WBB AND MONOPHOTON, TWO INTIMATELY RELATED ANALYSES

by

Thomas Mastrianni Perry

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The dissertation is approved by the following members of the Final Oral Committee:
Iam A. Professor, Professor, Geography
Iam A. Professor, Professor, Geography
Iam A. Professor, Assistant Professor, Geography
Iam A. Professor, Associate Professor, Geography
Iam A. Professor, Associate Professor, History

Dedicated to those who read it.

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I acknowledge that none of this arrived on time.

— T. Perry

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ABSTRACT

ABSTRACT

This space is for the abstract, of which I have one.

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

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

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 1.1.1 illustrates those combinations of lowest dimensionality.

Table 1.1: Representations of $SU(2) \times SU(2)$

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,

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

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

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

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 $\bar{\psi}$. 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 trasformation $\Psi \to e^{i\lambda}\Psi$ 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,

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

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 $\boldsymbol{\lambda}$ can each be used to construct a hermitian $(N \times N)$ matrix. In general, a complex $(N \times N)$ matrix has N^2 parameters, but the phase invariance ψ

1.2 The Process: $pp \to Wb\bar{b} \to \ell\nu b\bar{b}$

1.3 The Process: $pp \to \mathrm{Z}\gamma \to \nu\bar{\nu}\gamma$

2 W+BB PRODUCTION

within the context of the standard model

2.1 Production from Proton-Proton Collisions

protons

production mechanisms, feynman diagrams

2.2 Final State Observables

2.2.1 W boson

decays quickly, leptons/quarks

2.2.2 b-jets

quarks, jets/hadronization

heavy flavor - b quarks

displaced vertices

3 MONOPHOTON PRODUCTION

multiple production mechanisms

3.1 Standard Model Production

Z(nunu) Gamma

production mechanisms, feynman diagrams

3.2 Final State Observables

photon

missing energy

3.3 Other Monophoton Signals

Dark Matter, ADD extra dimensions

connection to SM observables

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