigma^1, -\sigma^2, -\sigma^3)$, σ^0 is an identity matrix, and the σ^i are the Pauli matrices. This Lagrangian is invariant under the global $SU(2)_L \times U(1)_Y$ transformation:

$$L \to L' = e^{i\theta} U L \tag{2.19}$$

$$e_R \to e'_R = e^{2i\theta} e_R \tag{2.20}$$

where

$$U = e^{-ia^k \sigma^k} \tag{2.21}$$

and θ and a^k are real numbers parameterizing the transformation. However, the Lagrangian is not invariant under a transformation where these parameters are allowed to vary as a function of space-time, i.e. a local transformation.

Following the same reasoning as in the previous section, we can introduce gauge fields and replace the space-time derivatives with an appropiately chosen covariant derivative. This time, we introduce a U(1) gauge field $B_\mu(x)$ and three SU(2) gauge fields $W_\mu(x) = W_\mu^k(x)\sigma_k$. Such fields must transform as

$$B_\mu(x) \to B'_\mu(x) = B_\mu(x) + \frac{2}{g_1}\partial_\mu \theta(x) \tag{2.22}$$

$$W_\mu(x) \to W'_\mu(x) = U(x) W_\mu(x) U^\dagger(x) + \frac{2i}{g_2}(\partial_\mu U(x)) U^\dagger(x) \tag{2.23}$$

where g_1 and g_2 are dimensionless parameters of the theory, the coupling strengths of the interactions. The necessary covariant derivatives are given by

$$D_\mu L_e = (\partial_\mu + i\frac{g_1}{2} Y B_\mu + i\frac{g_2}{2} W_\mu) L_e \tag{2.24}$$

$$D_\mu e_R = (\partial_\mu + i\frac{g_1}{2}YB_\mu)e_R \tag{2.25}$$

where Y is the hypercharge operator, whose eigenvalues are listed in Table 2.1. The weak hypercharge can be calculated as $Y = 2(Q - T_3)$, where T_3 is the third component of the weak isospin quantum number T.

	Particle	Q	T_3	Y	B	L
Quarks	$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} 2/3 \\ -1/3 \end{pmatrix}$	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	1/3	1/3	0
	u_R	2/3	0	4/3	1/3	0
	d_R	-1/3	0	-2/3	1/3	0
Leptons	$l_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	-1	0	1
	e_R	-1	0	-2	0	1

Table 2.1: Quantum numbers of the SM fermions

These covariant derivatives transform according to the same rule as the fields themselves. Combining the kinetic and gage interaction terms of the Lagrangian yields

$$\mathcal{L} = \mathcal{L}_{KE} + \mathcal{L}_{gauge} = L_e^\dagger \tilde{\sigma}^\mu i D_\mu L_e + e_R^\dagger \sigma^\mu i D_\mu e_R - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \sum_{i=1}^{3}\frac{1}{4}W^i_{\mu\nu}W^{i\mu\nu} \tag{2.26}$$

where $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ and $W_{\mu\nu} = [\partial_\mu + (\frac{ig_2}{2})W_\mu]W_\nu - [\partial_\nu + (\frac{ig_2}{2})W_\nu]W_\mu$ are the field strength tensors. This Lagrangian is now locally invariant.

The mediators of the electroweak force are the physical bosons $W^\pm$, the Z and the photon. All these are combinations of the gauge fields in the following way.

The $W^\pm$ are linear combinations of the W_1 and W_2, which are electrically charged and given by

$$W_\mu^\pm = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}} \tag{2.27}$$

The W_3 and B gauge fields are electrically neutral. The physical Z and photon are linear combinations of these fields, given by

$$Z_\mu = W_\mu^3 cos\theta_W - B_\mu sin\theta_W \tag{2.28}$$

$$A_\mu = W_\mu^3 sin\theta_W - B_\mu cos\theta_W \tag{2.29}$$

where the Weinberg angle θ_W is defined by $sin\theta_W = g_1/\sqrt{g_1^2 + g_2^2}$.

Now, the interactions contained in the Lagrangian only couple the $W^\pm$ to the left-handed lepton components, but couple the Z and photon to both the left- and right-handed components.

We can also see from here that the interaction strength is equal to the electromagnetic charge unit e, i.e. $g_2 sin\theta_W = g_1 cos\theta_W = e$.

Finally, in order to include second and third generation leptons, the Lagrangian generalizes to

$$\mathcal{L}^l = \sum_{leptons} (L_e^\dagger \tilde{\sigma}^\mu i D_\mu L_e + e_R^\dagger \sigma^\mu i D_\mu e_R) - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \sigma_{i=1}^3 \frac{1}{4} W_{\mu\nu}^i W^{i\mu\nu} \tag{2.30}$$

Quarks are included in the electroweak sector in a similar manner. The left-handed components of the u and d quark are place in SU(2) doublets, and the right-handed components in singlets.

$$Q_u = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R \tag{2.31}$$

Two additional doublets and four singlets exist for the second and third generation quarks. The covariant derivatives acting on the quark fields are the same as those which act on the lepton fields, but the quarks have different weak hypercharge assignments from the leptons. Therefore, the dynamic portion of the u and d quark Lagrangian is given by:

$$\mathcal{L}^q_{KE} = \sum_{quarks} Q^\dagger_u \tilde{\sigma}^\mu i D_\mu Q_\mu + u^\dagger_R \sigma^\mu i D_\mu u_R + d^\dagger_R \sigma^\mu i D_\mu d_R \tag{2.32}$$

Again, the W bosons couple only to the left-handed quark components, while the Z and photon couple to the right-handed components as well.

The full electroweak Lagrangian is a result of the addition of the lepton and quark kinetic components, as well as the gauge interaction component.

$$\mathcal{L}^{EW} = \mathcal{L}^l_{KE} + \mathcal{L}^q_{KE} + \mathcal{L}_{gauge} \tag{2.33}$$

Here, we should notice that a couple of symmetries arise from the form of the Lagrangian in Eq. If a U(1) transformation of the form $L_{e,\mu,\tau} \to e^{i\alpha} L_{e,\mu,\tau}$, $e, \mu, \tau_R \to e, \mu, \tau^{i\alpha} e, \mu, \tau_R$ leaves the Lagrangian invariant, which leads to conservation of lepton number. Additionally, a U(1) transformation multiplying all negatively (positively) charged fields by $e^{i\alpha}(e^{-i\alpha})$ leaves the Lagrangian invariant, and implies conservation of electric charge.

On the other hand, the EW Lagrangian is not invariant under charge conjugation C of a parity conservation P. Charge conjugation is the operation of changing the sign of all discrete quantum numbers, or equivalently exchanging all particles with antiparticles and vice-versa. A parity transformation is the inversion of spatial coordinates, $r \to -r$. The neutral current interactions, mediated by the Z and photon, preserve combined CP invariance. However, even combined CP symmetry is violated by weak current interactions, mediated by the $W^\pm$, in the quark sector. A third important potential symmetry is time reversal T, where $t \to -t$. Combined CPT invariance is required to mantain Lorentz invariance. Therefore, the breaking of CP also implied the breaking of T symmetry.

Finally, a notable property of the weak interaction is that it only acts on particles with weak isospin quantum number T and that T_3 is conserved in all interactions.

2.3.3 Strong Interaction

Quantum Chromodynamics is the theory that describes the interaction between quarks via the strong force. It is represented by a local $SU(3)_C$ gauge symmetry and the interaction mediator is the gluon.

Its corresponding charge is the color. Color charges can be green, red, and blue but only color neutral (or colorless) hadrons are allowed in nature. Baryons contain equal parts of each color and mesons contain color-anticolor pairs.

In QCD, quarks are represented in this theory as color triplets

$$q_u = \begin{pmatrix} u_r \\ u_g \\ u_b \end{pmatrix} \tag{2.34}$$

and gluons contain two color charges. The eight known combinations of color charges for the gluon are represented by eight gauge fields that will be introduced below.

As in the previous sections, we start building the interaction from an $SU(3)$ Lagrangian that is globally invariant in the form

$$\mathcal{L}^q_{QCD} = \sum_{i=1}^{6} \bar{q}_i i\gamma^\mu \partial_\mu q_i \tag{2.35}$$

This Lagrangian is invariant under a transformation of the form $q_i \rightarrow q_i' = Uq_i$ where U is a member is a member of $SU(3)$. If we allow for a transformation of the for $U(x)$, the Lagrangian is no longer invariant. To return invariance, we introduce 8 gauge fields ($G_\mu(x)$), which represent the gluons and an appropiate covariant derivative.

The transformation of the gauge fields and the covariant derivative will take the form:

$$G_\mu \rightarrow G'_\mu = UG_\mu U^\dagger + \frac{i}{g_s}(\partial_\mu U)U^\dagger \tag{2.36}$$

$$D_\mu q_i = (\partial_\mu + ig_s G_\mu)q_i \tag{2.37}$$

where g_s is the dimensionless coupling strength of the color interaction. The field strength tensor for QCD is:

$$G_{\mu\nu} = \partial_\mu G_\nu - \partial_v G_\mu + ig_s(G_\mu G_\nu - G_\nu G_\mu) \tag{2.38}$$

and the locally $SU(3)$ gauge invariant QCD Lagrangian is then given as:

$$\mathcal{L}^q_{QCD} = \sum_{i=1}^{6}(\bar{q}_i i\gamma^\mu D_\mu q_i) - \frac{1}{4}\sum_{i=1}^{8} G^i_{\mu\nu}G^{i\mu\nu} \tag{2.39}$$

In contrast to the EW interaction, C,P, and T are all conserved. The Strong force interaction range is about 10^{-15} which is enough to act on nucleons, i.e. protons and neutrons to form atomic nuclei.

QCD is a strongly coupled theory at low energies and large distance scales and weakly interacting at high energies and small distance scales. This fact is responsible for the hadronic bound states of quarks. At low energy scales, i.e. non-perturbative regime, QCD calculations are extremely difficult and techniques as lattice gauge theory must be exploited. On the other hand, at a high energy scale, or equivalently small distance scales, the strong interaction becomes weakly interacting and quarks are effectively free. In this regime the usual techniques of perturbation theory can be used, allowing high-precision calculations.

2.3.4 Brout-Englert-Higgs Mechanism and the Higgs Boson

As we have seen from the previous section, the EW and QCD Lagrangians do not contain any mass terms. This implies that the SM bosons should be massless, which contradicts the experimental results since the $W^\pm$ and Z bosons do indeed have mass. This is a result of the requirement of local $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge invariance in the Lagrangian.

The Brout-Englert-Higgs mechanism allows for W and Z bosons to have mass while preserving gauge invariance by adding one or more complex scalar fields, the Higgs field(s) to the SM Lagrangian. These fields will acquire a vacuum expectation value which will spontaneously break the symmetry of the Lagrangian.

The Goldstone theorem tells us that for every spontaneously broken continuous symmetry there will be a new massive scalar "Goldstone" boson. The number of new bosons will be equal to the number of broken generators of the symmetry group. The massless SM bosons then acquire mas by absorbing these Goldstone bosons.

THe BEH mechanism is also used to generate mass for the quarks and electrically charged leptons. The neutrinos, photon, and gluons remain massless, as observed experimentally.

Remember from previous section that there are four massless electroweak gauge bosons, W^1, W^2, W^3, and B^0. The experimentally observed bosons, however, are the massless photon, and three massive bosons (the $W^{\pm}$ and Z). We also know that electric charge Q is conserved in electroweak interactions. This means that the $SU(2)_L \times U(1)_Y$ electroweak theory is broken such that a new $U(1)_{EM}$ symmetry group is formed which corresponds to electromagnetism.

In order for three gauge bosons to acquire mass they must absorb three Goldstone bosons. The simplest method to acomplish this is to introduce a complex, scalar $SU(2)$ doublet Φ with hypercharge $Y = 1$.

$$\Phi = \begin{pmatrix} \Phi_A \\ \Phi_B \end{pmatrix} = \begin{pmatrix} \phi_1 \\ i\phi_2 \\ \phi_3 \\ i\phi_4 \end{pmatrix}, \tag{2.40}$$

The part of the SM Lagrangian which includes the electroweak gauge bosons and the leptons can be written as

$$\mathcal{L}_{SM} = -\frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \bar{L}_i (iD_\mu \gamma^\mu) L_i + \bar{e}_{R,i} (iD_\mu \gamma^\mu) e_{R,i} \tag{2.41}$$

where i runs over the three generations, μ and ν are Lorentz indices, and a runs over the generators in the gauge group. The field strengths are given by

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g_2 \epsilon^{abc} W^b_\mu W^c_\nu \tag{2.42}$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \tag{2.43}$$

and the covariant derivatives for the left- and right-handed leptons are

$$D_\mu L_L = (\partial_\mu - i g_2 T_a W_\mu^a - i g_1 Y B_\mu) L_L \tag{2.44}$$

$$D_\mu e_R = (\partial_\mu - i g_1 Y B_\mu) e_R \tag{2.45}$$

where T_a are the generators of the $SU(2)_L$ gauge group and g_1, g_2 are the coupling constants for the electroweak interaction.

The scalar part of the Lagrangian required by the addition of a scalar field is then

$$\mathcal{L}_S = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi^\dagger \Phi) \tag{2.46}$$

where the first term is the kinetic term and the second term is the scalar potential. While the form of the scalar potential is not known from first principles, we can make the assumption that it takes the simplest form possible which has the desired properties of spontaneous symmetry breaking and the ability to be renormalized. Then

$$V(\Phi^\dagger \Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \tag{2.47}$$

The value of λ must be positive in order for the vacuum to be stable. The sign of μ^2 specifies one of two cases for the potential.

- When $\mu^2 > 0$, the potential $V(\Phi)$ is always positive and has a minimum at

  $$< 0|\Phi|0 > \equiv \Phi_0 = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \tag{2.48}$$

  where no spontaneous symmetry breaking can occur.

- When $\mu^2 < 0$ the potential has a minimum value not located at the origin. In this case, the neutral component of the scalar field will acquire a vacuum expectation value v, a process that we will refer to as electroweak symmetry breaking (EWSB).

$$< 0|\Phi|0 >= \Phi_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \tag{2.49}$$

where $v = \sqrt{\frac{-\mu^2}{\lambda}}$

By only adding a vev to the neutral component of the scalar field, electromagnetism is unbroken and the $U(1)_{EM}$ symmetry keeps a conserved electric charge $Q = T_3 + \frac{Y}{2}$.

We can then expand the scalar field Φ around the minimum Φ_0 to get

$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \tag{2.50}$$

where $h(x)$ is a new scalar field.

Next we insert this field into the kinetic part of the Lagrangian and redefine the gauge fields as

$$W^{\pm}_{\mu} = \frac{1}{\sqrt{2}}(W^1_{\mu} \mp iW^2_{\mu}) \tag{2.51}$$

$$Z_{\mu} = \frac{1}{\sqrt{g_1^2 + g_2^2}}(g_2 W^3_{\mu} - g_1 B_{\mu}) \tag{2.52}$$

$$A_{\mu} = \frac{1}{\sqrt{g_1^2 + g_2^2}}(g_2 W^3_{\mu} + g_1 B_{\mu}) \tag{2.53}$$

which correspond to the observed gauge bosons.

After this the covariant derivative becomes

$$|D_{\mu}\Phi|^2 = \frac{1}{2}(\partial_{\mu}H)^2 + \frac{1}{2}g_2^2(v + H)^2 W^+_{\mu}W^{\mu-} + \frac{1}{8}(v + H)^2(g_1^2 + g_2^2)Z_{\mu}Z^{\mu} \tag{2.54}$$

From here we can see that the photon A_μ remains massless, but that the mass terms for the W and Z bosons take the general forms $M_W^2 W_\mu W^\mu$ and $M_Z^2 Z_\mu Z^\mu/2$ respectively.

Thus the masses of the electroweak gauge bosons are

$$M_W = \frac{1}{2} v g_2 \tag{2.55}$$

$$M_Z = \frac{1}{2} v \sqrt{g_1^2 + g_2^2} \tag{2.56}$$

$$M_A = 0 \tag{2.57}$$

Three of the degrees of freedom from the scalar field, which would have been two charged and one neutral Goldstone boson, have been absorbed by the gauge bosons in order to give them mass. There is one remaining degree of freedom, an oscillation in the radial direction of the scalar potential, which corresponds to the neutral Higgs boson.

Finally, fermions acquire mass by adding couplings between the fermion fields and the scalar field to the SM Lagrangian. The part of the Lagrangian that corresponds to the first generation fermions is given by

$$\mathcal{L}_F = -G_e \bar{L} \Phi e_R - G_d \bar{Q} \Phi d_R - G_u \bar{Q} \tilde{\Phi} u_R + h.c. \tag{2.58}$$

where $\tilde{\Phi} = i\tau_2 \Phi^*$ is the conjugate of Φ with negative hypercharge.

There are additional terms added to the full Lagrangian which correspond to the second and third generations which are not shown here.

By substituting Φ into the previous Lagrangian we find

$$\mathcal{L}_F = -\frac{1}{\sqrt{2}}[G_e \begin{pmatrix} \bar{\nu} & \bar{e} \end{pmatrix}_L \begin{pmatrix} 0 \\ v+H \end{pmatrix} e_R + G_d \begin{pmatrix} \bar{u} & \bar{d} \end{pmatrix}_L \begin{pmatrix} 0 \\ v+H \end{pmatrix} d_R + G_u \begin{pmatrix} \bar{u} & \bar{d} \end{pmatrix}_L \begin{pmatrix} 0 \\ v+H \end{pmatrix} u_R] + h.c. \tag{2.59}$$

$$= -\frac{1}{\sqrt{2}}(v+H)(G_e \bar{e}_L e_R + G_d \bar{d}_L d_R + G_u \bar{u}_L u_R) + h.c. \tag{2.60}$$

where $h.c.$ is a placeholder for the hermitian conjugate terms.

The fermion masses take the form $m\bar{f}_L f_R + h.c.$, which means that the fermion masses for the first generation are

$$m_e = \frac{G_e v}{\sqrt{2}}, m_u = \frac{G_u v}{\sqrt{2}}, m_d = \frac{G_d v}{\sqrt{2}} \tag{2.61}$$

The second and third generations have similar mass terms. For the case of the neutrinos, since there is no right handed neutrino in the SM the neutrinos that do exist remain massless.

Finally, the coupling constants, G, and the fermion masses are not predicted by the SM, so they must be measured and added to the model.

2.4 Lepton universality

One of the current assumptions of the SM is that electron, muon, and tau couplings are the same when interacting weakly. This is often referred to as lepton universality.

2.5 B-hadron anomalies

So far, no definite violation of this rule has been observed, but recent studies involving the decay rates of B mesons seem to challenge it. BaBar, LHCb and Belle experiments have reported anomalous deviations from SM in measurements of:

1. The angular distributions of the decay rate of $B \to K^* \mu^+ \mu^-$.

2. The branching ratios $R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$ and $R_{K^*} = \frac{BR(B^+ \to K^* \mu^+ \mu^-)}{BR(B^+ \to K^* e^+ e^-)}$.

Each of these results show a deviation from the expected SM value of 1 in the 2.4-2.6 σ range. These decay processes are very rare in the SM, making it hard to obtain a precise measurement. Also, a better understanding of the SM physics behind them (in terms of hadronic uncertainties) could also provide reconciliation with SM predictions. A more recent study combined the results for R_K and R_{K^*}, resulting in a 4σ deviation from the SM.

2.5.1 $b \to s$ quark transitions

This anomaly hints at the posibility that $b \to s$ quark transitions cannot be understood entirely within the SM framework.

Within the SM, the lowest order processes that could mediate the $b \to s$ quark transitions are at least of third order. Therefore, these processes are rarely observed.

2.6 The Z'

As an alternative, a possible explanation to the B-decay anomalies could postulate the existence of a new heavy neutral gauge boson, the Z'. Such a particle would couple to $b - s$ quarks and non-universally to leptons. In addition, it would be assumed to couple mostly to third generation quarks to explain why it has not been seen yet by any experiment.

2.6.1 Flavour-violating coupling δ_{bs}

In order to provide an explanation for B-decay anomalies, we need to consider the flavour-violating coupling δ_{bs}. Allowing the Z' boson to couple to s quarks in addition to b quarks results in two times more ways to produce the Z' and two times more ways for it to decay. A non-zero δ_{bs} will allow the Z's to be produced by b and $\bar{s}$ quarks (in addition to $b\bar{b}$ ones) and this significantly enhances the production cross section.

2.6.2 Lifetime calculation

2.6.3 4b Bottom Fermion Fusion

If we make the assumption that the Z' couples mostly to b quarks, the particle could have diagrams like the on on Figure, which we will refer to as Bottom Fermion fusion diagram (BFF) due to its similarity with Vector Boson Fusion (VBF) diagrams.

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