A Measurement of $Z(\nu\bar{\nu})\gamma$ Production and a Search for New Physics in Monophoton Events Using the CMS Detector at the LHC

by

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Abstract

This thesis presents several studies of monophoton final states using 35.9 fb^{-1} of 13 TeV proton-proton collision data collected by the CMS experiment at the LHC in 2016. The standard model $Z(\nu\bar{\nu})\gamma$ cross section is measured as a function of photon transverse momentum. No significant deviations from standard model predictions are observed. The results are also interpreted in the context of several new physics models. Limits are placed on coupling strengths of anomalous triple gauge couplings between photons and Z bosons, new particle masses in simplified models of dark matter, the suppression scale of a dark matter effective field theory model, and the graviton mass scale in a model of extra spatial dimensions.

Acknowledgements

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Chapter 1

Introduction

1.1 Overview

This thesis presents several analyses of event yields in "monophoton" final states, characterized by a single γ with high transverse momentum, along with an overall transverse momentum imbalance typically of equal magnitude and opposite direction to that of the photon. These analyses correspond to 35.9 fb^{-1} of 13 TeV proton-proton (pp) collision data collected in 2016 by the CMS detector at the LHC. A measurement of the production rate for the process $pp \to Z\gamma \to \nu\bar{\nu}\gamma$ is obtained and compared to predictions derived from the standard model (SM) of particle physics. No significant deviation from SM predictions is observed.

The predicted monophoton yield in several theories of physics beyond the SM (BSM) is higher than the SM prediction. This thesis examines two varieties of anomalous triple gauge coupling (aTGC), simplified models of dark matter (DM) interacting with SM matter via a vector or axial-vector mediator, an effective field theory (EFT) of DM interaction with γ and Z bosons, and a model of extra spatial dimensions. For each of these models, 95% confidence level (CL) limits are placed on relevant parameters based on the observed collision data.

1.2 Standard model of particle physics

The "standard model" of particle physics is our current best mathematical framework for describing the behavior of elementary particles. The set of particles described by the SM is illustrated in Fig. 1.1, which groups them according to certain fundamental characteristics. Each particle has an intrinsic angular momentum known as spin, specified by the lower number in each square of Fig. 1.1. Spin can be an integer or half-integer, according to which the particle is classified as a boson or fermion, respectively. The fundamental fermions comprise six "flavors" of quarks and six flavors of leptons, each of which has both a particle and an anti-particle variety; the quarks additionally come in three "colors". We denote a particle by a letter, e.g. q for a generic quark, and its antiparticle partner by an overbar, e.g. $\bar{q}$. The fundamental bosons comprise the scalar H as well as the gauge bosons, in turn comprising the Z, photon (γ), two Ws distinguished by their electric charge, and eight gluons (g) distinguished by a doublet of colors.

The particles are related to one another through various classes of interactions, each of which has a corresponding charge whose sum must be conserved in any physical process. The electromagnetic and weak interactions correspond to electric charge and weak isospin, respectively. In Fig. 1.1, the electric charge is specified by the middle number in each square. For quarks and leptons, weak isospin determines whether the particle is "up-type" (u, d, t, ν_{e}, ν_{μ}, ν_{τ}) or "down-type" (d, s, b, e, μ, τ). The H has a down-type weak isospin, the two W bosons each have a weak isospin matching their electric charge (but with twice the magnitude of that of the fermions), and the other bosons have none. By virtue of the H, the electromagnetic and weak

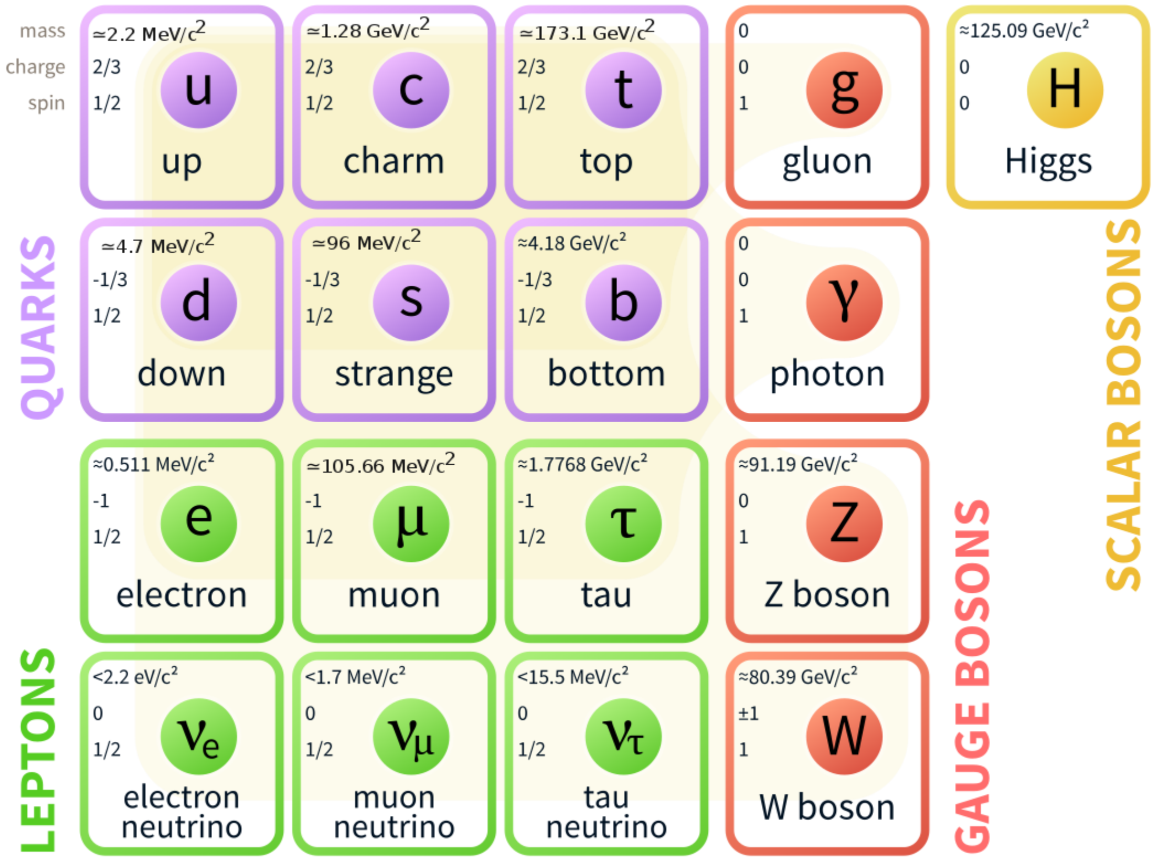

Figure 1.1: The particles of the Standard Model.

interactions are intermingled into what is called the electroweak (EWK) interaction. The three colors carried by quarks and gluons are associated with an interaction described by the theory of quantum chromodynamics (QCD). The preceding discussion applies to normal (i.e. not anti-) particles; antiparticles carry opposite values of all the aforementioned charges.

These interactions lead to the relationships illustrated in Fig. 1.2, in which every linkage represents a direct "coupling", which allows a particle at one end of the link to evolve directly into a particle at the other end. Particles with a nonzero electric charge are all coupled directly to the photon. The photon is coupled to the weak bosons (Z and W), which in turn couple to all of the fundamental fermions. The gluons couple directly with each other and with the quarks. Particles that couple directly to the H have an intrinsic mass (specified by the top number in each square of Fig. 1.1) tied to the strength of their coupling. In the SM, any particle that does not couple directly to the H is massless. The SM has been profoundly well-studied and is extremely successful in its predictive capacity, as documented in numerous comprehensive texts on the subject, e.g. [2, 3].

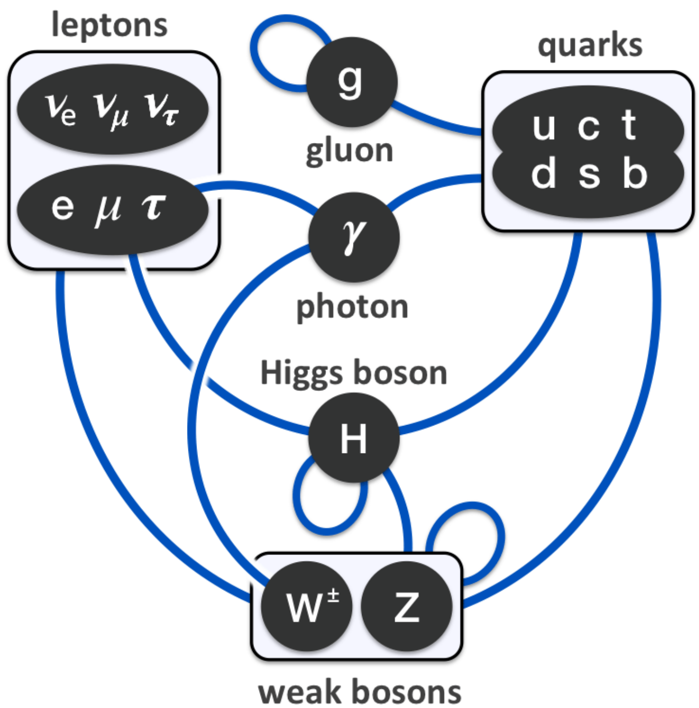

Figure 1.2: Standard Model couplings.

1.3 $Z(\nu\bar{\nu})\gamma$ and anomalous triple gauge couplings

Specific processes of particle evolution can be illustrated using Feynman diagrams. These are assembled by combining fundamental interaction vertices: the SM vertices relating the fermions and gauge bosons are listed in Fig. 1.3. A diagram without internal loops is called a tree-level diagram. A diagram with a loop has at least one more vertex than that same diagram with the loop removed, and the more vertices a diagram has, the less it tends to contribute to the expected yield for a given process. Hence, the simplest tree-level diagrams for a process are the most dominant in their effects.

In the SM, events with a monophoton signature arise at the LHC (chapter ??) primarily from the process $q\bar{q} \to Z\gamma \to \nu\bar{\nu}\gamma$, where q is any single species of quark, ν is any single species of neutrino, and the neutrino-antineutrino pair arises from the decay of a short-lived Z boson. The leading tree-level diagram for this process is shown in Fig.??. We typically abbreviate this process by reference to its final state, $Z(\nu\bar{\nu})\gamma$.

Putative vertices joining three particles that are not found in the SM are known as aTGCs. For example, there is no fundamental SM vertex joining a single γ to a pair of Zs, or a single Z to a pair of γs. A model describing the generic phenomenology of these aTGCs is developed in [4–6]. For an intermediate state $V = Z, \gamma$ decaying to a final state $Z\gamma$ pair, this model parametrizes the effective vertex interaction $Z\gamma V$ by a set of factors h_i^V (i from 1 to 4). Increasing the values of these parameters significantly increases the predicted rate of occurrence of $Z(\nu\bar{\nu})\gamma$ processes, by allowing the reaction to proceed via the diagram shown in Fig.??, in which the aTGC vertex is covered by an opaque circle.

The circle could be thought of as masking a more detailed process taking place underneath. The SM admits processes that are predicted to contribute to this effective vertex, but all SM contributions to $h_{3,4}^V$ have at least one internal loop that could fit within the circle, and further loops are required for $h_{1,2}^V$ contributions [5]. As a consequence, the SM contribution to all eight h_i^V parameters is quite close to zero.

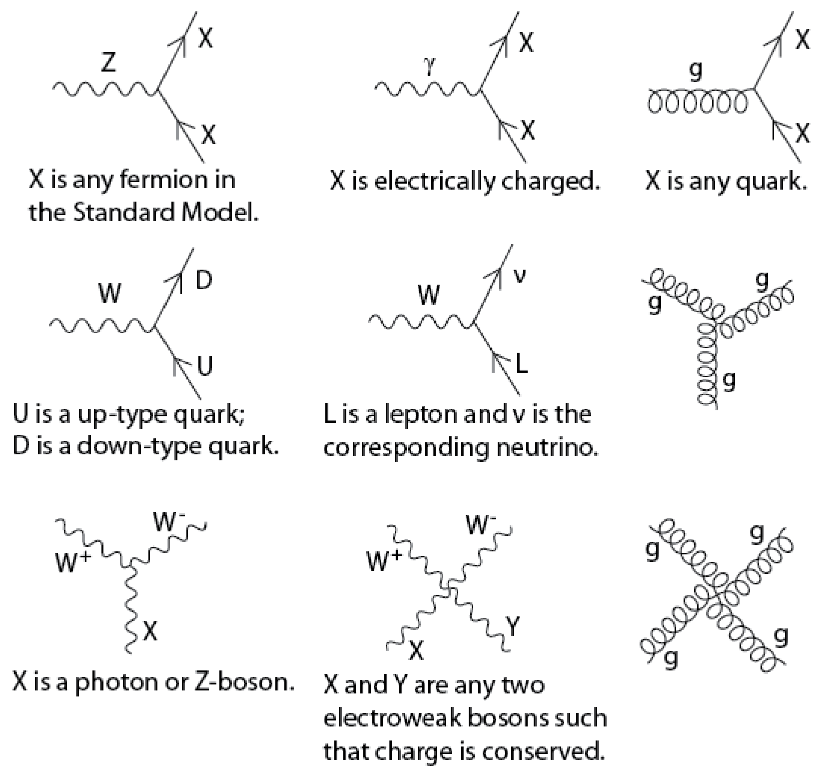

Figure 1.3: Fermion and gauge boson vertices of the standard model.

The observation of a substantial nonzero value for any h_i^V would be a compelling sign of BSM physics.

The contributions to the $Z(\nu\bar{\nu})\gamma$ production rate coming from $h_{1,2}^V$ are independent of those from $h_{3,4}^V$ (for any V), and also nearly identical in magnitude, so without loss of generality we only focus on scenarios for which $h_{3,4}^V$ are nonzero. The contributions from h_i^Z are largely independent of those from h_j^γ (for any i,j), so these are examined separately. However, the contributions from h_3^V are substantially correlated with those from h_4^V (and similarly for $h_{1,2}^V$), so we examine scenarios in which $h_{3,4}^V$ take on assorted pairs of values, both of which may be nonzero. The theoretical relationships between these parameters are explored in [5].

Previous searches

The LEP collider established constraints on each of the eight the parameters h_i^V in the context of the process $e^+e^- \to Z\gamma$. In a statistical combination of searches perfomed by the DELPHI, L3, and OPAL experiments, examining 3 fb^{-1} of e^+e^- collision data at center-of-mass energies ranging from 130 GeV to 209 GeV, the 95% CL intervals of seven of the parameters contain 0, with total ranges between 0.05 and 0.10 for h_i^γ and between 0.14 and 0.25 for h_i^Z; the 95% CL interval for the remaining factor h_4^γ spans 0.01 to 0.05 [7].

The LEP combined analysis assumed that all but one of the eight parameters were fixed to the SM expectation of 0. It was also the last major effort to obtain limits on $h_{1,2}^V$ independently of $h_{3,4}^V$, as subsequent searches have taken the present approach of focusing on $h_{3,4}^V$ alone, for the reasons listed above. Uniquely among the LEP experiments, the L3 Collaboration also placed limits on correlated pairs of parameters, shown in Fig. 1.4 [1].

This form factor was introduced in the common reference [5] but was not used in LEP [7] or subsequent LHC analyses, which treat the h_i^V parameters as constants.

None of these analyses report any significant deviation from SM predictions.

1.4 Dark matter simplified models

The SM does not explain every observed natural phenomenon. One example of a phenomenon with no apparent SM explanation is so-called “dark matter”. On cosmological scales there appears to be an abundance of massive matter with no interactions of any sort other than its gravitational pull. No SM particle is predicted to exhibit this behavior, and this has spurred the development of BSM theories aiming to account for it.

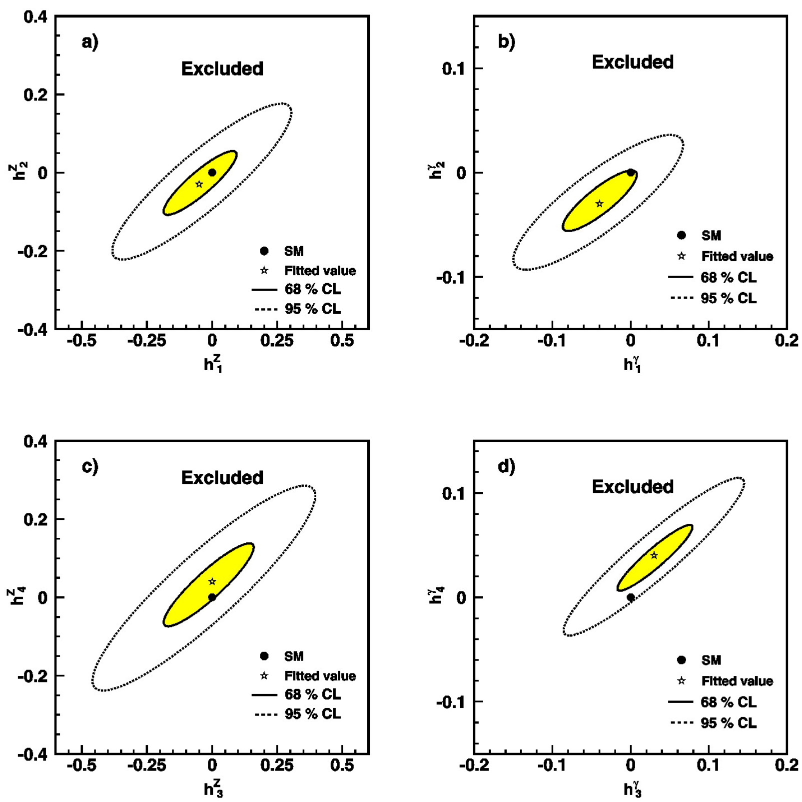

Figure 1.4: h_i^V exclusion contours from the L3 experiment at the LEP collider [1].

The circle obscuring the DM vertex denotes that this is an effective vertex in the generic model that mimics the behavior of true vertices in a full theory of particle physics, such as the SM. Like the ADD theory discussed in Sec. 1.5, this model is only capable of making meaningful physical predictions within a restricted kinematic range. These theories are meant to encapsulate highly generic, model-independent features of potential new-physics phenomena, but outside of their range of kinematic validity, the fully generic description must break down as more specific, model-dependent BSM signatures manifest themselves.

1.5 ADD gravitons

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