W$b\overline{b}$ and Monophoton measurements and searches at CERN

by

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1 INTRODUCTION

The Standard Model of particle physics (SM) is useful. It is a local Quantum Field Theory (QFT) representing the forefront of contemporary understanding of nature on its finest level and is simultaneously the most quantitavely verified pysical model of the constituent elements of the universe and known to be an incomplete description. It is therefore one of the goals of modern society to experimentally investigate particles and the interactions between particles within the context of the SM to validate the theory where possible and to guide directions for its extension where necessary. To acheive this goal, the governments from nearly 100 different countries, states and terratories have funded tens of thousands of scientists and engineers to build, operate and analyze data from the Large Hadron Collider (LHC) at the European Center for Nuclear Research (CERN). This thesis presents analyses of data taken with the Compact Muon Solenoid (CMS) detector using proton-proton collisions provided by the LHC during its operation in 2012 and 2015.

1.1 Local Quantum Field Theory

1.1.1 Representations of SU(2)

One of the key underlying principles behind any QFT is that of symmetry. In particular, QFTs arise from the combination of quantum mechanics with Lorentz symmetry which ensures that the equations used to describe the laws of physics remain equivalantly valid in all inertial reference frames. Local fields are therefore required to transform as representations of the Lorentz group, namely rotations, J_a, and boosts, K_a where $a \in \{1, 2, 3\}$ for the three spatial dimensions. Boosts transform as vectors under rotation and the two obey the Lie algebras given in Equation 1.1, where ϵ_{abc} is the Levi-Civita symbol.

$$[J_a, J_b] = i\epsilon_{abc}J_c, \quad [K_a, K_b] = -i\epsilon_{abc}J_c, \quad [J_a, K_b] = i\epsilon_{abc}K_c \ . \tag{1.1}$$

Both J_a and K_a are hermitian, but it is natural to define the non-hermitian objects

$$L_a = \frac{1}{\sqrt{2}}\left(J_a + iK_a\right), \quad R_a = \frac{1}{\sqrt{2}}\left(J_a - iK_a\right) \tag{1.2}$$

which commute with each other and each independently obey the commutation relations of $SU(2)$,

$$[L_a, L_b] = i\epsilon_{abc}L_c, \quad [R_a, R_b] = i\epsilon_{abc}R_c, \quad [L_a, R_b] = 0 \ . \tag{1.3}$$

Because of this, the Lorentz group may be expressed in terms of representations of $SU(2)_L \times SU(2)_R$.

The group $SU(2)$ can be thought of as the set of 2×2 complex matrices with unit determinant under the operation of matrix multiplication, and the $(2^2 - 1)$ generators of the group are the Pauli matrices,

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \tag{1.4}$$

which combine with the unit matrix to form $\sigma^\mu = (\mathbf{1}, \vec{\sigma})$. Representations of $SU(2)$ are labelled by a quantum number, $\lambda \in \{0, 1/2, 1, 3/2, ...\}$, with the fundamental representation being $\lambda = 1/2$ and the dimensionality, d, of a representation being set by $d = 2\lambda + 1$. Representations of the full symmetry are therefore constructed by combining representations from the L and R components, and Table 1.1 illustrates those combinations of lowest dimensionality.

Table 1.1: *Selected representations of the Lorentz group are formed by combining representations of $SU(2)$ in the structure $SU(2)_L \times SU(2)_R$. The first column labels the quantum numbers, λ, and the second column translates this into dimensionality. The third column indicates the kind of object which meets the symmetry requirements.*

(λ_L, λ_R)	(d_L, d_R)	Name	
$(0, 0)$	$(1, 1)$	ϕ	Scalar
$(1/2, 0)$	$(2, 1)$	ψ_L	Left-handed Weyl spinor
$(0, 1/2)$	$(1, 2)$	ψ_R	Right-handed Weyl spinor
$(1/2, 1/2)$	$(2, 2)$	A_μ	Gauge potential

Rotations take spatial coordinates into spatial coordinates, but boosts mix spatial coordinates with time, which have opposite signs in the spacetime metric. Therefore, under the parity operation, P, which inverts the signs of spatial coordinates,

$$P : J \to J, \quad P : K \to -K \ \ , \tag{1.5}$$

while, under conjugation, C, because J and K are hermitian,

$$C : J \to J, \quad C : K \to K \ \ . \tag{1.6}$$

Using Equation 1.2 then, the $(1/2, 0)$ and $(0, 1/2)$ representations transform as

$$P : \psi_{L(R)} \to \psi_{R(L)}, \quad C : \psi_{L(R)} \to \sigma_2 \psi^*_{R(L)}, \quad CP : \psi_{L(R)} \to \sigma_2 \psi^*_{L(R)} \quad . \tag{1.7}$$

which illustrates the point that because ψ_L and ψ_R can be interchanged via these discrete transformations, they are not independent. The full $SU(2)_L \times SU(2)_R$ symmetry can thus be mantained by considering only one of the two, and it is customary to work with ψ_L, the 'left' component, henceforth simply denoted as ψ, with $\sigma_2 \psi^*_R$ denoted as $\overline{\psi}$. An object which transformes as a vector can be made from spinors by noting that $(1/2, 1/2) = (1/2, 0) \times (0, 1/2)$. Therefore $\psi^\dagger \sigma^\mu \psi$ transforms in the appropriate way, and to make this Lorentz-invariant, the spacetime index μ must be contracted. The derivative operator $\partial_\mu = (\partial/\partial t, \partial/\partial \vec{x})$ is translation-invariant and does not give a surface contribution if inserted between the two instances of ψ, motivating the canonical kinetic term for spinors,

$$i\psi^\dagger \sigma^\mu \partial_\mu \psi \quad . \tag{1.8}$$

1.1.2 Yang-Mills Theory

The above construction for canonical kinetic terms in the Lagrangian was generalized by Chen Ning Yang and Robert Mills for N spinor fields as

$$i \sum_{a=1}^{N} \psi^{a\dagger} \sigma^\mu \partial_\mu \psi_a = i\Psi^\dagger \sigma^\mu \partial_\mu \Psi \quad , \tag{1.9}$$

and while the existence of this object is imposed by the Lorentz symmetry, further symmetries can be made apparant. A simple example is global phase invariance. For λ which is not a function of x, the transformation $\Psi \to e^{i\lambda}\Psi$ leaves the kinetic term in Equation 1.9 unchanged. The derivative passes through $e^{i\lambda}$ which combines with $e^{-i\lambda}$ from $\Psi^\dagger$ to form unity.

A more complicated example is gauge invariance. The symmetry of global phase invariance can be extended by introducing $(N^2 - 1)$ traceless hermitian matrices, $\boldsymbol{\lambda}_A$ which satisfy the Lie algebra,

$$[\boldsymbol{\lambda}_A, \boldsymbol{\lambda}_B] = i f_{ABC} \boldsymbol{\lambda}_C, \quad \mathrm{Tr}\,(\boldsymbol{\lambda}_A \boldsymbol{\lambda}_B) = \frac{1}{2}\delta_{AB} \quad , \tag{1.10}$$

where f_{ABC} are the structure functions for $SU(N)$ and δ_{AB} is the Kroniker delta function. For $N = 2$, $f_{ABC} = \epsilon_{abc}$ used in Equations 1.1 and $\boldsymbol{\lambda}_A$ are the Pauli matrices from Equations 1.4. For $N = 3$, f_{ABC} is a totally anti-symmetric operator and $\boldsymbol{\lambda}_A$ are the Gell-Mann matrices.

These $\boldsymbol{\lambda}_A$ can each be used to construct a hermitian $(N \times N)$ matrix. One degree of freedom is factored out as the overall phase of the trace, demonstrated to be a symmetry of Ψ. This leaves $(N - 1)$ degrees from the real diagonal elements and $2 \times {}^{(N^2 - N)}\!/\!_2$ from the unique complex off-diagonal elements. These $(N^2 - 1)$ overall degrees of freedom correspond to the $\boldsymbol{\lambda}_A$ which are used to construct

$$\mathbf{H} = \frac{1}{2} \sum_{A=1}^{N^2-1} \omega_A \boldsymbol{\lambda}_A \tag{1.11}$$

using ω_A as the parameter of expansion.

$\mathbf{H}$ can then be used to produce a unitary matrix

$$\boldsymbol{U} = e^{i\mathbf{H}} \tag{1.12}$$

whose unitarity is evident by the hermicity of $\mathbf{H}$. Unitarity is crucial for the final cancellation to leave Equation 1.9 invariant under the gauge transformation $\Psi \to \boldsymbol{U}\Psi$, but to ensure locality, the particular expansion, ω_a, could have dependence on position and thus interact with ∂_μ.

To accomadate for this, the derivative is generalized into an $(N \times N)$ covarient derivative matrix, $\boldsymbol{D}_\mu$, which has the property

$$\boldsymbol{D'}_\mu \boldsymbol{U}\Psi = \boldsymbol{U}\boldsymbol{D}_\mu \Psi \tag{1.13}$$

and thus behaves under gauge transformations as

$$\Psi \to \boldsymbol{U}\Psi, \quad \boldsymbol{D}_\mu \to \boldsymbol{D'}_\mu = \boldsymbol{U}\boldsymbol{D}_\mu \boldsymbol{U}^\dagger \quad . \tag{1.14}$$

Explicitly, $\boldsymbol{D}_\mu$ is constructed using $(N^2 - 1)$ gauge potentials, A_μ, in the form of a hermitian matrix,

$$\mathbf{A}_\mu = \frac{1}{2} \sum_{B=1}^{N^2-1} A_\mu^B \boldsymbol{\lambda}_B \tag{1.15}$$

which transforms under gauge transformations as

$$\mathbf{A}_\mu \to \mathbf{A'}_\mu = -i\boldsymbol{U}\partial_\mu \boldsymbol{U}^\dagger - i\boldsymbol{U}\mathbf{A}_\mu \boldsymbol{U}^\dagger \quad . \tag{1.16}$$

The field strength matrix is formed by taking the commutator

$$\mathbf{F}_{\mu\nu} = -i[\boldsymbol{D}_\mu, \boldsymbol{D}_\nu] \tag{1.17}$$

which leads to a kinetic term that is invariant under both gauge and Lorentz transformations, $-1/2g^2 \mathrm{Tr}\left(\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu}\right)$ where g is the coupling strength, and thus the Lagrange density of

$$\mathcal{L}_{\mathrm{YM}} = -\frac{1}{2}\mathrm{Tr}\left(\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu}\right) + i\Psi^\dagger\sigma^\mu\boldsymbol{D}_\mu\Psi + i\overline{\Psi}^\dagger\sigma^\mu\overline{\boldsymbol{D}}_\mu\overline{\Psi} \quad . \tag{1.18}$$

For $N = 2$, this is the QED Lagrangian with a massless electron, and for $N = 3$, this is QCD.

1.2 The Standard Model

1.2.1 Gauge symmetry in $\mathbf{SU(3) \times SU(2) \times U(1)}$

The Standard Model (SM) Lagrangian uses the Yang-Mills construction on the group $SU(3) \times SU(2) \times U(1)$. Strong interactions are described by $SU(3)$ (color) which has eight gluons, G^A_μ, $A \in 1, 2, ..., 8$. Electroweak interactions incorporate the mixing of $SU(2) \times U(1)$ via the higgs mechanism with $SU(2)$ (weak charge) having three weak bosons, W^a_μ, $a \in 1, 2, 3$ and $U(1)$ (hypercharge) having one hyperon B_μ. The field strengths are independent, with independent coupling constants g_3, g_2, g_1, each calculated using the appropriate covarient derivative in Equation 1.17. This is part of the SM Lagrangian describing the gauge bosons,

$$\mathcal{L}_{\text{bosons}} = -\frac{1}{4g_3^2} G^A_{\mu\nu} G^{\mu\nu A} - \frac{1}{4g_2^2} W^a_{\mu\nu} W^{\mu\nu a} - \frac{1}{4g_1^2} B_{\mu\nu} B^{\mu\nu} \quad . \tag{1.19}$$

The matter (antimatter) components are the spin-$1/2$ fermions which are built from the L representation of Weyl spinors and are listed in Table 1.2. The portion of the SM Lagrangian coming from the fermion kinetic terms is found by exchanging the derivative for the appropriate covariant derivative in Equation 1.9 to be

$$\mathcal{L}_{\text{fermion}} = i \sum_{i=1}^{3} \left(L_i^\dagger \sigma^\mu \boldsymbol{D}_\mu L_i + \bar{e}_i^\dagger \sigma^\mu \boldsymbol{D}_\mu \bar{e}_i + \mathbf{Q}_i^\dagger \sigma^\mu \boldsymbol{D}_\mu \mathbf{Q}_i + \overline{\mathbf{u}}_i^\dagger \sigma^\mu \boldsymbol{D}_\mu \overline{\mathbf{u}}_i + \overline{\mathbf{d}}_i^\dagger \sigma^\mu \boldsymbol{D}_\mu \overline{\mathbf{d}}_i \right) \quad . \tag{1.20}$$

Table 1.2: *Fermions in the standard model consist of three families ($i \in 1, 2, 3$) of leptons and quarks in the singlet and doublet configurations. The symmetries are notated as $(SU(3)^c, SU(2))_Y$ where Y is chosen to satisfy the Gell-Mann-Nishijima formula, Equation 1.21.*

Name	Symbol	I_3	Symmetry
Quark doublet	$\mathbf{Q}_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}$	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	$(3^c, 2)_{1/3}$
Lepton doublet	$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}$	$\begin{pmatrix} 1/2 \\ -1/2 \end{pmatrix}$	$(1^c, 2)_{-1}$
Quark singlet	$\overline{\mathbf{u}}_i$	0	$(3^c, 1)_{-4/3}$
Quark singlet	$\overline{\mathbf{d}}_i$	0	$(3^c, 1)_{2/3}$
Lepton singlet	$\bar{e}_i$	0	$(1^c, 2)_2$

Both quarks and leptons come in three families, known as generations for the quarks and flavors for the leptons. The leptons are colorless and therefore do not couple to gluons, but the quarks do and come in three color varieties for each generation. The singlet configurations contain only electrically charged fermions, and all fermions have their charge set by the Gell-Mann-Nishijima formula,

$$Q = I_3 + \frac{Y}{2} \quad , \tag{1.21}$$

where I_3 is the z-component of weak isospon, $SU(2)$.

All quarks and leptons can exist in $SU(2)$ doublet configurations, and the different I_3 values further break quarks and leptons into types. For quarks, there are u-type (u, c, t) = (up, charm, top) which have charge $+2/3$, and there are d-type (d, s, b) = (down, strange, bottom) which have charge $-1/3$. Leptons are either charged (e, μ, τ) = (electron, muon, tauon) or neutral $(\nu_e, \nu_\mu, \nu_\tau)$ = (electron-, mu-, tau-neutrino), and all charged fermions are arranged such that mass increases with successive generations. In units where $c = 1$, the top ($m_t = 173$ GeV) and bottom ($m_b = 4$ GeV) are the heaviest quarks of their respective types, with the bottom weighing three orders of magnitude greater than the lightest quark, up ($m_u = 2$ MeV). The mass separation for the charged leptons ($m_\tau = 1.7$ GeV$, m_e = 0.5$ MeV) also spans multiple orders of magnitude, but while the observations of neutrino oscillations indicate that neutrinos have mass, only upper limits on the values they may have have been set on the order of MeV.

1.2.2 Symmetry breaking in $\mathbf{SU(2) \times U(1) \rightarrow U(1)}$

Fermions and gauge bosons are massless as written in $\mathcal{L}_{\text{fermions}}$ and $\mathcal{L}_{\text{bosons}}$, but are observed to be massive in nature and can acquire mass through the Brout-Englert-

Higgs mechanism. A scalar (spin-zero) field as given in the top row of Table 1.1 is introduced in a doublet configuration. This adds a Higgs term to the SM Lagrangian,

$$\mathcal{L}_{\text{Higgs}} = \left(\boldsymbol{D}_\mu H\right)^\dagger \boldsymbol{D}_\mu H + m_H H^\dagger H - \lambda\left(H^\dagger H\right)^2 \quad , \tag{1.22}$$

where the first term is the canonical kinetic term for a scalar, the second term generates the mass of the Higgs boson (m_H) and the third term is a potential. This is minimized when

$$H_0^\dagger H_0 = \frac{m^2}{2\lambda} = \frac{v^2}{2}, \quad H_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \quad . \tag{1.23}$$

Taking perturbations about the minimum vacuum expectation value using the Kibble parameterization, the unitary matrix containing three Nambu-Goldstone bosons from the symmetry breaking is factored out and $h(x)$ is introduced as such a perturbation, yielding

$$H = \frac{1}{\sqrt{2}}\boldsymbol{U}(x)\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad . \tag{1.24}$$

In this gauge, the weak bosons, $W^a_{\mu\nu}$, and the hyperion, B_μ appear in linear combiations as the massive W and Z bosons, and as the massless photon (γ) respectively,

$$W^\mp_\mu = \frac{1}{\sqrt{2}}\left(W^1_\mu \pm iW^2_\mu\right) \quad , Z_\mu = \cos\theta_W W^3_\mu - \sin\theta^W B_\mu \quad , A_\mu = \sin\theta_W W^3_\mu + \cos\theta^W B_\mu \quad . \tag{1.25}$$

with Z_μ and A_μ orthogonal.

The couplings between the fermions and gauge bosons are illustrated in Figure 1.1.

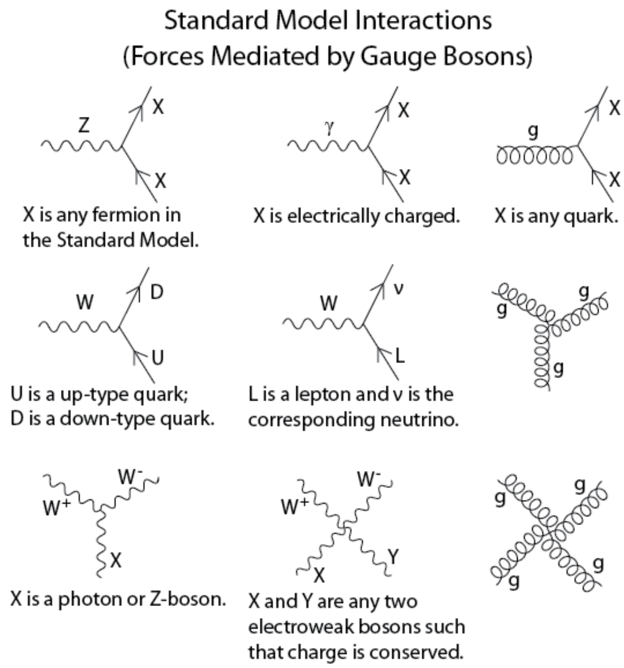

Figure 1.1: *The couplings for the SM gauge interactions.*

and the photon only couples to charged particles. If kinematically allowed, a gluon is able to split into a quark-antiquark pair and W bosons can decay into lepton-neutrino pairs with the lepton and the neutrino belonging to the same type. The Z boson can decay into any fermion-antifermion pair, but charge must be conserved in such an interaction and interactions involving fermions and neutral bosons must remain within a given generation.

1.2.3 QCD and Proton Structure

A key feature of the $SU(3)$ symmetry of the strong force is that the gluons carry one unit of color and one unit of anticolor charge while the quarks carry one unit of color charge. This is what allows gluons to interact with each other as well as with quarks, and that quark confinement is necessitated by the $SU(3)$ structure has not been conclusively determined, but observationally, a free gluon or quark has never been observed. Instead, quarks appear as bound in colorless combinations as mesons ($q\bar{q}$) or as baryons (qqq or $\overline{qqq}$), held together by gluons.

Protons are a type of baryon and at low energy, may combine with a single electron to form a neutral hydrogen atom. At higher energies, the internal structure of the proton becomes more evident, that it contains three valence quarks, uud, which are held together with gluons. When probed at high enough energy, or equivalantly, at short enough length scales, these gluons can also each split into a $q\bar{q}$ pair which typically reannihialate with each other. With gluons inside the proton splitting into quarks and coupling with other gluons, this forms a 'sea' of quarks and gluons, and as protons are acceleratded to energies of GeV or TeV as is the case at the LHC at CERN, the fraction of the momentum of the proton attributed to the gluons becomes higher than that attributed to the valence quarks.