Shining Light on Dark Matter, One Photon at a Time

by

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Abstract

A search is conducted for new physics in final states containing a photon and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV. The data collected by the CMS experiment at the CERN LHC correspond to an integrated luminosity of 35.9 inverse femtobarns. No deviations from the predictions of the standard model are observed. The results are interpreted in the context of dark matter production and limits on new physics parameters are calculated at 95% confidence level. For the two simplified dark matter production models considered, the observed (expected) lower limits on the mediator masses are both 950 (1150) GeV for 1 GeV dark matter mass.

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Chapter 1

Motivation

1.1 The Standard Model

The Standard Model (SM) of particle physics describes the physical properties and dynamics of fermions, the fundamental constituents of matter, and their interactions in the language of a Lorentz-invariant quantum field theory (QFT). The Standard Model consists of a set of fermion fields, shown in Table 1.1 and the local gauge symmetry group that acts on them

$$G_{\mathrm{SM}} = \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y, \tag{1.1}$$

which is composed of the subgroups

$$G_{\mathrm{QCD}} = \mathrm{SU}(3)_C \qquad \text{and} \tag{1.2}$$

$$G_{\mathrm{EWK}} = \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y, \tag{1.3}$$

corresponding to the *strong* and *electroweak* interactions, respectively. Each fermion field exists in a unique representation of G_{SM}, also summarized in Table 1.1. The possible represenations of $\mathrm{SU}(3)_C$ are triplet, conjugate, and singlet, denoted by $\mathbf{3}$, $\bar{\mathbf{3}}$, and $\mathbf{1}$, respectively, while the possible representations of $\mathrm{SU}(2)_L$ are doublet and singlet, denoted by $\mathbf{2}$ and $\mathbf{1}$, respectively. All fermions exist in the singlet representation of $\mathrm{U}(1)_Y$, only distinguished by differing values of the weak hypercharge Y. Conversely, all fermions in non-singlet representations of $\mathrm{SU}(3)_C$ and $\mathrm{SU}(2)_L$ have the same interaction strength, a feature known as universality.

Table 1.1: The categories of SM fermions and the action of the SM local gauge symmetry group G_{SM}. Each category contains three members, one for each generation of the Standard Model. A corresponding table exists for the charge conjugated fields representing the anti-fermions. The subscripts L and R denote whether the field is left- or right-handed.

Name	Symbol	Y	$\mathrm{SU}(2)_L$ rep.	$\mathrm{SU}(3)_C$ rep.
Left-handed quark	q_L	$1/6$	**2**	**3**
Right-handed up-type quark	u_R	$2/3$	**1**	**3**
Right-handed down-type quark	d_R	$-1/3$	**1**	**3**
Left-handed lepton	ℓ_L	$-1/2$	**2**	**1**
Right-handed charged lepton	e_R	-1	**1**	**1**
Right-handed neutrino	ν_R	$1/6$	**1**	**1**

For each category of fermion listed in Table 1.1, there exist three generations or copies in the Standard Model, identical except for differing masses. The lepton electroweak doublets contain the left-handed charged leptons and neutrinos

$$\ell_L = \begin{pmatrix} \nu_e \\ e_L^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu_L^- \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau_L^- \end{pmatrix}, \tag{1.4}$$

and the right-handed lepton singlets contain the right-handed projections of the same leptons and neutrinos. The quark electroweak doublets contain the left-handed up-type and down-type quarks

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix}, \tag{1.5}$$

and the right-handed quark singlets contain the right-handed projections of the same quarks. Quarks also exist in a strong triplet, which will be denoted with a superscript c as necessary.

1.1.1 Strong Interactions

The strong interactions of quarks and gluons are described by quantum chromodynamics (QCD), with the Lagrangian

$$\mathcal{L}_{\mathrm{QCD}} = i\bar{q}^a_f \not{D}^{ab} q^b_f + m_f \bar{q}^a_f q^a_f - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \theta \frac{g_s^2}{72\pi^2} \epsilon_{\mu\nu\rho\sigma} G^{c,\mu\nu} G^{c,\rho\sigma}, \tag{1.6}$$

where repeated indices are contracted. The q^a_f are the quark-field Dirac spinors of flavor $f \in \{u, d, c, s, t, b\}$, color $a \in \{r, g, b\}$ (he basis element of the triplet representation), and mass m_f. The first term in Equation 1.6 contains the QCD covariant derivative

$$D^{ab}_\mu = \delta^{ab} \partial_\mu - i g_s \sum_c t^{ab}_c G_{c,\mu}, \tag{1.7}$$

where g_s is the strong interaction coupling strength, t_c are the eight 3×3 Hermitian traceless matrices that serve as the generators of the triplet representation of $\mathrm{SU}(3)_C$, and G_c are the corresponding eight gluon fields. The third term in Equation 1.6 contains the gluon field strength tensors

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g_s f^{abc} G^b_\mu G^C_\nu, \tag{1.8}$$

where f^{abc} are the structure constants of $\mathrm{SU}(3)_C$. The non-Abelian structure of the $\mathrm{SU}(3)_C$ group means allows for 3-gluon and 4-gluon interactions in addition to the quark-antiquark-gluon interactions.

The last term in Equation 1.6 violates CP conservation and produces a non-zero electric dipole moment (EDM) for the neutron. Experimental limits on the neutron EDM constraint the θ parameter to be smaller than 10^{-10}. The Peccei-Quinn theory provides a possible method to force θ to zero by introducing the hypothetical axion particle. The axion is a potential dark matter candidate and will be discussed further in Section **??**.

1.1.2 Electroweak Interactions

The electroweak interactions of fermions are described by $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ gauge group, with the Lagrangian

$$\mathcal{L}_{\mathrm{EWK}} = i\bar{\psi}_i \not{D} \psi_i - \frac{1}{4}\vec{W}_{\mu\nu} \cdot \vec{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \tag{1.9}$$

where repeated indices are contracted and $\psi \supseteq \{q_L, u_R, d_R, \ell_L, e_R, \nu_R\}$ is the set of SM fermions, and the gauge field tensors are given by

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \qquad \text{and} \tag{1.10}$$

$$\vec{W}_{\mu\nu} = \partial_\mu \vec{W}_\nu - \partial_\nu \vec{W}_\mu + g\vec{W}^\mu \times \vec{W}^\nu, \tag{1.11}$$

where $\vec{W}_\mu$ and B_μ are the gauge fields for $\mathrm{SU}(2)_L$ and $\mathrm{U}(1)_Y$, respectively, and g is the coupling strength for $\mathrm{SU}(2)_L$. The first term in Equation 1.9 contains the EWK covariant derivative

$$D_\mu = \partial_\mu - ig\vec{T} \cdot \vec{W}_\mu - ig'YB_\mu, \tag{1.12}$$

where g' is the coupling strength for $\mathrm{U}(1)_Y$, Y is the $\mathrm{U}(1)_Y$ hypercharge of the fermion field, and $\vec{T}$ are the generators of the doublet representation of $\mathrm{SU}(2)_L$. The generators can be written in terms of the Pauli spin matrices $\vec{T} = \vec{\sigma}/2$ and only have non-zero action on left-handed particles. The values of the hypercharge Y shown in Table 1.1 are chosen such that the physical electric charge of each fermion is given by $Q = T_3 + Y$.

Notice that Equation 1.9 does not contain a Dirac mass term like that found in Equation 1.6. This is because the term

$$m\bar{\psi}\psi = m\left(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L\right) \tag{1.13}$$

mixes the left-handed and right-handed fermions leading to a Lagrangian that is no longer invariant under $\mathrm{SU}(2)_L$. As the observed fermions are not massless, the Lagrangian given in Equation 1.9 is incomplete and an additional mechanism needs to be introduced to produce non-zero fermion masses.

1.1.3 Electroweak Symmetry Breaking

Spontaneous electroweak symmetry breaking provides the mechanism we need, as well as providing masses to the weak gauge bosons. The $\mathrm{SU}(2)_L$ symmetry is broken by introducing a left-handed complex scalar doublet ϕ with $Y_\phi = {}^1\!/\!{}_2$ to the Lagrangian in the following manner

$$\mathcal{L}_{\mathrm{EWK}} \mapsto \mathcal{L}_{\mathrm{EWK}} + |D_\mu \phi|^2 + \mu^2 \phi^2 - \lambda\, |\phi|^4 . \tag{1.14}$$

We choose to write this complex doublet, known as the complex Higgs field, in terms of four real-valued fields so that

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} . \tag{1.15}$$

Fortunately, the two self-interaction terms create a Higgs potential with a degenerate global minimum at the vacuum expectation value (vev)

$$v \equiv \langle |\phi| \rangle = \sqrt{\frac{\mu^2}{\lambda}}, \tag{1.16}$$

and through gauge rotations we set $\langle \phi_{1,2,4} \rangle = 0$, removing three degrees of freedom and producing three massless Nambu-Goldstone bosons. The remaining degree of freedom is the real Higgs field H which expresses small peturbations around the vev in the third component of the complex Higgs field $\phi_3 = v + H$.

The kinetic term in Equation 1.14 couples the complex Higgs field to the EWK gauge bosons as follows at the vev

$$|D_\mu \phi|^2 = \frac{v^2}{8} \left[\left(gW_\mu^1\right)^2 + \left(gW_\mu^2\right)^2 + \left(g' B_\mu - gW_\mu^3\right)^2 \right] . \tag{1.17}$$

Diagonalizing this term gives rise to the three massive weak bosons and the massless photon that we observe in nature:

$$
\begin{array}{l|l}
W_\mu^\pm \equiv \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp W_\mu^2\right) & m_W = \frac{1}{2}vg \\
Z_\mu \equiv \cos\theta_\mathrm{W} W_\mu^3 - \sin\theta_\mathrm{W} B_\mu & m_Z = \frac{1}{2}v\sqrt{g^2 + (g')^2} \\
A_\mu \equiv \sin\theta_\mathrm{W} W_\mu^3 + \cos\theta_\mathrm{W} B_\mu & m_A = 0,
\end{array}
\tag{1.18}
$$

where $\tan\theta_\mathrm{W} = g'/g$.

We can also expand Equation 1.14 about the vev giving us the following Higgs Lagrangian

$$
\mathcal{L}_H = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}m_H^2 H^2 - \frac{1}{2}m_W^2 W_\mu^+ W^{-\mu} - \frac{1}{2}m_Z^2 Z_\mu Z^\mu \tag{1.19}
$$

$$
+ \frac{m_H^2}{2v}H^3 + \frac{2m_W^2}{v}W_\mu^+ W^{-\mu} H + \frac{m_Z^2}{v} Z_\mu Z^\mu H \tag{1.20}
$$

$$
+ \frac{m_H^2}{8v^2}H^4 + \frac{m_W^2}{v^2}W_\mu^+ W^{-\mu} H^2 + \frac{m_Z^2}{2v^2} Z_\mu Z^\mu H^2, \tag{1.21}
$$

where $m_H = \mu\sqrt{2}$. Thus, we see that the real Higgs field H has trilinear and quartic couplings to itself and the weak gauge bosons with coupling strengths proportional to the mass squared of the appropriate boson. This suggests a way to introduce fermion masses through the Higgs field.

1.1.4 Fermion Masses

Introducing Yukawa couplings between the complex Higgs field ϕ and the SM fermion fields enables us to add mass terms for the fermions. First, we start with the terms for charged leptons,

$$
\mathcal{L}_\mathrm{Y}^\mathrm{leptons} = \bar{\ell}_L Y_e \phi e_R + \bar{e}_R Y_e \phi^\dagger \ell_L, \tag{1.22}
$$

where Y_e is the Yukawa matrix for the charged leptons. In general, Yukawa matrices and thus mass matrices are non-diagonal and hence we need to convert from the electroweak eigenstates $f_{L,R}$ to the mass eigenstates $\tilde{f}_{L,R} = U_{L,R}^f f_{L,R}$ where $U_{L,R}^f$ is a unitary matrix. With this we rewrite Equation 1.22 in terms of the mass eigenstates

$$\mathcal{L}_{\rm Y}^{\rm leptons} = \bar{\tilde{\ell}}_L U_L^e Y_e \phi U_R^{e\dagger} \tilde{e}_R + \bar{\tilde{e}}_R U_R^e Y_e \phi^\dagger U_L^{e\dagger} \tilde{\ell}_L \tag{1.23}$$

$$= \bar{\tilde{\ell}}_L \tilde{Y}_e \phi \tilde{e}_R + \bar{\tilde{e}}_R \tilde{Y}_e^\dagger \phi^\dagger \tilde{\ell}_L, \tag{1.24}$$

where $\tilde{Y}_e = U_L^e Y_e U_R^{e\dagger}$ is the diagonalized Yukawa matrix for the charged leptons. After electroweak symmetry breaking, these terms become

$$\mathcal{L}_{\rm Y}^{\rm leptons} = -\frac{v+H}{\sqrt{2}} \left(\bar{\tilde{e}}_L \tilde{Y}_e \tilde{e}_R + \bar{\tilde{e}}_R \tilde{Y}_e^\dagger \tilde{e}_L \right) \tag{1.25}$$

$$= -\left(1 + \frac{H}{v}\right) \left(\bar{\tilde{e}}_L \tilde{M}_e \tilde{e}_R + \bar{\tilde{e}}_R \tilde{M}_e^\dagger \tilde{e}_L \right) \tag{1.26}$$

$$= -\tilde{M}_e \bar{e} e - \frac{\tilde{M}_e}{v} \bar{e} e H, \tag{1.27}$$

where $\tilde{M}_e = v\tilde{Y}_e/\sqrt{2}$ is the diagonalized mass matrix for the charged leptons and e is the set of massive Dirac spinors for the charged leptons.

From Equation 1.27, we see that the Yukawa couplings between the complex Higgs field ϕ and the charged leptons result in a Dirac mass term and a coupling to the real Higgs field H that is proportional to the mass of the charged leptons and the vev. The same procedure is used to introduce mass terms for the down-type quarks whereas for the neutrinos and up-type quarks we must use the conjugate doublet $\phi_c = -i\sigma_2\phi^*$ in place of ϕ to obtain the same result. Note that for the charged leptons and up-type quarks, it is possible to define a basis of simultaneous electroweak and mass eigenstates, so in practice $\tilde{Y}_{e,u} = Y_{e,u}$ as $U_L^{e,u} = U_R^{e,u} = \mathbf{I}$. However, it is not possible to do this for the neutrinos at the same time as the charged leptons or for the down-type quarks at the same time as the up-type quarks.